

# Abstract

Once a gas field is developed liquid production may start and persists sometime during the production life of most dry gas wells. This liquid could be condensate, water or both, resulting from condensate dropout due to reduction of pressure or water breakthrough. Liquids can accumulate in the wellbore if the liquid fraction increases or if gas rates decrease (e.g. with depletion) and are not able to carry liquids to surface. This phenomenon is known as liquid loading and can cause further reduction of gas rates due to excessive back-pressure on the formation and erratic production. To effectively plan and design a gas well that will eventually produce liquid, it is essential to be able to accurately predict the onset of liquid loading.

In this thesis, several aspects on gas flow with associated liquid in upward inclined pipes have been studied. Experimental and numerical work have been carried out, with the following goals: (a) improve the understanding of the effect of liquid viscosity and inclination on flow map, liquid loading onset and post-loading behaviour. (b) quantify accuracy of existing liquid loading onset models using laboratory and literature data and development of an improved model with more predictability. (c) evaluate the behaviour of existing liquid loading onset models when the droplet fraction is taken into account. (d) quantify the variability in the onset rates predicted by several onset criteria and pressure drop models.

Several experimental tests were performed and data acquired for three different fluid systems (air-water, air-Exxsol D80 and air-mixed oil) and wide range of pipe inclinations. The experimental data was compared against numerical models to quantify their accuracy in predicting the flow pattern transition between annular and slug flow.

In general, the liquid droplet-based models considered underestimated the critical gas velocity while the models based on liquid film were more conservative. Moreover, liquid film models have better accuracy than liquid droplet models. The commercial transient simulator (OLGA 7.3) did not capture properly the influence of viscosity nor predicted transitions for pipe inclinations lower than  $60^\circ$  from horizontal. The model of Shekhar et al. (2017) had the best accuracy from all models considered.

Including the entrainment of droplets in the gas core in liquid film models improved modestly their accuracy when predicting the experimental data and data reported in the literature.

The new liquid loading onset model developed in this work is based on the model of Barnea (1986) and uses the liquid holdup in the momentum equation instead of assuming an uniform film thickness. The model successfully reproduces the experimental data and

literature data, with a higher accuracy than the model of Shekhar et al. (2017). Therefore, it represents a significant improvement and contribution of the present work.

Finally, the numerical study performed on a synthetic vertical well shows that the loading criteria and pressure drop model used affect considerably the onset rate predicted. The variation in the gas liquid loading onset rate is considerable. In general, when the gas rate is lowered below the liquid loading onset rate, the wellbore transitions rapidly from unloaded to fully loaded, except for one of the models studied.

# Preface

The work presented in this dissertation was performed at the Norwegian University of Science and Technology (NTNU) between January 2016 and December 2019. It was part of a joint academic project sponsored by Norad (through EnPe), headed by Eduardo Mondlane Univeristy (UEM) and NTNU. I am indebted to the sponsors for financing the three and half year of my doctoral work.

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- Muito Obrigado -

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# Nomenclature

## Latin letters

|          |                                    |
|----------|------------------------------------|
| $A$      | Pipe cross section area, [ $m^2$ ] |
| $D$      | Pipe diameter, [m]                 |
| $dp/dx$  | Pressure gradient, [Pa/m]          |
| $E$      | Droplet entrainment, [-]           |
| $f$      | Friction factor, [-]               |
| $g$      | Gravity acceleration, [ $m/s^2$ ]  |
| $H_L$    | Liquid holdup, [-]                 |
| $h_L$    | Liquid level, [-]                  |
| $p$      | Pressure, [Pa]                     |
| $p_{wf}$ | Bottom flowing pressure [Psia]     |
| $p_{wh}$ | Wellhead pressure [Psia]           |
| $Re$     | Reynolds number, [-]               |
| $S$      | Wet perimeter, [mm]                |
| $v_{sg}$ | Superficial gas velocity, [m/s]    |
| $v_{sl}$ | Superficial liquid velocity, [m/s] |

## Greek letters

|          |   |
|----------|---|
| $\alpha$ | In-situ volume fraction of gas  |
| $\beta$  | Half of angle confirmed by liquid wetted periphery in stratified flow, [ $^\circ$ ] |
| $\delta$ | Film thickness, [m]   |
| $\mu$    | Viscosity, [cP]   |
| $\Phi$   | Pipe circumferential, [ $^\circ$ ]  |
| $\rho$   | Density, [ $kg/m^3$ ]   |
| $\sigma$ | Surface tension, [N/m]  |
| $\tau$   | Shear stress, [Pa]  |
| $\theta$ | Pipe angle from horizontal, [ $^\circ$ ]  |

## Subscripts

|       |             |
|-------|-------------|
| $atm$ | atmospheric |
| $g$   | gas         |
| $i$   | interfacial |
| $l$   | liquid      |
| $s$   | superficial |
| avg   | average     |



|     |         |
|-----|---------|
| max | maximum |
| min | minimum |
| NS  | no-slip |

### **Abbreviations**

|       |                                   |
|-------|-----------------------------------|
| Calc  | Calculated                        |
| CV    | Control valve                     |
| DQA   | Data acquisition system           |
| elmag | Electromagnetic                   |
| Exp   | Experimental                      |
| FH    | From horizontal                   |
| FR    | Flow Regime                       |
| FRM   | Flow regime maps                  |
| ID    | Inner diameter                    |
| LL    | Liquid loading                    |
| Obs   | Observed                          |
| std   | Standard deviation                |
| STP   | Standard Temperature and Pressure |
| VBA   | Visual Basic for Applications     |
| WGR   | Water-gas ratio                   |

# Chapter 1

## Introduction

### 1.1 Background

Production of natural gas is becoming more and more attractive, mainly due to the environmental footprint, which is relatively small compared to oil and coal production. Advances in engineering practices in unconventional gas fields (e.g. shale fields in U.S) and large offshore gas discoveries in countries like Mozambique and Tanzania have sparked interest of many oil companies in developing projects in such fields. Besides production of natural gas, these wells also produce liquids, such as condensate and water, in moderate amounts, but if accumulated in the wellbore, it can hinder the wells productivity.

At early production, the gas flow rate is high enough to carry any existing co-produced liquid out of the well, which makes the well produce at stable condition. However, at some later period in the life of the well, as reservoir pressure declines, the gas production rate drops as well as its capacity of lifting any liquid to the surface. Under such conditions, non-removed liquid accumulates in the wellbore, leading to a phenomenon commonly known as liquid loading. If not counteracted, the accumulated liquid creates a back-pressure against the formation, leading to increased resistance along the gas production pathway, causing further accumulation of liquid, a reduction of the natural flow of gas from the reservoir to the surface, and eventually a premature abandonment of the well. This leads to economic losses due to reduction in hydrocarbon sales and to increase of operational expenses. For many years research in this area was aiming at accurately predicting the onset of liquid loading, to predict when the problem might arise, so that corrective and preventive measures could be taken well in advance. Hence, many models have been proposed for liquid loading predictions in gas wells. A standard model extensively used to predict the onset of liquid loading is based on the “critical velocity” concept.

The critical gas velocity concept assumes that most of the liquid phase is distributed as droplets dispersed in the gas. When the gas velocity is equal to the critical velocity, the liquid phase is moving neither upward nor downward. When the gas velocity falls below the critical gas velocity, the liquid will start to accumulate in the wellbore and gas production becomes erratic.

The ultimate goal of present research work is to contribute to improving current onset of liquid loading criteria and modelling practices. To reach this goal a comprehensive understanding of the liquid loading multiphase flow phenomenon using experimental and numerical modelling studies was conducted. Experimental data acquired at the Multiphase Flow laboratory at NTNU were used to evaluate applicability of existing theoretical models and to validate the new proposed model.

## 1.2 Objectives

The primary objective of this work was to improve the understanding of liquid loading of gas-liquid flow in deviated pipes by performing experimental work and data analysis of information available in the literature. The specific objectives of this work were:

- Perform experimental investigation on multiphase flow mechanics related to gas-liquid flow in inclined pipes using water, light oil and viscous oil.
- Build a numerical model to compare the experimental data and data in the literature against numerical models available in the public domain.
- Quantify the accuracy and deficiencies of existing liquid loading onset models.
- Investigate the effect of entrainment droplets in the gas core in the existing liquid film models.
- Develop a new model for prediction of the onset of liquid loading in inclined pipe.
- Analyse and quantify liquid accumulation along the wellbore vs. gas flow rate, considering several onset criteria and pressure drop models.

## 1.3 Contributions

During the research period several contributions were made, in terms of modelling work and experimental work. This work's contributions include:

- Multiphase lab upgrades related to start-up and shutting-down procedures, and the modification of existing experimental facility, by:
  - Installing and calibrating appropriate instrumentation to measure pressure gradient covering the whole range of pipe inclination tested.
  - Installing high-speed camera and lighting (LED panel) to enable a better visualization of the flow present in the pipe.
- Experimental data acquisition on gas-liquid two-phase flow in upwards inclined pipe by investigating :
  - Effect of liquid viscosity on the flow pattern transition in an inclined pipe.
  - The effect of fluid type, inclination angles and flow rates on the liquid loading deposition mechanism.

- Theoretical investigation on the applicability of available models for the prediction of:
  - Flow pattern transition in inclined pipe.
  - Liquid loading deposition mechanism in inclined pipe.
- Numerical analyses on existing dynamic multiphase flow simulator to quantify the accuracy and deficiencies of the simulator on the prediction of:
  - Flow pattern transition in inclined pipe.
  - Liquid loading deposition mechanism in inclined pipe.
- Development and validation of a new model for prediction of the onset of liquid loading in inclined pipe.

## 1.4 Research overview

The work performed in this research was partly experimental and partly numerical. A test matrix (see Section 3.4) was designed and executed to support the study of flow regime transition model and onset of liquid loading in gas-liquid flow in inclined pipes.

The diagram presented in Figure 1.1 summarises the activities of the research work, where the major activities encompassed literature survey, experimental and flow simulation. Experimental data were compared with results from existing numerical models and from a commercial transient simulator.

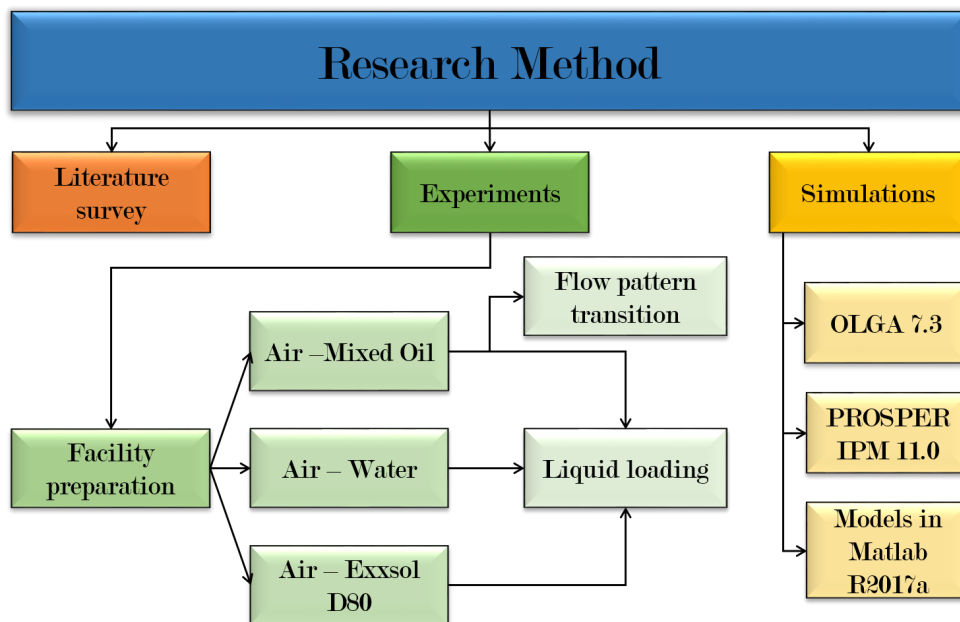


Figure 1.1. Research activity overview

At the beginning of the research project, a careful and detailed literature survey on topics related to liquid loading and two-phase gas-liquid multiphase flow in upward inclined pipes were carried out.

The experimental stage started with facility preparation, which gradually included improvements of instrumentation, updating the acquisition system and familiarisation with laboratory equipment handling, such as start-up; testing; shutdown and safety procedures. Later on, numerical studies were performed, where acquired data was used for evaluation of existing methods.

### 1.4.1 Thesis structure

Five chapters and three appendices define the dissertation subdivisions. The chapters cover the following topics. Theoretical background on diverse aspects within the research topic. Experimental work procedures and techniques. Results of different evaluations. Conclusions and recommendations of further work.

Thus, Chapter 2 gives a general review of the most relevant theories and concepts available in the literature on experimental and analytic studies related to the scope of the thesis. Chapter 3 provides a detailed description of the experimental procedures, test section, data acquisition and processing methods as well as of the instrumentation, which might be useful as basis for future experiments in similar or distinct work. Chapter 4 presents the results and the discussion on validation of the model found in the literature with the data acquired. Chapter 5 concludes the work, and recommends further studies.

### 1.4.2 Paper list

This PhD work has produced the following publications:

- **Paper 1 (Conference paper, published):** Vieira, C., Kallager, M., Vassmyr, M., Forgia, N., Yang, Z., 2018, Experimental investigation of two-phase flow regime in an inclined pipe, 11<sup>th</sup> North American Conference on Multiphase Production Technology, Banff, Canada, 6-8 June 2018
- **Paper 2 (Conference paper, published):** Vieira, C., Stanko, M. 2019, Applicability of models for liquid loading prediction in gas wells, 81<sup>st</sup> SPE Europec featured at 81st EAGE Conference and Exhibition, London, 3-6 June 2019
- **Paper 3 (Conference paper, published):** Vieira, C., Stanko, M. 2019, Effect of droplet entrainment in liquid loading prediction, 19<sup>th</sup> international conference on multiphase production technology. France, Cannes, 5-7 June 2019
- **Paper 4 :** Vieira, C., Stanko, M., Oplt, T., An improved model to predict liquid loading onset in inclined pipes considering a non-uniform liquid wall film.  
*Draft paper to be submitted to the Journal of Natural Gas Science and Engineering*

# Chapter 2

## Review of inclined gas-liquid flow

For several years, efforts have been directed towards improving the understanding of multiphase flow complexity, as well as to develop technical solutions for handling and controlling flow behaviour. Basically, multiphase flow refers to the physical phenomenon with two or more phases flowing in a pipe. In multiphase flow, the phases exhibit different distribution configurations in the pipe depending on the characteristics of the system, the properties of the fluid and operational conditions. The geometrical configurations are called flow patterns or flow regimes. Determination of flow regime in multiphase flow analysis is a major challenge, and pressure drop, holdup and phase velocities are strongly dependent on flow pattern (Shoham, 2006). Two-phase flow can be characterised as liquid-liquid or gas-liquid system, where the first case means that the two liquids are immiscible. Three-phase flow is normally characterised by liquid-liquid-gas systems. Gas-liquid two-phase flow can occur in various industrial fields such as chemical and nuclear reactors in a wide range of engineering applications. In the petroleum industry, this type of flow can occur during production and transportation of oil and gas, in production tubing, in flow-lines and in processing plants. For instance, in gas wells, the decline of pressure and temperature during long-term production could lead to condensation of liquid from the gas, thereby creating a complex two-phase flow system that must be studied in detail. Gas wells have in general drawn much attention among researchers regarding their behaviour, especially for the phenomenon called liquid loading.

The literature review deals with gas-liquid two-phase flow in upward inclined pipe. The review presented in this section is limited to gas dominated flows with low liquid content, for which annular flow and transition to intermittent flow (slug or churn flow) are the dominant flow regime of interest. Other flow patterns were also explored. A summary of all the most relevant studies are presented in Table 2.1 and Table 2.2 at the end of the Chapter.

## 2.1 Flow pattern maps in inclined pipe

For many years the flow pattern classification in two-phase gas-liquid flow have been a topic highly subjective to lack of agreement among investigators, due to complex patterns that is usually classified individually by visual observations, videos and photos of the flow. For the industry this has been a disadvantage, since different visual interpretations were reported under identical flow conditions. Therefore, many empirical correlations to classify and identify the flow patterns quantitatively were proposed.

Nowadays, with exploration into deep water from central installations, production wells tend to be highly deviated wells with inclinations between  $10^\circ$  to  $85^\circ$ . For inclined wells little information is available and most of the existing correlations have not been successful in predicting their flow behaviour. Normally, pipe with a low upward inclination angle from horizontal can present considerable higher gravitational pressure gradient than the frictional pressure gradient. If not well predicted this difference can have a considerable impact on the designing of field processing equipment such as gas-liquid separators. Therefore, accurate prediction of flow behaviour is required.

Several authors have proposed flow regime maps from experimental work and developed empirical correlations for flow pattern predictions for different conditions for either horizontal or vertical pipe: Kosterin (1949), Baker (1953), Eaton et al. (1965), Aziz and Govier (1972), Taitel and Dukler (1976) and Weisman and Kang (1981) (cited in Shoham (2006)). Studies on gas-liquid two-phase flow for inclined pipe began in the mid 1970's, when Singh and Griffith investigated slug flow at small upward inclination angles using air and water and developed simple correlations for pressure drop and liquid holdup. Beggs and Brill (1973) developed a correlation for pressure gradient prediction in two-phase flow that could be applied to the entire range of inclination angles. Taitel and Dukler (1976) proposed a physical model that predicted flow regime transitions in horizontal and near horizontal ( $\pm 10^\circ$ ) gas-liquid flow. They compared the experimental flow pattern transition presented by Mandhane et al. (1974) with their own model prediction.

In 1980 Barnea et al. published flow regime maps from experimental measurements performed for air-water upward and downward system in  $\pm 10^\circ$  inclined pipe. The data was compared with the Taitel and Dukler (1976) model which led to the conclusion that the model was applicable to  $\pm 10^\circ$  inclination with good accuracy. Weisman and Kang (1981) conducted experiments on flow pattern transition during co-current gas-liquid flow in vertical and upwardly inclined pipe. The collected data were used to develop an improved dimensionless correlations of flow pattern boundaries. They concluded that the effect of the inclination angle in upward co-current flow was not very significant on the flow regime boundary.

Shoham (1982) attempted to define an acceptable set of flow patterns over the entire range of inclination angles, namely horizontal flow, upward/downward inclined flow and upward/downward vertical flow. He classified two-phase flow into four main regions: **Stratified**, subdivided into stratified-smooth (SS) and stratified-wavy (SW); **Intermittent** with elongated-bubble (EB), slug (SL) and churn (CH) flow; **Annular** with annular (A) and annular-wavy (WA) and **Dispersed-bubble** or **Bubble** region. Figure 2.1 and 2.2 present an example and illustration of flow regime maps classification for two-phase

flow in inclined pipes.

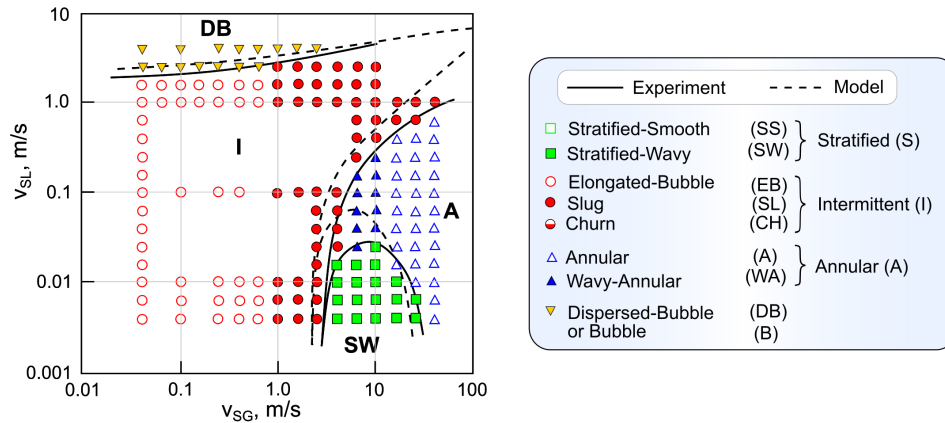


Figure 2.1. Example of flow pattern maps classification for air-water flow at standard temperature-pressure (STP) in 2.54 cm  $0.25^\circ$  upward inclined pipes. Adapted from Shoham (2006)

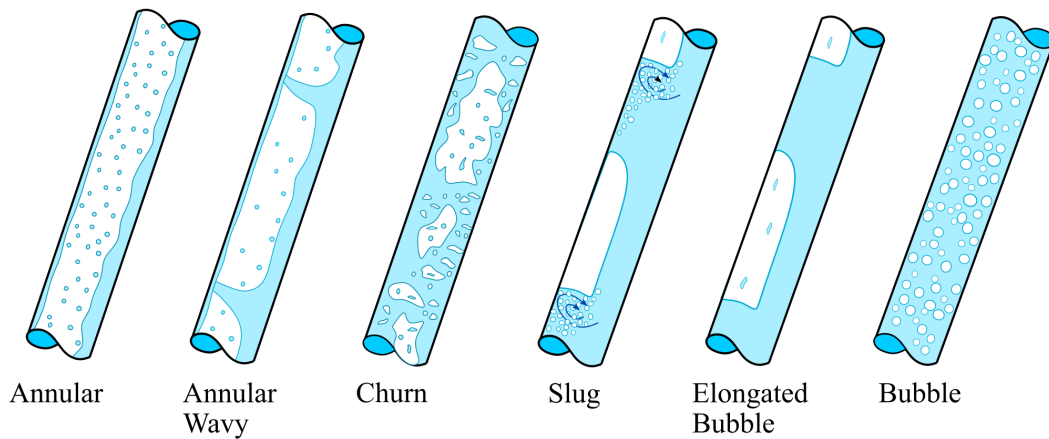


Figure 2.2. Flow regime maps for gas-liquid flow in inclined pipes. Adapted from Shoham (2006)

**Stratified flow** is characterised by phase segregation due to gravity, where liquid flows at the bottom of the pipe and the gas on the top. Stratified flow is mainly present in horizontal pipes at relatively low pipe inclination angles. It also occurs at low gas and liquid flow rates. Stratified wavy flow is identified in the presence of stable waves formed at the interface, while stratified smooth is defined when the gas-liquid interface is smooth. Stratified smooth flow can occur in upward inclination less than  $0.25^\circ$  (Barnea et al., 1980b).

**Intermittent flow** is normally characterised by alternate flow of liquid and gas, where liquid fill the entire pipe cross-sectional area while the gas flows as gas pockets. The flow might also contain a stratified liquid layer flowing at the bottom of the pipe, in case of low inclination. In vertical pipes the gas phase flows as large bullet-shaped bubbles known as “Taylor bubble”. The bubble diameter is almost equal to the pipe diameter. In the case of churn flow the liquid phase flows with an oscillation motion while flowing upwards. This flow pattern occurs at high gas flow rates and is similar to slug flow but much more



chaotic and the Taylor bubble breaks slowly up into dispersed bubbles. At relatively low gas rates, the flow is calmer and elongated-bubble can occur.

**Annular flow** is characterised by the presence of a high velocity gas core, which might contain dispersed liquid droplets and is surrounded by thin annular liquid film that flow along the pipe wall. For vertical flow, the thickness of the liquid film is approximately uniform. For horizontal and slightly inclined pipes the liquid film at the bottom of the pipe is usually thicker than the top, depending of the gas and liquid flow rates. At lower gas flow rates, annular wavy flow is identified at the bottom of the pipe, while aerated unstable waves are swept around the pipe which can make the flow appear both stratified wavy and slugging.

**Dispersed-bubble flow** is defined as the flow where the gas phase is distributed as discrete bubbles within the continuous liquid phase. In this flow regime the phases move at almost the same velocity as a result of high liquid flow rates.

Barnea et al. (1985) reported a new set of experimental data covering inclinations ranging from  $0^\circ$  to  $90^\circ$ . They modified and extended the model of Taitel and Dukler (1976) and Taitel et al. (1980) to provide mechanistic models for flow pattern transition boundaries estimations over the entire inclination range. Stanislav et al. (1986) reported flow patterns, pressure gradients and liquid holdup for a two-phase flow using air and oil. The data was compared to Taitel and Dukler's theory and Nicholson et al. (1978) intermittent flow model and showed a good agreement. Afterwards, Barnea (1987) proposed a unified model to predict the steady-state transition boundaries for the whole range of pipe inclinations through equations and dimensionless maps, that incorporated the effect of flow rates, fluid properties, pipe size and pipe inclination. The model was an extension of the suggested model by Barnea (1986) where the transition from annular to intermittent flow and from dispersed bubble flow were suggested and previously published by Barnea et al. (1982*a,b*, 1980*b*, 1985). The validation of Barnea model was performed using experimental data from Shoham (1982). Gokcal et al. (2008) experimentally studied the effect of high viscosity liquid on the flow pattern for oil-gas flow in horizontal pipe. Later Jeyachandra et al. (2012) extended the study using slightly inclined pipe ( $\pm 2^\circ$  from horizontal). They reported flow pattern and pressure drop. The results were then used to evaluate different flow pattern maps and two-phase flow correlations. They also confirmed the observations of Kokal and Stanislav (1989*b*), who claimed that pressure gradients were flow pattern dependent.

The present thesis focuses on the transition mechanism from annular to intermittent flow and will use as a starting point the model described by Barnea (1986). Other flow types, such as stratified, dispersed bubble and elongated bubble, will only be briefly described. A detailed description of the annular-intermittent transition mechanism is presented in Appendix B.1.

### 2.1.1 Pressure gradient

Pressure gradient in two-phase flow is of particular interest to many industries. In the petroleum industry for instance, pressure gradient prediction is important during system design. Compared to single phase flow, pressure gradient in two-phase flow is more com-

plicated and difficult, due to the complexity of the flow.

Several studies on the determination of pressure gradient in two-phase flow have been performed for horizontal and vertical pipes (Baker, 1953; Flanigan, 1958; Dukler et al., 1964*a,b*; Orkiszewski, 1967; Aziz and Govier, 1972 and Shoham, 2006). Orkiszewski (1967) for instance, developed a pressure drop prediction scheme for vertical pipes based on an identification of the flow pattern and application of selected mechanistic and empirical methods of individual flow patterns. Shoham (2006) presented total pressure gradient for different flow patterns in vertical and horizontal pipes. He used data reported by Aziz and Govier (1972) for a 25 mm inner diameter pipe with air-water at standard conditions.

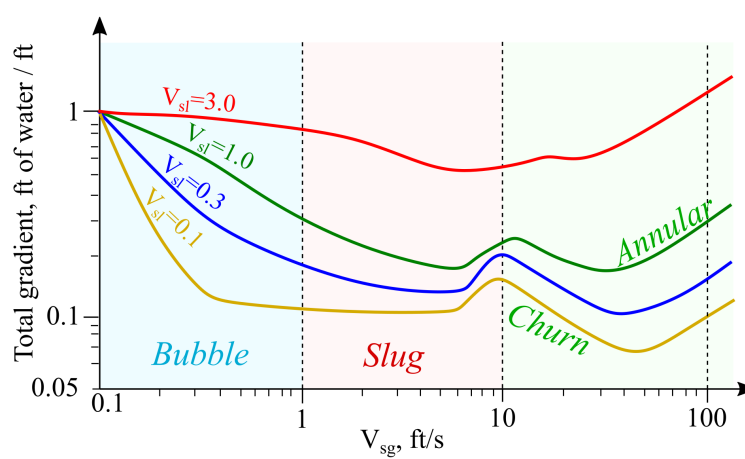


Figure 2.3. Pressure gradient vs. superficial gas velocity in vertical flow. Adapted from Shoham (2006)

Figure 2.3 presents pressure gradient dependence on flow pattern for vertical flow, at constant superficial liquid velocity. As can be seen, for low superficial gas and liquid velocities, the flow is bubble flow, exhibiting high pressure gradients. This is due to high liquid content present in the pipe, which results in high gravitational pressure gradient. Keeping the superficial liquid velocity constant, as the superficial gas velocity increases, total pressure gradient reduces and the flow pattern become intermittent flow. The increase of gas flow rate leads to a reduction of liquid content, resulting in lower gravitational pressure drop. On the other hand, frictional pressure gradient effect is not high since moderate superficial gas velocity is encountered in intermittent flow. Thus, total pressure gradient exhibits a minimum value, which is the sum of the gravitational and frictional gradient. At further increase of superficial gas velocity, the flow pattern becomes annular and total pressure gradient rises due to high frictional pressure gradient. However, these proposed correlations were not corrected for inclined flow.

In 1973 Beggs and Brill published a correlation for prediction of pressure drop when gas, liquid or both are flowing in a pipe. The development of the correlation was based on horizontal pipe and then extended to cover the whole range of inclination pipe. For pressure drop prediction the correlation often checks for flow regime that would occur if the pipe were horizontal. Afterwards the liquid holdup is corrected for other inclination angles, though inclination correction factors differs for each flow regime.

Gray (1978) developed a correlation for pressure drop for vertical gas wells producing

free water and/or condensate. In the petroleum industry Gray's correlation have been widely used for pressure loss predictions along the wellbore, especially for gas well with low liquid fraction. The correlation was based on the mechanical energy balance, where the pressure loss was a result of hydrostatic head, frictional head loss and acceleration. A detailed description of Equation 2.1 is presented in Appendix B.2.

$$\frac{dp}{dx} = \underbrace{\frac{g\bar{\rho}}{144g_c}}_{\text{Gravity}} + \underbrace{\frac{2f\rho_{NS}v_m^2}{144g_cD}}_{\text{Friction}} + \underbrace{\rho_{NS}v_m \frac{dv_m}{dz}}_{\text{Acceleration}} \quad (2.1)$$

## 2.2 Liquid loading

Most mature gas wells eventually enter into a period when start experiencing a period where the flow rate of the produced gas is not sufficient to carry all the co-produced liquid to the surface. Under this condition, the non-produced liquid accumulates at the wellbore, resulting in reduction of the gas production or even causing a premature abandonment of the well. This phenomenon is often defined as liquid loading. The co-produced fluid can be free liquid flowing from the reservoir and/or condensate and water that drop out of the gas due to pressure and temperature reduction along the tubing.

Figure 2.4 illustrates gas well behaviour with time once the reservoir pressure depletes.

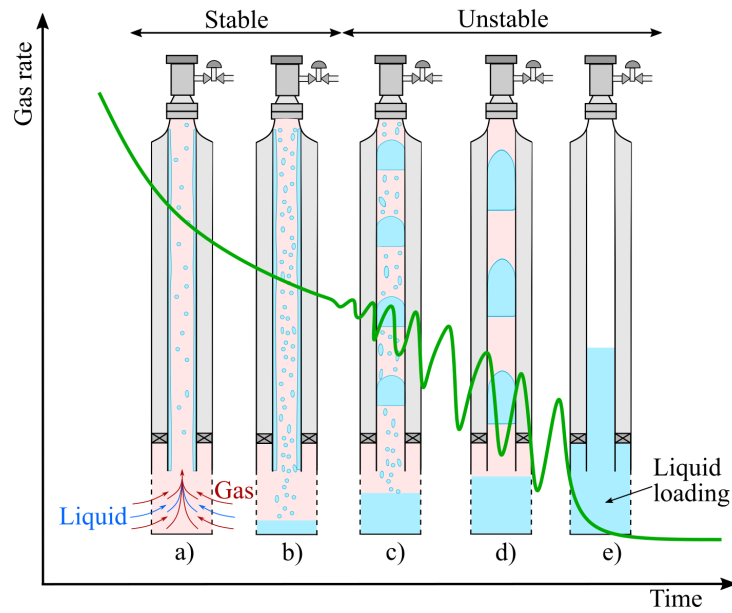


Figure 2.4. Production profile for gas wells experiencing liquid loading. Adapted from Fernandez et al. (2010)

At the beginning of the production, reservoir pressure is sufficiently high to achieve gas production rates that can transport any co-produced liquid phase that might exist to the surface, which makes the well produce at stable condition (annular flow regime). The liquid phase is normally transported as droplets entrained in the gas core and/or as film attached to the pipe wall.

As the pressure in the reservoir goes down, the gas rate drops as well as its capacity of lifting the liquid, reaching a critical gas rate. At the critical gas rate, liquid present in the wellbore starts to flow counter-current and accumulates in the bottom of the production tubing. This situation is followed by the start of intermittent flow pattern present in some parts of the tubing, leading to an unstable production condition. Liquid loading typically starts occurring at the bottom-hole, where pressure is maximum and gas velocity is minimum, or close to the wellhead, where the temperature is lower and liquid content is maximum. The accumulated liquid creates a back-pressure against the formation resulting in a further reduction of gas production and premature abandonment of the well due to further accumulation of the liquid.

To counteract liquid loading and to maintain production, deliquification methods such as gas lift, plunger lift, production cycling, down-hole pumps, etc, are typically installed in these wells. The operator must make an accurate prediction of the onset of liquid loading to support the choice of the method to be used to prevent the well from abandonment. Despite the extensive availability of models used for predicting the behaviour of such wells, the basic flow mechanism is not accurately accounted for by current models. This is due to lack of experimental data, especially for wells with inclined sections.

Several researchers (Vitter Jr, 1942; Jones, 1946; Duggan, 1961 cited by Turner et al., 1969; Guo et al., 2005 and Chupin et al., 2007) have suggested different methods, correlations based on field and experimental data, equations from physical properties to determine when the liquid starts to accumulate in the well. Almost all these analyses indicated the existence of two physical models for liquid removal in gas wells (see Figure 2.5): (a) liquid is transported as droplets entrained in the high velocity gas core and (b) liquid is transported as film moving along the walls of the pipe.

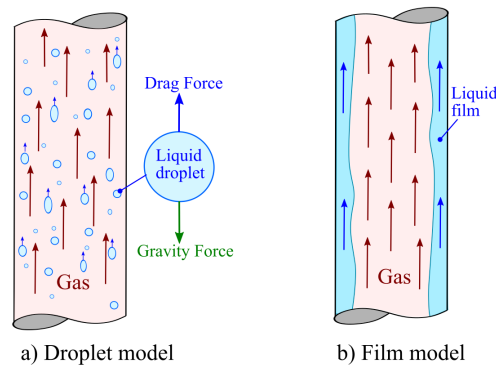


Figure 2.5. Illustrative diagram of liquid transportation in gas well

### 2.2.1 Liquid droplet model

The liquid droplet entrained model, also known as liquid droplet reversal, assumes that the falling of liquid droplets present in gas core is the main cause of liquid loading. Turner et al. (1969) proposed an equation that calculates minimum gas velocity necessary to lift the largest droplet present in gas core. When the gas velocity in the tubing drops below this minimum gas velocity, liquid loading will likely occur. The equation was developed based on drag and gravity forces that act on the falling liquid droplet. Turner's equation for critical superficial gas velocity (m/s):

$$v_{g,min} = 6.556 \left[ \frac{\sigma(\rho_l - \rho_g)}{\rho_g^2} \right]^{1/4} \quad (2.2)$$

To match their field data during model validation the original coefficient was corrected by 20%. Therefore, the value of 5.463 was changed to 6.556.

Many researchers made refinements and modifications to Turner et al. (1969) droplet model to better match different sets of data with varying degrees of success (Coleman et al., 1991; Nosseir et al., 1997; Li et al., 2001; Wang et al., 2010 and Sutton et al., 2010). Modification were addressed on the shape of the liquid droplet, adjustment of the equation coefficient value and effect of flow condition among others.

The Turner et al.'s equation has been widely used in the petroleum industry as a primary method to predict liquid loading in gas well, but it was not long before the need of predicting the phenomenon in deviated wells came up. Thus, the droplet model was modified to include the effect of inclination. Flores-Avila et al. (2002) proposed a new droplet model based on the Turner et al. model. They adapted to field units and included a coefficient to account for well deviation angle. Flores's equation for critical superficial gas velocity (m/s):

$$v_{g,min} = 14.27 \left[ \frac{\sigma(\rho_l - \rho_g)}{K_d \cos(\alpha) \rho_g^2} \right]^{1/4} \quad (2.3)$$

$$K_d = 4 \left[ \frac{24}{N_{Re}} + \frac{4}{N_{Re}^{0.468}} + 0.5 \right]$$

where,  $\alpha$  is the deviation angle from vertical,  $K_d$  is the drag coefficient that corresponds to the Reynolds number at flowing condition of the continuous phase as suggested by Nosseir et al. (1997).

In 2008 Belfroid et al. studied the effect of pipe inclination angle on the droplet model prediction. Plotting the critical gas velocity, a function of inclination angle using data from Van't Westende (2008), presented in Figure 2.6, they observed that as the inclination angle changed downwards from vertical, the critical gas velocity increased, reaching a maximum value.

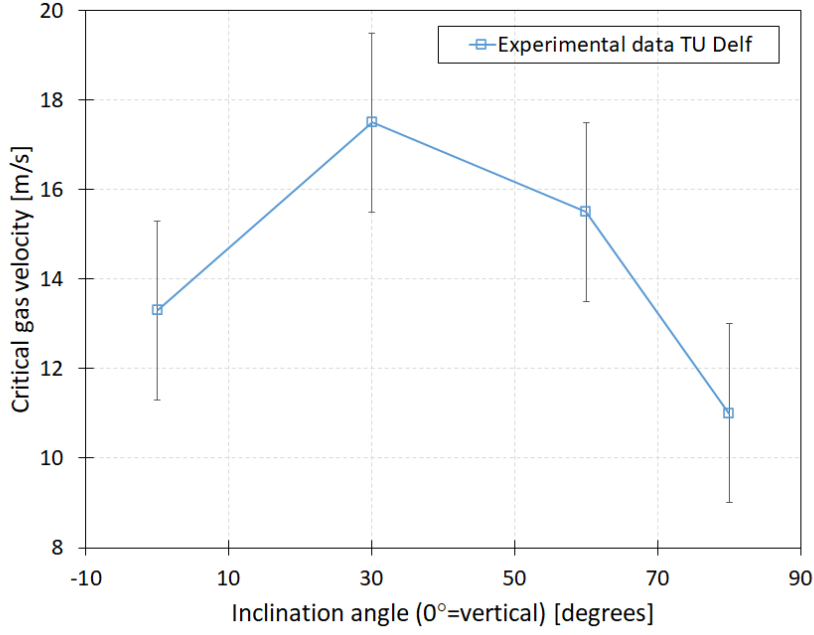


Figure 2.6. Critical gas velocity vs. inclination angle (Belfroid et al., 2008)

The behaviour was then related to the decrease of gravitational forces perpendicular to the flow and increase of film thickness along the full circumference of the tubing. To account for the effect of inclination angle on the critical gas velocity prediction they proposed a new droplet model. The proposed model resulted from a combination of Fiedler and Auracher (2004) model with the conventional Turner equation. Belfroid's equation for critical superficial gas velocity (m/s):

$$\dot{m}_{g,min} = \left( 3.1A\sqrt{\rho_g}(g\sigma(\rho_l - \rho_g))^{1/4} \right) \frac{(\sin 1.7\theta)^{0.38}}{0.74} \quad (2.4)$$

where  $\dot{m}_{g,min}$  is the minimum gas mass flow rate [kg/s],  $\rho_g$  and  $\rho_l$  the gas and liquid density [kg/m<sup>3</sup>],  $\sigma$  the surface tension [N/m] and  $\theta$  the inclination angle referred to horizontal (where  $\theta = 0^\circ$ ).

Recently, Wang et al. (2016) performed an experimental study on air-water flow system in coiled pipes with 30 mm and 40 mm inner diameter at an inclination angle of 15° to 76° from horizontal. Based on the experimental data, they proposed a modification on Belfroid et al. (2008) model to include the effect of pipe diameter on the prediction of critical gas velocity. Wang's model for critical superficial gas velocity (m/s):

$$v_{g,min} = (5.13 \ln D - 14.1) \left[ \frac{\sigma(\rho_l - \rho_g)}{\rho_g^2} \right]^{1/4} \frac{(\sin 1.7\theta)^{0.38}}{0.74} \frac{1}{\ln(45.6v_{sl}^2 - 9.5v_{sl} + 3.1)} \quad (2.5)$$

Even though the droplet model is simple, easy to use and tune, there is some field and experimental evidence that shows limited predictability (Guo et al., 2005; Zhou and Yuan, 2009; Veecken et al., 2010; Yuan, 2011 and Shekhar et al., 2017).

## 2.2.2 Liquid film model

The liquid film model also known as liquid-film-reversal model assumes that liquid is transported as film moving along the walls of the conduit while the gas core flows in the centre. The liquid accumulation in the well starts when the liquid film can no longer be lifted to the surface. Turner et al. (1969) on basis of field data analyses, concluded that liquid film does not represent the controlling liquid transport mechanism. To identify when the liquid film is no longer lifted to the surface, approach was proposed based on pressure gradient measures and flow regime transitions.

Zabaras et al. (1986) conducted an experimental study on the film flow for vertical upwards concurrent annular gas-liquid flow, where instantaneous local film thickness, wall shear stress and pressure gradient were measured. They concluded that at low gas flow rates the film motion is controlled by a switching mechanism. This switch mechanism was designated as churn flow, that is coupled to the instability of the liquid film due to decreasing of both film-thickness and the interfacial friction. Several subsequent authors have shown that liquid loading is accompanied by flow regime transition from annular flow to slug or churn flow (intermittent flow). The annular-intermittent transition model of Barnea (1986, 1987) is widely used for the onset of liquid loading in deviated pipes (see Appendix B.1). The model assumes no variation in film thickness around the pipe for all inclination angles.

In 1994 Paz performed experimental and theoretical investigation on two-phase annular flow focused on the effect of inclination angle on the liquid film thickness distribution in the circumferential of the pipe. They observed that as the pipe inclination approaches horizontal conditions liquid phase tends to accumulate at the bottom of the pipe. This results in a thicker liquid film at the bottom and a thinner film at the top (Figure 2.7). They concluded that inclination angle strongly affects the liquid film thickness ( $\delta$ ) proving Barnea's assumption wrong.

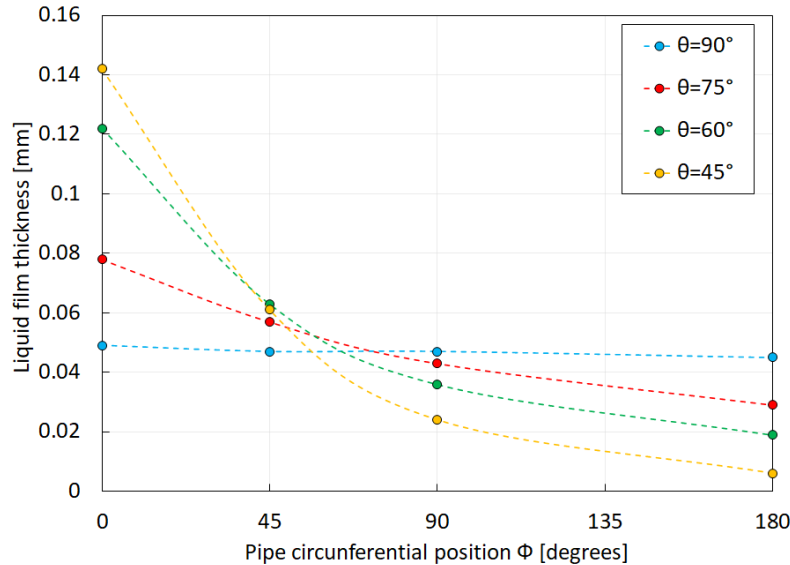


Figure 2.7. Liquid film thickness distribution around the pipe circumference ( $\Phi=0^\circ$  at the bottom of the pipe) for  $v_{sg}=18.29$  m/s,  $v_{sl}=0.0124$  m/s, different pipe inclination ( $\theta=90^\circ$  is vertical) observed by Paz (1994)

Recently, Luo et al. (2014) published a correlation that took into account the non-uniform film thickness (Equation 2.9) and used Barnea (1986) methodology to predict the onset of liquid loading, i.e., annular-intermittent transition. They used Fore et al. (2000) interfacial friction factor correlation (Equation 2.6) instead of Wallis (1969) (Equation B.12).

$$f_i = 0.005 \left\{ 1 + 300 \left[ \left( 1 + \frac{17,500}{Re_g} \right) \tilde{\delta}_L - 0.0015 \right] \right\} \quad (2.6)$$

The new correlation was developed by comparing a uniform and non-uniform film thickness model shown in Figure 2.8. For the case of uniform film thickness they approximated the area of the film to the area of an expanded rectangle, while for non-uniform case the film was approximated to a trapezoid (see Equation 2.7) that was used in the work of Barnea (1986).

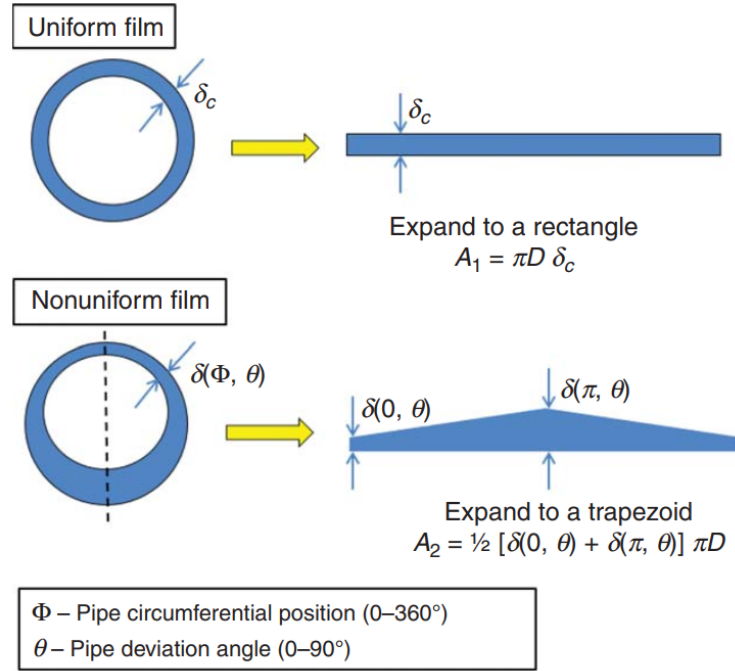


Figure 2.8. Schematic of uniform and non-uniform liquid film thickness. Taken from Luo et al. (2014)

$$A_1 = \pi D \delta_c \quad A_2 = \frac{1}{2} [\delta(0, \theta) + \delta(\pi, \theta)] \pi D \quad (2.7)$$

where  $D$  is the pipe diameter,  $\delta_c$  is the constant film thickness,  $\delta(0, \theta)$  is the film thickness at the top of the pipe and  $\delta(\pi, \theta)$  is the film thickness at the bottom of the pipe. Considering,  $A_1$  equals  $A_2$ , constant film thickness was expressed as

$$\delta_c = \frac{1}{2} [\delta(0, \theta) + \delta(\pi, \theta)] \quad (2.8)$$



For film distribution along the pipe circumferential position for different pipe deviation they proposed the following empirical equation

$$\delta(\phi, \theta) = (1 - \alpha\theta \cos \phi) \delta_c \quad (2.9)$$

$$\alpha = \begin{cases} 0.0287 & 0 \leq \theta < 30 \\ 0.55\theta^{-0.868} & 30 \leq \theta \leq 90 \end{cases}$$

To incorporate the equation for the variation of film thickness due to pipe inclination into Barnea's model, the film thickness ( $\widetilde{\delta}_l$ ) that satisfy Equation B.14 is considered to be  $\delta_c$ , and the new film thickness is assumed to be corrected for inclined pipe.

Later, Shekhar et al. (2017) proposed a new set of empirical correlations keeping the same concept of film thickness variation with pipe inclination (Equation 2.10). They used the same criterion as developed by Barnea (1986), except they assumed that in inclined pipe the liquid loading onset would begin when the liquid film at the bottom of the pipe starts falling back.

$$\delta(\phi, \theta) = \left[ 1 - \left( \frac{1 - e^{-0.088\theta}}{1 + e^{-0.088\theta}} \right) \cos \theta \right] \widetilde{\delta}_{avgL} \quad (2.10)$$

To calculate the critical gas velocity, they estimate the maximum film thickness for required shear stress given by Equation B.8, and then converted the film thickness using the relation given in Equation 2.11. Thereafter, their corrected  $\widetilde{\delta}_{avgL}$  is substituted back on Barnea (1986) Equation B.8, for determination of the critical superficial gas velocity.

$$\widetilde{\delta}_{avgL} = \frac{1}{2} \left( 1 + e^{-0.088\theta} \right) \widetilde{\delta}_{max} \quad (2.11)$$

In addition, they modified Wallis (1969) (Equation B.12) interfacial friction fraction ( $f_i$ ) and proposed a correlation that is dependent on the inclination angle (Equation 2.12).

$$f_i = 0.005 \left\{ 1 + \left[ 340 (1 + \cos \theta) \widetilde{\delta}_{avgL} \right] \right\} \quad (2.12)$$

The validation of the new model was performed though the use of data from Alsaadi (2013) and Guner (2012), which have shown an improvement on the prediction of onset of liquid loading.

Along with the concept of film fall reversal due to switch mechanism, nodal analysis concept was taken as a new criterion to predict of onset of liquid loading. The nodal analysis concept suggests that once the pressure drop in the production tubing decreases reaching a minimum pressure liquid starts to accumulate at the wellbore.

Zabaras et al. (1986) through experimental data observed that the pressure drop displays a minimum as the gas flow rate is reduced for a given constant liquid flow rate. They related the minimum pressure with a dimensionless gas velocity  $v_g^* = 1.06$  where,

$$v_g^* = v_g \times \rho_g^{1/2} [gD(\rho_l - \rho_g)]^{-1/2} \quad (2.13)$$

This behaviour was earlier observed by Hewitt et al. (1965), who reported  $v_g^* = 1.12$  as mentioned on Zabaras et al. (1986).

This behaviour of the pressure drop was accompanied with the annular-intermittent flow transition. Erratic behaviour of the flow (intermittent flow) was observed on the left region of the minimum pressure point, while on the right region a more stable flow (annular flow) was dominant. Figure 2.9 illustrates the gas well pressure behaviour vs gas velocity.

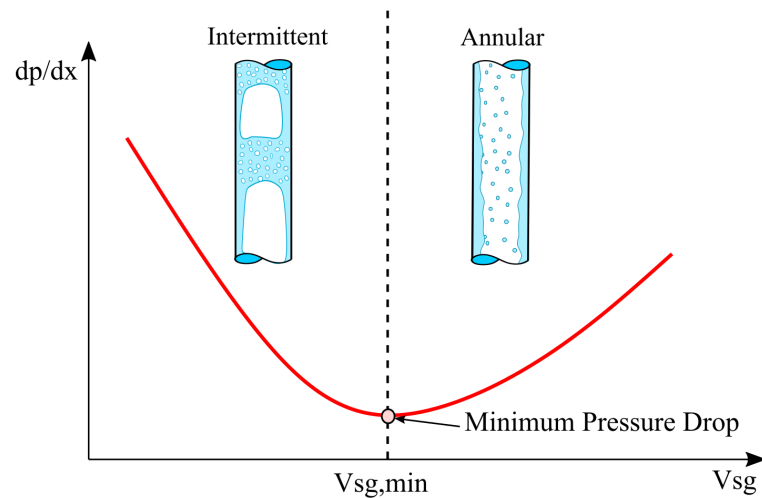


Figure 2.9. Schematic of the total pressure gradient on vertical pipe observed. After Zabaras et al. (1986)

Afterwards, researchers like Kelkar et al. (2013), Sarica et al. (2013), Luo et al. (2014) and Waltrich et al. (2015) started to use the concept of minimum pressure to define the initiation of liquid loading.

Tables 2.1 and Table 2.2 below show a summary of most relevant works within, gas-liquid two-phase flow and liquid loading. Information such, year of publication, purpose of the work and flow conditions were also presented in the tables.

Table 2.1. Experimental studies on upwards gas-liquid two-phase flow

| Source                        | Meas.                | Test fluid   | $v_{sg}$ (m/s) | $v_{sl}$ (m/s) | ID(mm)                    | $\theta$ (deg.)   | FH | Purpose   |
|-------------------------------|----------------------|--------------|----------------|----------------|---------------------------|---|----|---|
| Singh and Griffith (1970)     | dP/dx, void fraction | air-water    | -              | -              | 5.9, 20.9, 27, 34.7, 40.6 | 5, 10, 15   |    | simple model of two-phase slug flow in inclined pipes is proposed                               |
| Beggs and Brill (1973)        | dP/dx, $H_L$         | air-water    | 0 – 98         | 0 – 3.7        | 25.4, 38.1                | $\pm 90$ , $\pm 85$ , $\pm 75$ , $\pm 55$ , $\pm 35$ , $\pm 20$ , $\pm 15$ , $\pm 10$ , $\pm 5$ , 0 |    | empirical model for pressure drop and liquid holdup calculation                                 |
| Barnea et al. (1980b)         | FRM                  | air-water    | 0.03 – 26      | 0.003 – 2.5    | 25.5                      | 0, 0.25, 2, 10  |    | evaluate the performance of Taitel and Dukler (1976) model                                      |
| Shoham (1982)                 | FRM                  | air-water    | 0.03 – 26      | 0.003 – 2.5    | 25, 51                    | 15, 20, 30, 50, 70, 80, 85  |    | effect of pipe inclination on flow pattern transition   |
| Barnea et al. (1985)          | FRM                  | air-water    | 0.03-26        | 0.003-2.5      | 25, 51                    | 0 – 90  |    | extend model to predict flow pattern for entire inclination range                               |
| Stanislav et al. (1986)       | dP/dx, $H_L$ , FRM   | air-oil      | 0.1 – 30       | 0.05 – 4       | 25.8                      | 0, 1, 5, 9  |    | evaluate the performance of Taitel and Dukler (1976) and intermittent flow model                |
| Kokal and Stanislav (1989a,b) | dP/dx, $H_L$ , FRM   | air-high oil | 0.1 – 30       | 0.05 – 4       | 25.8, 51.2, 76.3          | 0, $\pm 1$ , $\pm 5$ , $\pm 9$  |    | proposed a new model for flow pattern transition and compared data with Taitel and Dukler model |
| Gokcal et al. (2008)          | dP/dx, $H_L$ , FRM   | air-oil      | 0 – 20         | 0.01 – 1.75    | 50.8                      | $\pm 2$   |    | effect of viscosity on flow pattern, pressure drop and liquid holdup                            |
| Jeyachandra et al. (2012)     | dP/dx, FRM           | air-oil      | 0 – 10         | 0.01 – 1.75    | 50.8                      | $\pm 2$   |    | effect of viscosity on flow pattern   |

Table 2.2. Studies on liquid loading on upward two-phase gas dominant flow

| Source                     | Meas.                      | Test fluid    | $v_{sg}$ (m/s) | $v_{sl}$ (m/s)         | ID(mm)  | $\theta$ (deg.)    | FH | Purpose  |
|----------------------------|----------------------------|---------------|----------------|------------------------|---------|--------------------|----|--|
| Zabaras et al. (1986)      | dP/dx, $\delta$ , $\tau_w$ | air-water     |                |                        | 50.8    | 90                 |    | introduced a switch mechanism concept  |
| Flores-Avila et al. (2002) | $H_{L0}$                   | air-water     | 0.34–11.46     |                        | 154.1   | 15, 30, 50, 70, 90 |    | modified Turner's equation to account pipe deviation                                     |
| Van't Westende (2008)      | dP/dx                      | dry air-water | 10–40          | 0.01, 0.02, 0.04, 0.08 | 50      | 90                 |    | investigate the dispersed-phase  |
| Yuan (2011)                | dP/dx, $H_L$ , $v_{g,min}$ | air-water     | 10–35          | 0.005–0.1              | 76.2    | 60, 75, 90         |    | explored the mechanisms of liquid loading and investigated the effect of well deviations |
| Alsaadi (2013)             | dP/dx, $H_L$               | air-water     | 2 – 40         | 0.01 – 0.1             | 76.2    | 2, 5, 10, 20, 30   |    | evaluate the effect of deviation angle and liquid flow rates on critical gas velocity    |
| Sarica et al. (2013)       | dP/dx, $H_L$ , $v_{g,min}$ | air-water     | 10 – 35        | 0.005 – 0.1            | 76.2    | 60, 75, 90         |    | evaluate the minimum velocity with the deviation angle                                   |
| Kelkar et al. (2013)       | dP/dx, $H_L$ , $v_{g,min}$ | air-water     | 10 – 30        | 0.01–0.05              | 51, 102 | 90                 |    | study the effect of pipe diameter in liquid loading                                      |
| Waltrich et al. (2015)     | dP/dx, $H_L$ , T           | air-water     |                | 0.15–0.3               | 50(PVC) | 90                 |    | evaluate available liquid loading prediction models                                      |
| Guner et al. (2015)        | dP/dx, $H_L$ , $v_{g,min}$ | air-water     | 1.5–40         | 0.01, 0.05, 0.1        | 76.2    | 45, 60, 75, 90     |    | compare available model used to predict the liquid loading                               |

# Chapter 3

## Experimental methodology

Experiments were carried out at the Multiphase Flow Laboratory located in the department of Energy and Process Engineering at NTNU in Trondheim, Norway. The laboratory facility consists of several flexible test sections and mini loops, that have been extensively used to generate multiphase flow experimental data for diverse conditions. Three-phases; water, oil and air, can be simultaneously circulated. The infrastructure includes fixed elements such as flow meters, control valves, pumping system, mixing sections, separator and tanks, allowing fluid supply and operational condition control. All lab instrumentation are connected to a data acquisition system and controlled by a main program written in LabView<sup>®</sup> where output signals are provided. For this research work the inclined test section was used for further investigation on the effect of pipe inclination on the multiphase flow systems and on liquid loading phenomena.

### 3.1 Experimental setup

Figure 3.1 presents a schematic representation of the inclined facility, showing the main single phase flow lines and equipment installed in the inclined test section. The inclined test section comprises of a 60 mm inner diameter, approximately 7 m long inclined transparent acrylic pipe, leaning on a steel beam connected to a lift mechanism, which allows the section to be easily adjusted to a desired inclination angle by using a connected lift handle. The test section inclination range spans vary from 0° to 90° (referenced to horizontal). However, the range of variation of inclination angle was limited because the structure that supports the steel beam had a maximum of 78° predetermined inclination due to safety. The section had two possible mixing sections for liquid and gas. One located before the test section pipe (mix point1) where gas and liquid phases flowed together through a flexible pipe before entering the test section. When the second mixing section was used (mix point2), the phases flowed separately through the flexible pipes and were mixed at the bottom of the test section. The second mixing section was preferred, to avoid flow instabilities and transients caused by the flexible pipe. After entering the mixing section the fluids flowed through the test section to a separator located at the top of the pipe where the air was vented to the atmosphere while water and/or oil passed into a secondary separator and finally fell back into the main separator at the basement. To improve the separation of oil and water the main separator contained mesh coalescers.

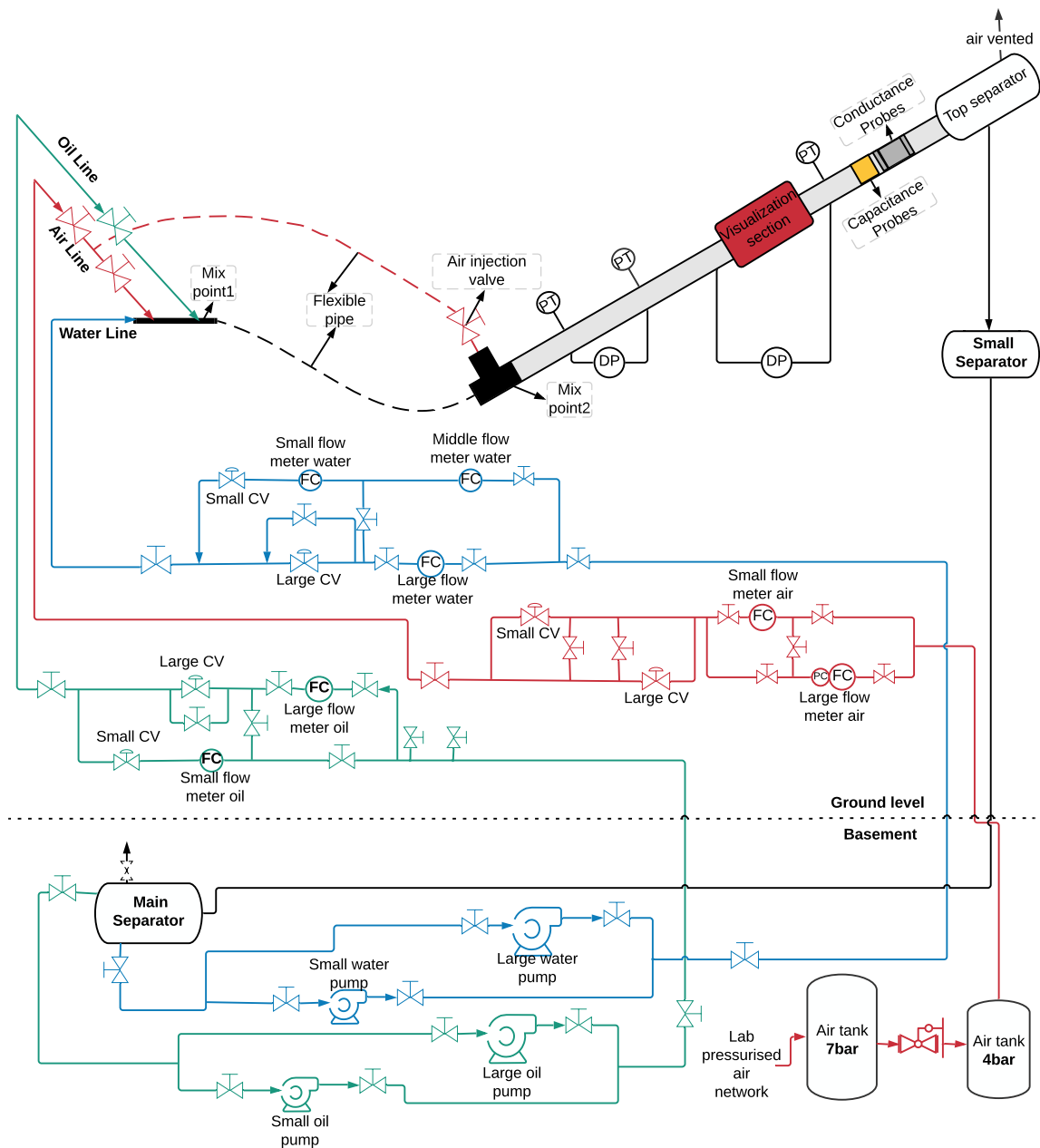


Figure 3.1. Sketch of the inclined test section at NTNU

### 3.1.1 Fluid system

Experiments were carried out using mineral oil and water as liquid phase and compressed air as gas phase. Air was supplied at 7 bar by the pressurised air network of the building and reduced to operational pressure of approximately 4 bar. A ball valve was installed on the air line inlet allowing a direct control on gas injection in the test section. Oil and water were supplied through individual lines by the pumping system and stored in the main separator located in the basement of the laboratory. To visually discriminate oil and water a dye that gave a yellow-green colour (fluorescein sodium  $C_{20}H_{10}Na_2O_5$ ) was added to the water.

Two distinct mineral oil were used in the experimental campaigns, Exxsol D80 and mixed oil. Diaz (2016) who had performed experimental tests previous to this research, reported that the mixed oil present in the main separator was a combination of 5600 litres of Nexbase 3080 (79% by volume) diluted with 1500 litres of Exxsol D80 (21% by volume). Prior to a new experimental campaign samples of the liquid were taken from the flow loop separator. Fluid properties are summarised in Table 3.1.

Table 3.1. Liquid and gas properties @ 1 atm and 20°C

| Phase  | Fluid      | Density [kg/m <sup>3</sup> ] | Viscosity [cP] | Surface tension [mN/m] |
|--------|------------|------------------------------|----------------|------------------------|
| Liquid | Mixed oil  | 840.1                        | 25             | 28                     |
|        | Exxsol D80 | 802.6                        | 1.8            | 24.9                   |
|        | Water      | 997.9                        | 1.1            | 60                     |
| Gas    | Air        | 1.2                          | 0.018          | -                      |

Laboratory temperature variation was monitored during the experiments using a thermocouple. From one experiment to the other, the temperature was around 20°C with a variation of  $\pm 3^\circ\text{C}$ .

Oil and water densities were measured by filling a pycnometer with known volume and then weighting it on a precision scale. Considering air as an ideal gas, the density was determined by the ideal gas law equation.

Oil and water dynamic viscosity were measured using a rotational rheology meter (model Ares-G2- from TA Instruments). The rheology meter used determines the viscosity by measuring the shear stress between the plate and the fluid while varying the shear rate. The effect of pressure on viscosity was neglected. The effect of temperature in the fluid viscosity could also be estimated by using a heating plate. Figure 3.2 shows the variation of the fluid viscosity with temperature at atmospheric pressure. Due to the difference on the fluids viscosity range secondary axis was used for water and Exxsol D80 measurements.

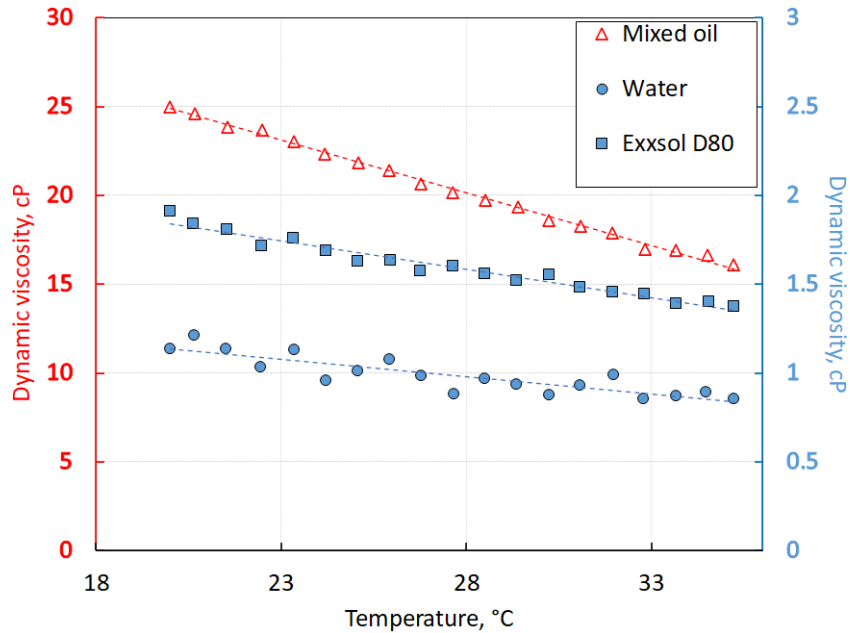


Figure 3.2. Dynamic liquid viscosity variation with temperature

It can be seen from Table 3.1, that the water present in the flow loop exhibited a slightly higher viscosity than pure water. This might be due to emulsification with oil present in the separator. The effect of temperature on the working liquid viscosity was estimated using Lewis-Squire correlation (Equation 3.1) from Chupin (2003):

$$\mu_l^{-0.2661} = \mu_K^{-0.2661} + \frac{T - T_K}{233} \quad (3.1)$$

where  $\mu_K$  is the measured liquid viscosity in cP at  $T_K = 293.15K$ , T and  $T_K$  are in K,  $\mu_l$  and  $\mu_K$  in cP. Considering a temperature variation of  $\pm 3^\circ C$  in the lab, the variations in mixed oil viscosity, water viscosity and Exxsol D80 viscosity did not exceed  $\pm 3cP$ ,  $\pm 0.06cP$  and  $\pm 0.1cP$  respectively.

Oil and water surface tension were measured with a drop shape analyse tensiometer (model DSA100 from Krüss) using the Pendant drop method. Pendant drop method measures the surface tension or interfacial tension from the shadow image of a drop suspended from a needle in a bulk liquid or gas phase. Figure 3.3 shows the measurement of surface tension, where air drop is suspended in Exxsol D80.

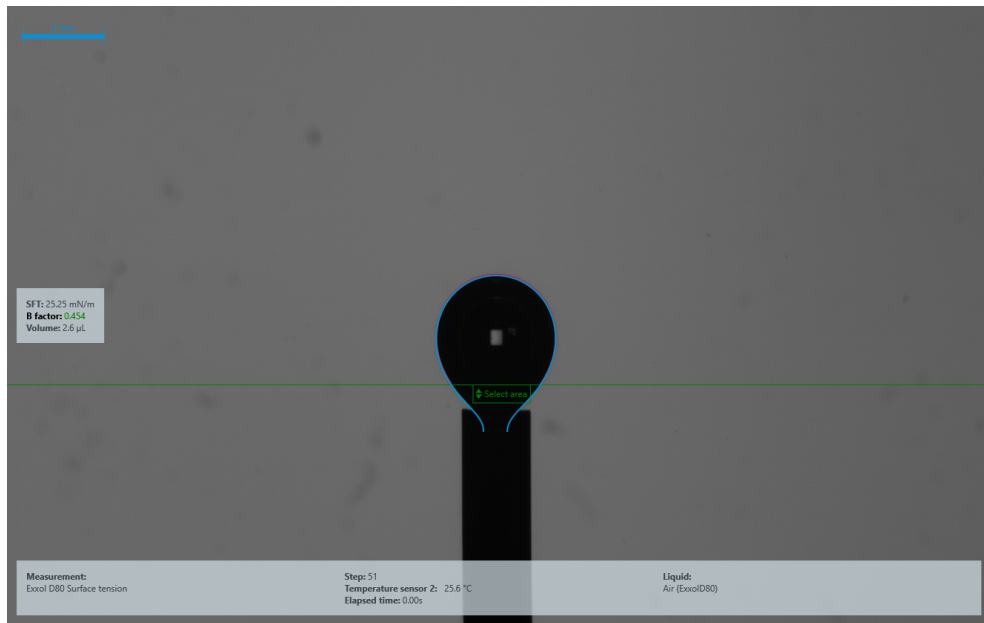


Figure 3.3. Drop shape analysis for liquid surface tension measurement

After the test, the tensiometer outputs gave a report where a mean value for the surface tension was displayed. From Table 3.1 it is possible to see that the surface tension of water is lower compared with pure water (typically 72 mN/m), probably due to a contamination by surface active agents coming from either the oil or small organisms living in the water.



## 3.2 Instrumentation

### 3.2.1 Flow rate measurements

The multiphase laboratory was equipped with six flow meters. For each flow line (oil, water and air) two flow meters were connected as shown in Figure 3.1. The selection of the flow meter was dependent on the experiments to be conducted. Table 3.2 summarises the specifications of the flow meters including the operating range and accuracy.

Table 3.2. Flow meter specifications

| Fluid | Model                       | Type     | Range             | Accuracy( $\pm$ ) |
|-------|-----------------------------|----------|-------------------|-------------------|
| Air   | MicroMotion CMF025 Elite    | Coriolis | 0.12 - 80 kg/h    | 0.5%              |
|       | Endress & Hauser Prowir 77W | Vortex   | 0 - 85 l/h        | 1%                |
| Oil   | Micromotion F025            | Coriolis | 100 - 1000 kg/h   | 0.15%             |
|       | Micromotion F025            | Coriolis | 1000 - 5000 kg/h  | 0.15%             |
| Water | Endress & Hauser Promag 33  | Elmag    | 0.053 - 0.987 l/s | 0.5%              |
|       | Fisher-Porter COPAXM Series | Elmag    | 0.83 - 10 l/s     | 0.5%              |

In case of air flow rate measurement, the Coriolis meter provides a direct measurement of the mass flow rate, while the vortex meter located on the high-pressure side of the facility gives a volumetric flow rate. Pressure readings from a pressure transducer ( $p_{vortex}$ ) located next to the vortex meter was used to estimate the superficial gas velocity using Equation 3.2.

$$v_{g,atm} = \frac{1}{A} q_{vortex} \frac{p_{vortex}}{p_{atm}} \quad (3.2)$$

where A is the pipe cross section of the test section.

### 3.2.2 Pressure gradient measurements

Pressure gradient was obtained from the measurement of two differential pressure transmitters (DPT) and three absolute pressure sensors. Instrument specifications are given in Table 3.3

Table 3.3. Specifications of the pressure sensors

| Instrument tag          | DPT 4.02         | DPT 4.03    | PT 4.08  | PT 4.11  | PT 4.12  |
|-------------------------|------------------|-------------|----------|----------|----------|
| Serie type <sup>a</sup> | Fuji FKCW22      | Fuji FKCW22 | Aplisens | Aplisens | Aplisens |
| Range limit[bar]        | $\pm 0.06$       | $\pm 0.06$  | 1 - 1.4  | 0 - 1    | 0 - 1    |
| Serie type <sup>b</sup> | Aplisens 2000ALW | Fuji FHCW22 | Keller   | Keller   | Keller   |
| Range limit[kPa]        | $\pm 50$         | $\pm 64$    | 0 - 200  | 0 - 200  | 0 - 200  |

<sup>a</sup>Sensor used in experimental campaign: February 2017 to July 2017

<sup>b</sup>Sensor used in experimental campaign: March 2017 to December 2018

The pressure sensors were connected to the test section through pressure taps (see Figure 3.4) glued on the outside wall of the pipe at specified location (see Figure 3.5). The absolute pressure sensors were connected to the upper wall pressure taps while differential pressure cells were connect to the bottom through small impulse nylon tubes (6 mm inner diameter) filled with a known fluid to avoid that bubbles trapped in the nylon lines could damp the pressure signal. The DPT were fixed separately to the pipe section to avoid vibration error due to high values of gas velocity used during the experiments.

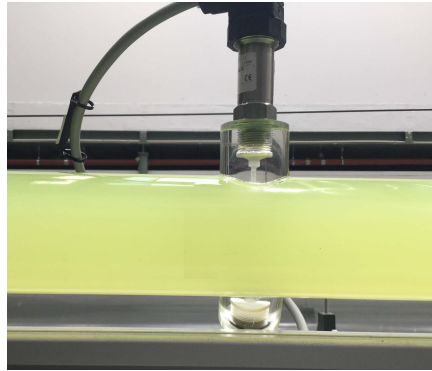


Figure 3.4. Pressure tap glued to the test section

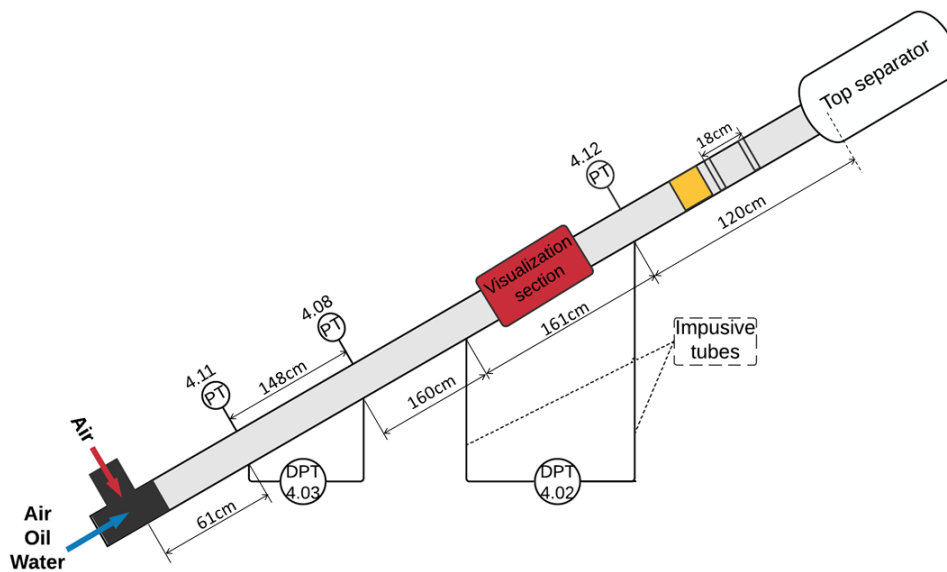


Figure 3.5. Schematic diagram of the instrumentation implemented in the test section. This diagram provides an overview of the instrumentation installed and position of each instrument

Each pressure transducer was calibrated individually and showed very good linearity, as presented in Figure 3.6.

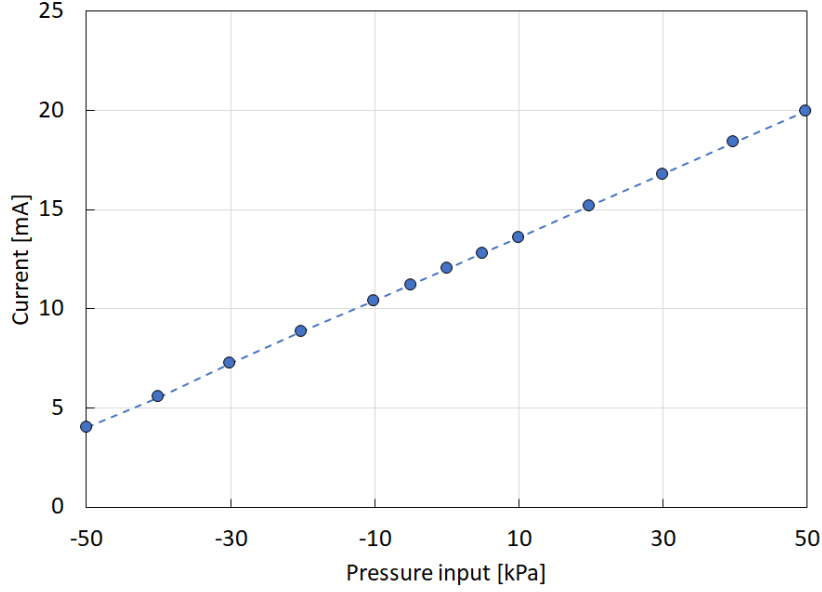


Figure 3.6. Example of calibration results for one of the pressure transducers

Besides the individual calibration, daily verification was performed prior to the experiments to ensure acceptable accuracy on the pressure gradient measured. For the absolute pressure sensors, the test section was fully filled with water which would be flowing for at least 15 minutes to ensure no bubble were present in the test section and on the pressure taps. After 15 minutes pumping the system was stopped and pressure recorded for each absolute pressure sensor. The recorded pressure was then compared with the hydrostatic pressure determined by Equation 3.3.

$$p_{PT,i} = p_{atm} + \rho_{l,pipe} g \Delta h_{PT,i} \quad (3.3)$$

where  $p_{atm}$  is the atmospheric pressure,  $\rho_{l,pipe}$  is the liquid density present in the pipe section,  $g$  is the acceleration of gravity and  $\Delta h_{PT,i} = \sin \theta L_{PT,i}$  is the height of the water column above each corresponding pressure sensor.

Figure 3.7 shows the result of daily verification for different pipe inclinations used in the research work. Measured pressure values exhibit a good match with the calculated hydrostatic pressure.

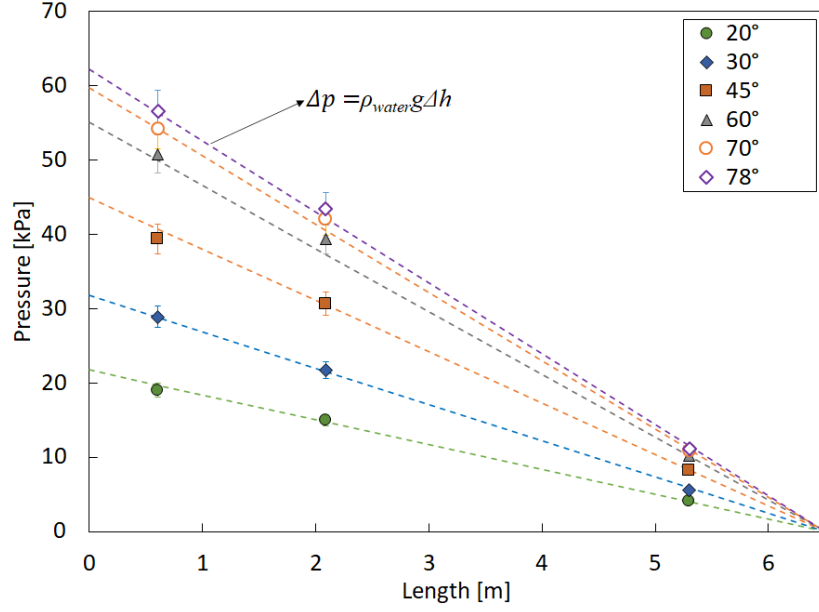


Figure 3.7. Daily calibration verification results for the absolute pressure transducers for different pipe inclinations

As the pipe section is tilted from horizontal position, static pressure is added to the pressure measured by the differential pressure. This pressure comes from the liquid inside the impulse tubes which connected the pressure taps with the differential cells. So, for the differential pressure transmitter the pressure was recorded when the pipe section was empty, and the impulsive tubes were filled with a known liquid. The recorded data was then compared with a pressure gradient determined by Equation 3.4.

$$\Delta p_{DPT,i} = \rho_{l,it} g \sin \theta L_{DPT,i} \quad (3.4)$$

where  $\rho_{l,it}$  is the known liquid density inside the impulse tubes,  $L_{DPT,i}$  is the distance between the high to the low pressure side of the differential pressure transmitter.

Figure 3.8 shows the result of daily verification for the differential pressure transmitter for different pipe inclination. Measured pressure gradient presented a good match with the calculated.

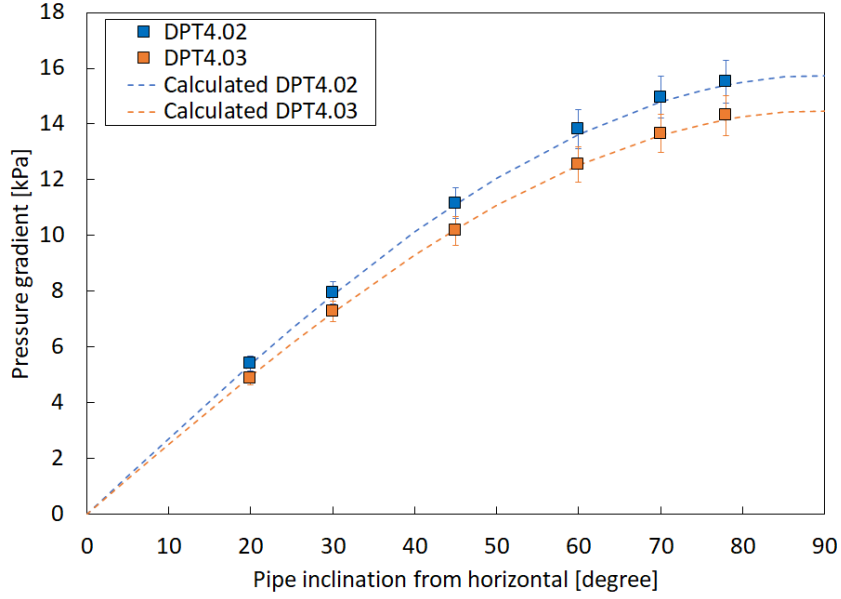


Figure 3.8. Daily calibration verification results for the differential pressure transmitter for different pipe inclinations - impulsive tubes filled with water

The pressure gradient measured during the experimental work had to be corrected for the additional hydrostatic pressure difference in the tubes. Thus, the values of Figure 3.8 were subtracted from the pressure readings coming from the differential transmitters. In order to improve the accuracy of the measurements, the set of pressure range for the DPT was defined for each pipe inclination based on the hydrostatic pressure created by the liquid in the impulsive tubes.

### 3.2.3 Liquid holdup measurements

Liquid holdup was measured experimentally by using electrical impedance probes. This method is also known as electrical conductivity and capacitance probes and it is widely used in research due to simplicity of installation and low cost. The idea behind the electrical probes is to place an electrical field in the pipe perimeter and measure the response of the impedance between the electrodes, which can be related to the liquid fraction inside the pipe. The impedance probe type is normally selected depending on the working fluid.

For conductance probes, in order to measure the conductivity of the fluid inside the pipe, electrodes were fixed to the inner wall of the pipe (Figure 3.9). Thus, a continuous phase is required by this technique in order to conduct electricity and should be in contact with the wall. The capacitance probe does not require a conductive continuous phase and can therefore be placed in the outer part of the pipe (Figure 3.10). On the present work for oil-gas two-phase flows the capacitance was used since oil exhibits dielectric properties. For water-gas two-phase flows conductance probes was used since water is a conductor.

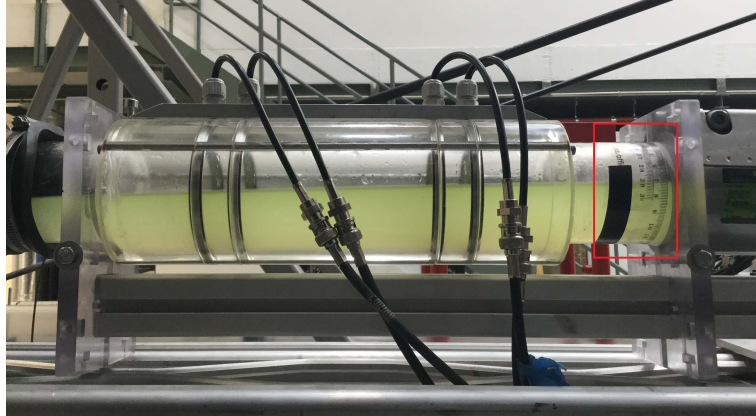


Figure 3.9. Conductance probes



Figure 3.10. Capacitance probes

The capacitance and conductance probes were provided by the multiphase laboratory at NTNU and have previously been successfully used in the experiments of Johansen (2006) and Diaz (2016) experiments. The capacitance probe consisted of a copper or aluminium foil wrapped around the perimeter of the pipe. The inner strips on the foil, acted as the electrodes, while the outer acted as the active guard. To avoid external interference from the surroundings, the sensor was covered by an outer copper foil. While the conductance probe consisted of a pair of metallic rings annealed in the pipe inner wall with the same inner diameter as the pipe. Figure 3.9 shows two pair of conductance rings, which gave separated signal.

Each conductance probe and the capacitance installed in the test section should be calibrated prior to the experiments. High sensitivity to environmental conditions could change the reference values and lead to higher error in the holdup measurements.

The calibration of the instruments consisted of filling the pipe while in horizontal position with a known liquid level and read the voltage. Simultaneously, the wetted perimeter was measured by a scale strip wrapped around the external wall of the pipe next to the instruments as shown in Figure 3.9. For the case of conductance probe the signal from the electrodes was collected by two coaxial cables that were connected to an amplifier, sampled by DAQ card and then logged by a computer using a LabView program made specifically for operations involving the rig in the laboratory.

Liquid holdup was then calculated from the horizontal stratified flow through relations below:

$$\begin{aligned}
 \beta &= \frac{S_L}{r} \\
 X &= r \cos\left(\frac{\beta}{2}\right) \\
 A_L &= \frac{\beta}{2}r^2 - Xr \sin\left(\frac{\beta}{2}\right) \\
 H_L &= \frac{A_L}{A}
 \end{aligned} \tag{3.5}$$

where,  $S_L$  is the wetted perimeter measured,  $r$  pipe radius,  $\beta$  angle of the sector and  $h_L$  liquid level, which are defined in Figure 3.11.

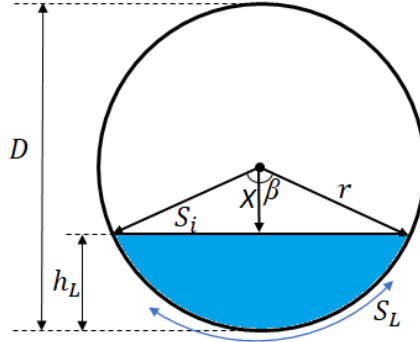
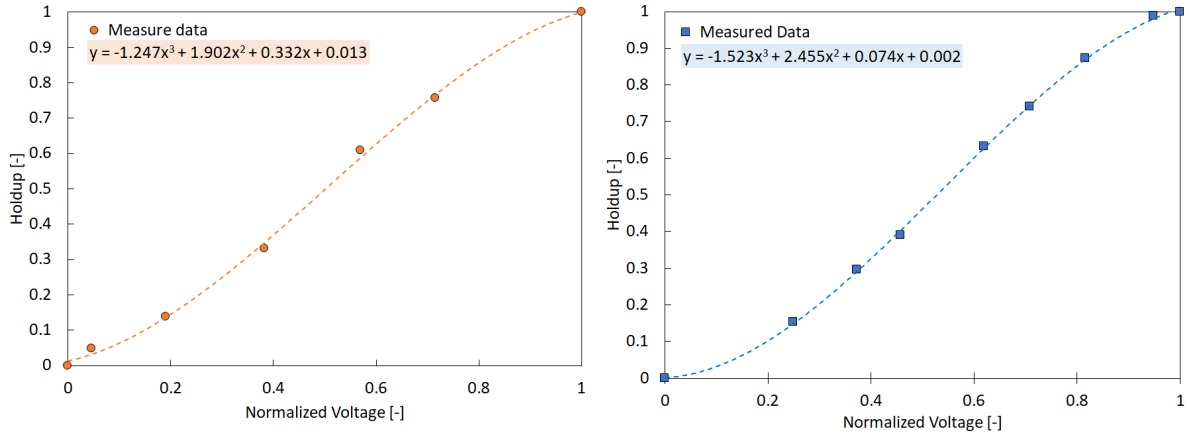


Figure 3.11. Geometrical parameters for stratified flow used on probes calibration

Maximum and minimum voltages were recorded in order to have updated reference values of full and empty pipe. The reference values were then used to normalise the voltage signal through Equation 3.6

$$V^* = \frac{V - V_{min}}{V_{max} - V_{min}} \tag{3.6}$$

After calculating the holdup and normalising the voltage a calibration curve was plotted for both instruments. An example of the calibration S-curve for one capacitance and conductance ring are presented in Figure 3.12.



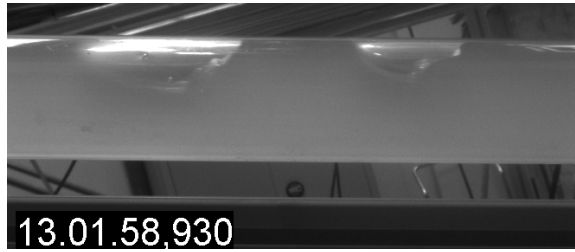
(a) Conductance (b) Capacitance  
 Figure 3.12. Calibration S-curve for the impedance probes

The fitting equation were then used to relate the instruments output signal with the fraction of liquid present in the pipe. The calibration was performed with the test section in horizontal position due to the inability of having stratified flow in inclined pipe. Thus, the calibration S-curves could eventually be a source of error when used in experiments with inclined pipe.

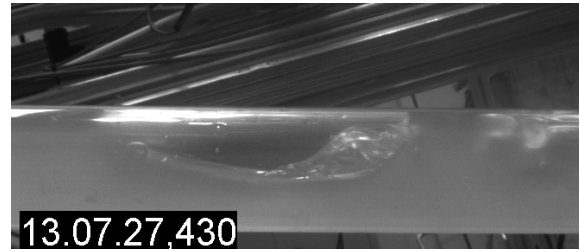
### 3.3 Flow pattern classification and detection of liquid loading onset

Recognition of flow pattern and onset of liquid loading was made by visual observations, pictures and video recordings on the flow loop. For flow pattern classification three synchronised GigE cameras model Basler acA640 with maximum resolution of 659x494 pixels in black and white were used. The videos were recorded at 120 frames per second and simultaneously recorded, registered, saved using a program written in LabView for the acquisition system. The program allowed to choose between saving the recording in frames, as a video, or both and stopping the video simultaneously for all the cameras. The location of the cameras varied for different pipe inclination depending on the accessibility of the test section. Thus, for some inclinations it was not possible to have a clear picture of the flow pattern present in the test section. The criteria established to classify the flow pattern for two-phase flow in this study is shown in Figure 3.13. Stratified-wavy (SW), elongated-bubble (EB), cap-bubble (CB), slug (SL), churn (CH) and annular (AN) flow patterns were observed. Discriminating between annular, churn and stratified wavy using visual inspection was sometimes challenging. Other researchers might end up with a slightly different flow pattern map for the same conditions and fluids. The flow pattern present in the test conditions was decided after circulating for a long time (15 minutes), to avoid errors due to transient phenomena.

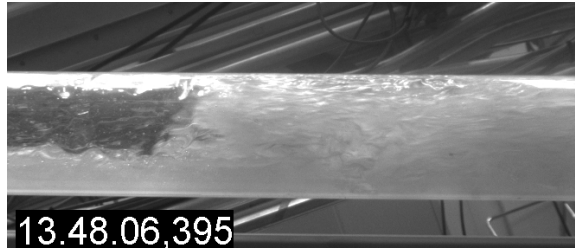




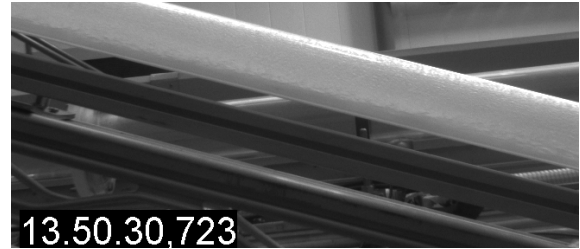
(a) Cap-bubble flow



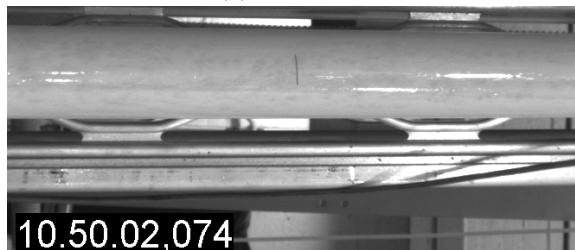
(b) Elongated-bubble flow



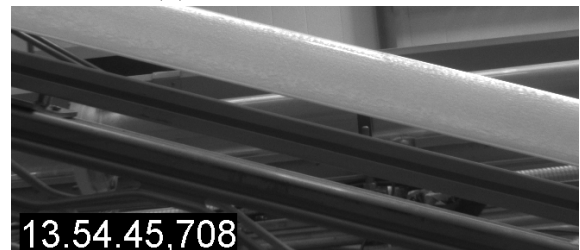
(c) Slug flow



(d) Stratified-wavy flow



(e) Churn flow



(f) Annular flow

Figure 3.13. Classification criteria for flow patterns

For onset of liquid loading identification, a high-speed camera model GoPro Hero 6 Black<sup>®</sup> was installed in the test section. The videos were recorded at 120 frames per second in 1920 x 1080 pixels resolution and simultaneously recorded, stored, saved using a camera application installed in the computer. Pictures and videos were recorded through a visualisation section approximately 4 m above the test section entrance. Due to quick transition from annular to intermittent flow, time signals from pressure sensors and conductance probe rings were also used as an extra support on the identification of onset of liquid loading. Figure 3.14 shows a time series of the pressure sensor when transitioning from annular to slug flow.

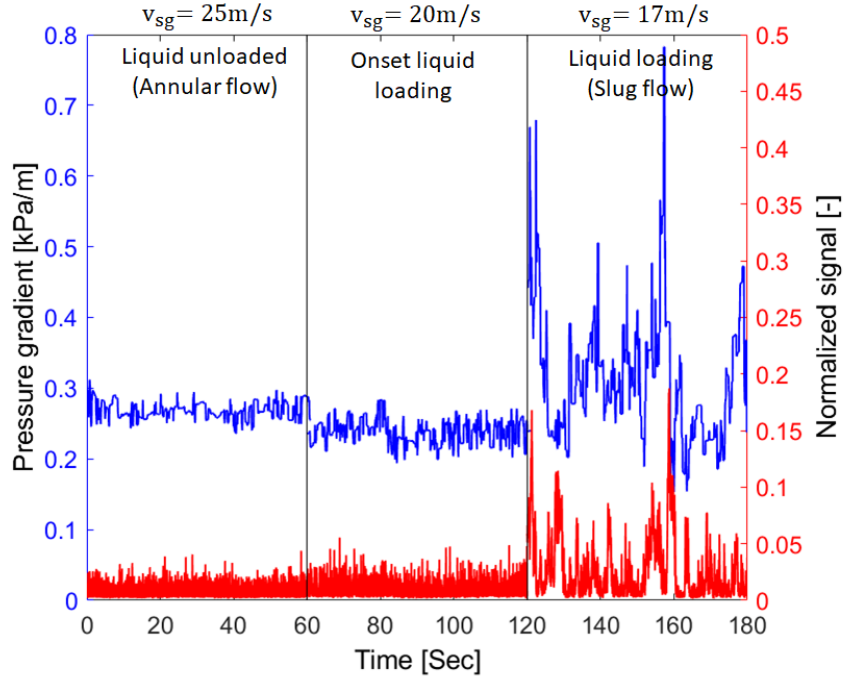


Figure 3.14. Output signal of the differential pressure cell and conductance probes when reducing step-wise the gas rate (air-water system  $\theta=30^\circ$ ,  $v_{sl}=0.01\text{m/s}$ )

It's clear that at full annular flow (stable flow) the amplitude of the pressure fluctuations was smaller than when the slug flow was present (initiation of liquid loading). At slug flow the larger amplitude was due to the instability of the flow, which led to accumulation of liquid in the test section.

For the conductance probe, the holdup values were very small when the flow pattern was annular flow, but increased and fluctuated significantly when the flow pattern changed to slug flow. This technique for flow pattern identification using conductivity probes was suggested earlier by Barnea et al. (1980a).

Visually experimental results for the liquid loading were subdivided in three groups; Loaded for cases where the flow was defined as full intermittent (slug flow), onset liquid loading (*Onset LL*) when the liquid started to move counter-current to the gas flow direction and Unloaded for cases where annular flow was visible.

### 3.4 Experimental conditions

Experiments were conducted for air-water, air-Exxsol D80 and air-mixed oil two-phase flow systems, where several combinations of pipe inclination, superficial velocity of liquid and superficial velocity of gas were tested. Preliminary experiments were performed to define the test matrix, considering the limitations on the availability of the liquid volume present in the main separator, pump capacity and flow meters range.

### 3.4.1 Air-water system

For air-water system inclination angles of 20°, 30°, 45°, 60°, 70° and 78° (from horizontal), superficial liquid velocities of 0.01, 0.02, 0.05, 0.1 and to 0.2 m/s, and superficial gas velocities ranging from 60 to 3 m/s, were tested. The matrix was defined to investigate the effect of pipe inclination on liquid loading onset by decreasing gas flow rate.

### 3.4.2 Air-Exxsol D80 system

Air-Exxsol D80 system experiments were possible only for inclination angles of 30°, 45° and 60° (from horizontal), due to excessive fog created by oil particles, which affected air extraction system and the laboratory fire alarm. Superficial velocity of liquid and gas varying from 0.01 to 0.2 m/s and 50 to 5 m/s, respectively, were tested. Prior tests were performed for each selected inclination in order to identify possible experimental matrix that covers annular to intermittent transition.

### 3.4.3 Air-mixed oil system

To investigate the effect of pipe inclination and fluid viscosity on the flow pattern transition boundary, several combinations of pipe inclination and fluid velocities were tested. For every inclination 10°, 15°, 20°, 25°, 30°, 45°, 60°, 70° and 78° (from horizontal), combinations of superficial liquid and gas velocity ( $v_{sl}$  and  $v_{sg}$ ) varied from 0.1 m/s to 1.2 m/s, and 0.14 m/s to 32 m/s, respectively.

## 3.5 Experimental procedure

In this thesis different two-phase flow measurements have been performed, all with the objective of studying the effect of pipe inclination on the flow regime map and on the onset of liquid loading. For the experimental execution a necessary start-up it was recommended by NTNU to test the instrumentation to avoid large uncertainties during the measurements, and to meet some safety requirements. Procedures to prepare the facility for the experiment, are described in Appendix A.

Start-up and daily calibration the experiments were conducted as follows:

1. Start the water/oil pump and open the control valve through LabView. The opening percentage on the control valve and pump frequency determined the liquid flow rate.
2. Set the desired liquid flow rate and circulate the liquid in the section for at least 5 minutes, until no bubble can be seen flowing.
3. With the air injection valve closed, open the air control valve allowing the air to fill the flexible hose (red coloured flexible pipe in Figure 3.1).
4. Set the desired air rate using the air injection valve.
5. Wait for the two-phase flow in the test section to become stable. The waiting time vary from one experiment to the other.

6. Once stable conditions are reached log the data from the instruments in LabView for at least 5 minutes.
7. Capture the high-speed videos and pictures necessary for the visual observation and support for decision making.
8. Insert logged data for flow rates, pressure drop, temperature and probes signal in Excel template containing needed adjustments to the data.
9. Repeat these steps for different gas and liquid flow conditions and pipe inclinations.

### **3.5.1 Data processing**

All laboratory instruments, such as flow meters, control valves, pumps, pressure sensors, thermocouples and probes, can be remotely supervised by a program in LabView. The instruments are wired to a central cabinet where their output signal is converted into voltage signal. The voltage is further directed to an external data logging instrument from which it is digitised and sent to the main lab computer. One generated file contained low and high-speed data recorded at rates of 20 Hz and 2000 Hz respectively.

In order to process high volume of collected experimental data, processing tools were developed using Excel and Matlab program. For each type of data, the processing tool was developed to read the file and calculate the average measurement over the recorded period of two minutes. The tool provided a time-efficient method on the data processing. In addition, they were used to check and identify if the test condition needed to be repeated, while the experiment was running.

## **3.6 Measurement results**

In this section the acquired experimental results are presented. The measured data includes flow pattern map, pressure gradient and liquid holdup.

The objective of the experimental test campaigns was to acquire data-sets to evaluate the applicability of the existing methods used on the prediction of liquid loading onset in an inclined pipe and to proposed possible improvements. Therefore, the main flow regime studied was annular flow and transition to intermittent flow (slug or churn flow). In addition, experimental data was acquired to study the effect of viscous fluid on the flow regime maps for two-phase flow in an inclined pipe. The measurement results are presented in Tables C.2.1, C.2.2 and C.2.3 in Appendix C.

### **3.6.1 Air-mixed oil system**

#### **3.6.1.1 Flow regime transition**

Figures 3.15a–3.15i shows the flow pattern maps observed during the experiments performed to evaluate the flow pattern boundary transition for a two-phase flow system when a viscous fluid and inclined test section was used.

Overall, six flow regimes, namely stratified-wavy, elongated-bubble, cap-bubble, slug, churn and annular flow pattern were observed during the experiments. From the classification presented in Figure 2.2 stratified-smooth and dispersed-bubble flow regime were not experimentally identified, due to minimum pipe inclination tested and limitation of the liquid volume available in the laboratory respectively. In Barnea et al. (1985) stratified-smooth flow pattern could be observed only for inclination angles less than  $0.25^\circ$ , which was not the case of pipe inclination tested in this work. Experimentally, churn flow has a similar behaviour as the one verified by Barnea et al. (1985) where the first appearance of this pattern occurred at  $70^\circ$  inclination (Figure 3.15h).

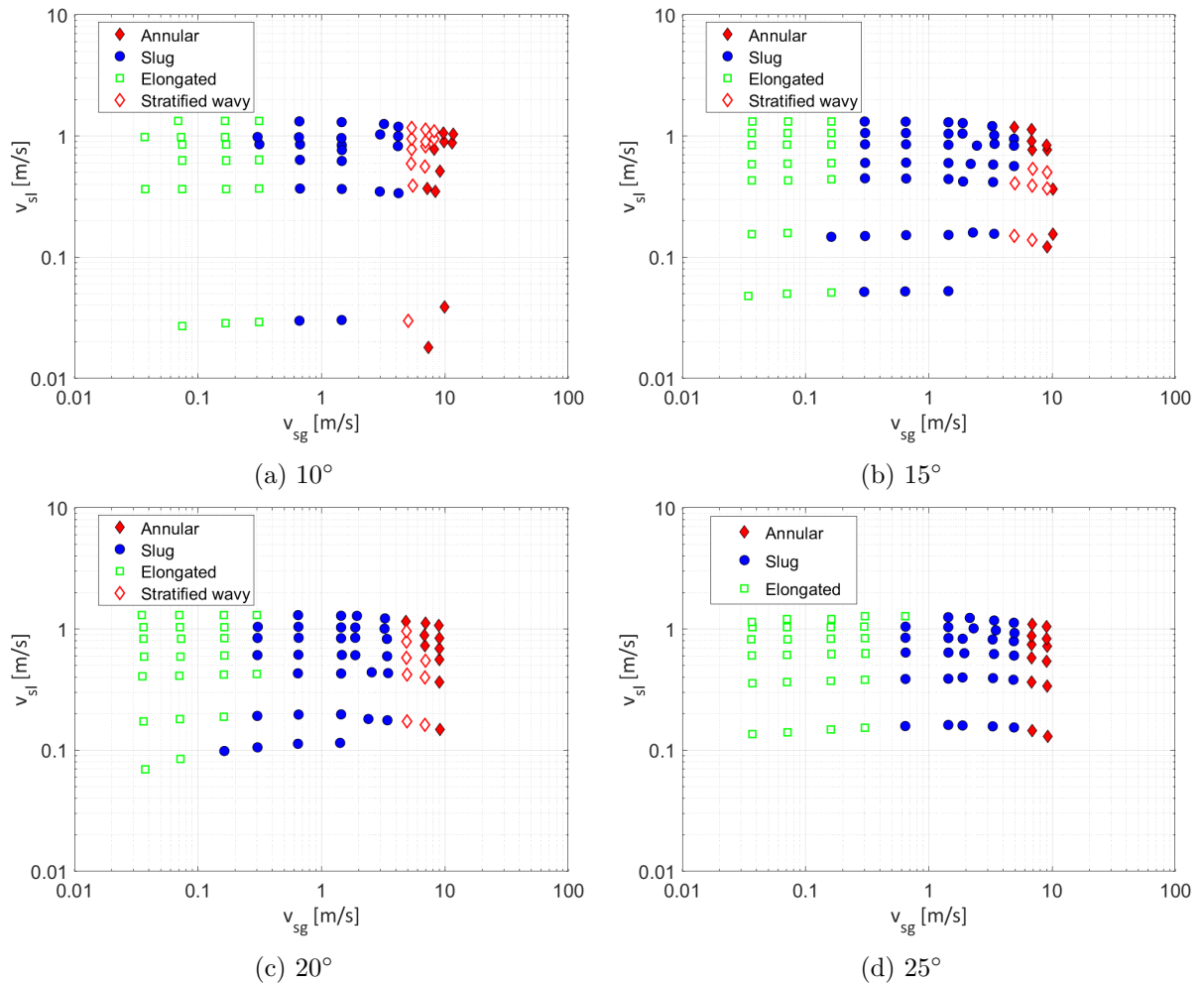


Figure 3.15. Experimental tests on flow pattern transitions for air-mixed oil system for different inclination angles (from horizontal)

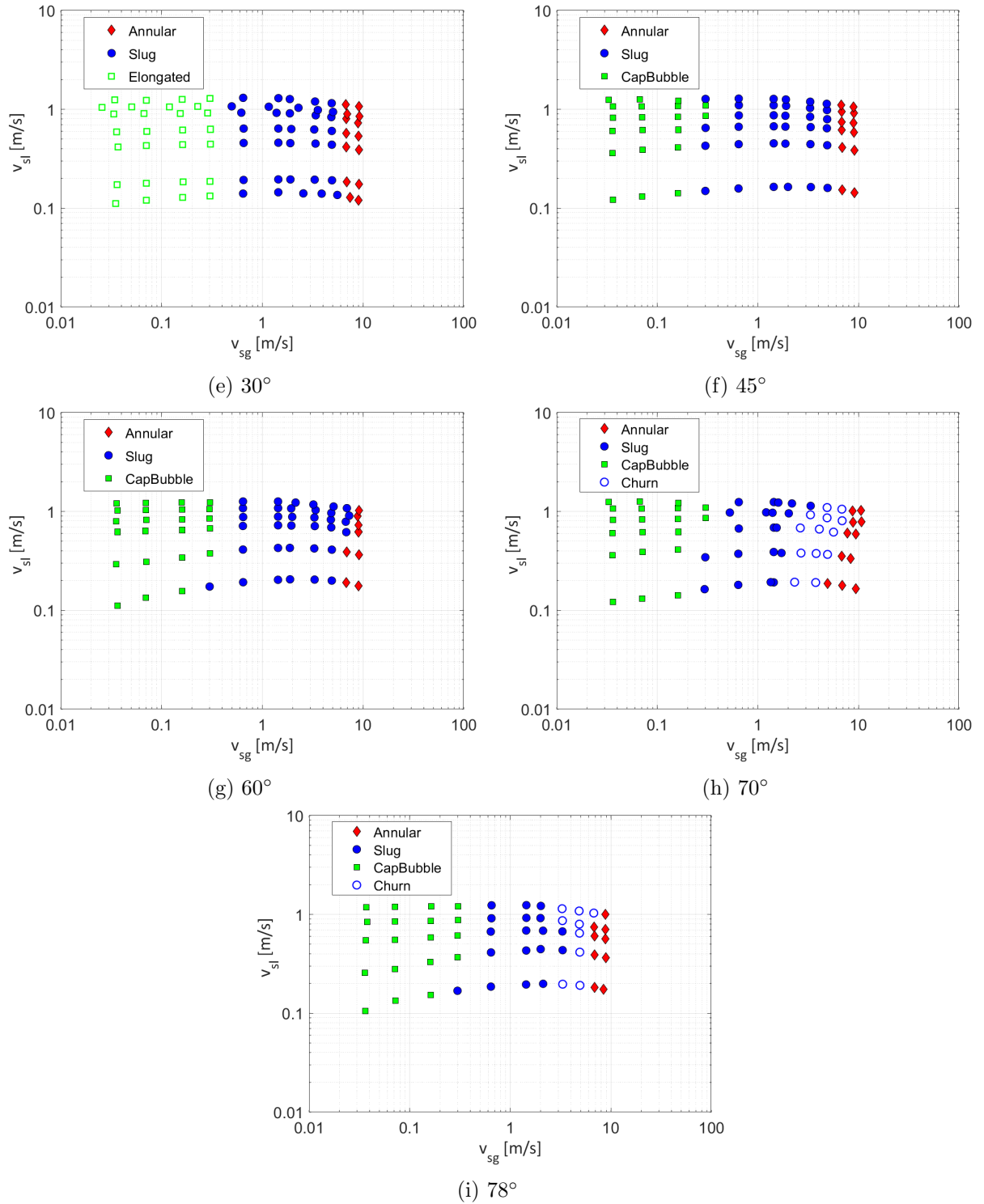


Figure 3.15. (*cont.*) Experimental tests on flow pattern transitions for air-mixed oil system for different inclination angles (from horizontal)

Stratified-wavy flow was not observed for inclinations above 20°, which is similar to what was observed by Barnea (1987).

Barnea et al. (1985) and Barnea (1987) observed that elongated-bubble disappeared, and cap-bubble flow took place at angles above 30° for upward inclined pipe, this was also observed experimentally. Slug and annular flow were observed for the entire range of

pipe inclinations. Higher superficial gas velocity was not possible due to safety reasons of the laboratory since a viscous fluid was being used. At high gas flow rates, small oil particles would create a fog ambient in the lab with would activate the fire alarm.

### 3.6.1.2 Pressure gradient

Figures 3.16a–3.16g presents change in pressure gradient vs. superficial gas velocity, given a constant superficial liquid velocity for pipe inclination, tested for air-mixed oil flow system. Differential pressure transducers were used to measure the pressure drop in the test section, where the output signal was processed and corrected for the added static pressure using Equation 3.4 where  $\rho_{l,it}=840 \text{ kg/m}^3$ .

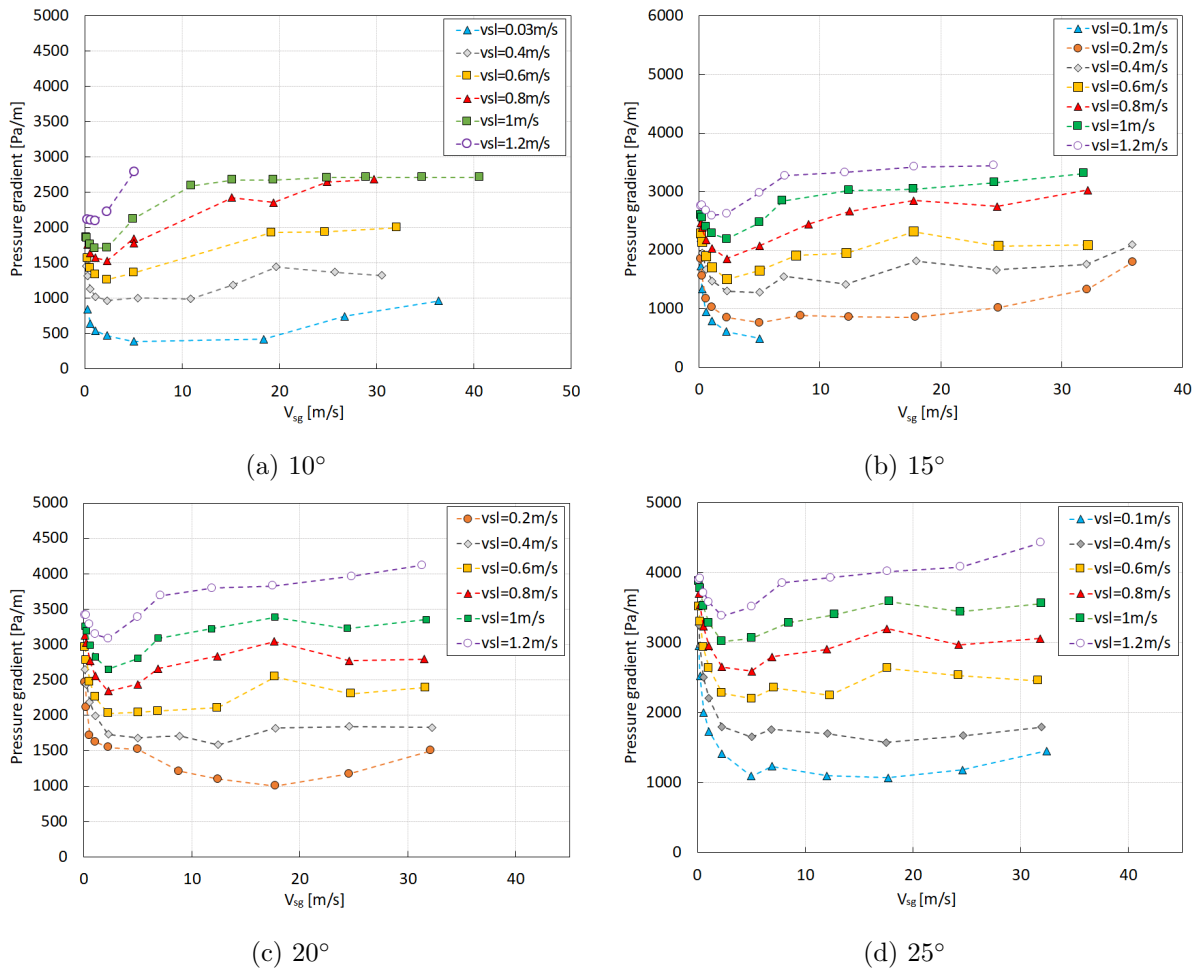
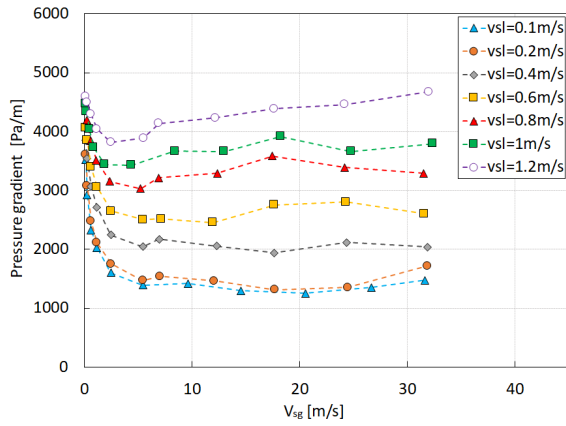
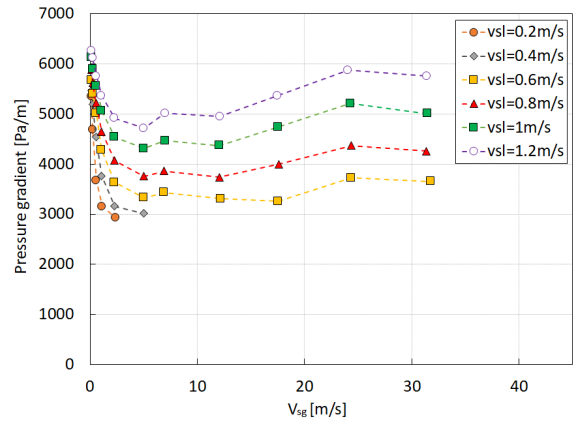


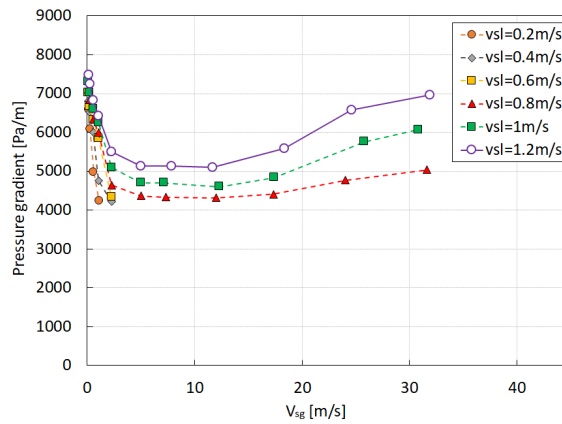
Figure 3.16. Pressure gradient variation vs. superficial gas velocity for air-mixed oil system at STP conditions for different inclination angles (from horizontal)



(e) 30°



(f) 45°



(g) 60°

Figure 3.16. (cont.) Pressure gradient variation vs. superficial gas velocity for air-mixed oil system at STP conditions for different inclination angles (from horizontal)

For some pipe inclinations such as 10°, 45°, 60°, 70° and 78° at given liquid flow rate, total pressure drop to be measured was out of the calibration range of the used differential pressure transmitters. Thus, the measurement could not be considered accurate and was therefore not plotted.

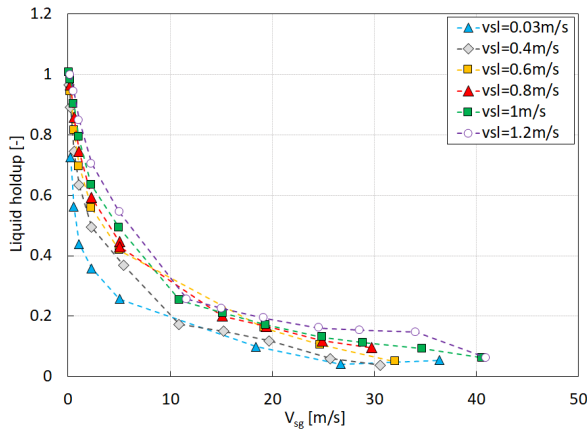
Overall, it was observed that the pressure drop response depended on the flow pattern present in the test section as well as with the pipe inclination. For low gas and liquid superficial velocities were bubble flow (elongated and cap) was identified, the pressure drop curve reaches a minimum point. This minimum is due to large liquid holdup that occurs in bubble flow, which results in a large gravitational pressure gradient, and due to low friction pressure gradient because of the low velocities (Shoham, 2006).

### 3.6.1.3 Liquid holdup

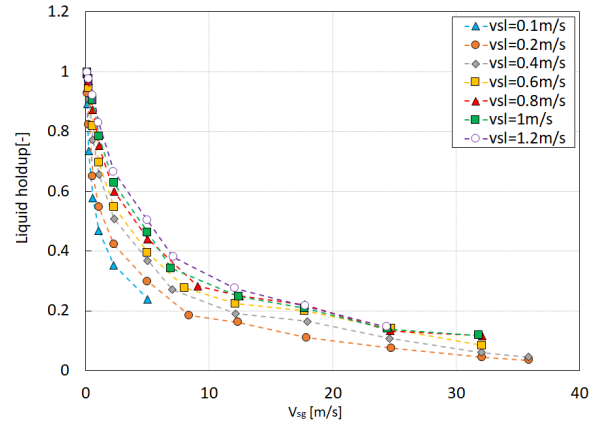
Figures 3.17a–3.17h present the liquid holdup vs. superficial gas velocity given a constant superficial liquid velocity pipe inclination tested for air-mixed oil flow system.

For each data set, the average voltage was converted to the normalised signal and used as input in the S-curve (Figure 3.12b) which the liquid holdup was calculated.

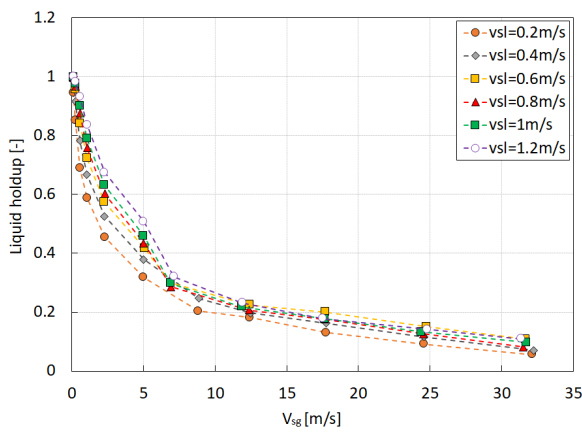




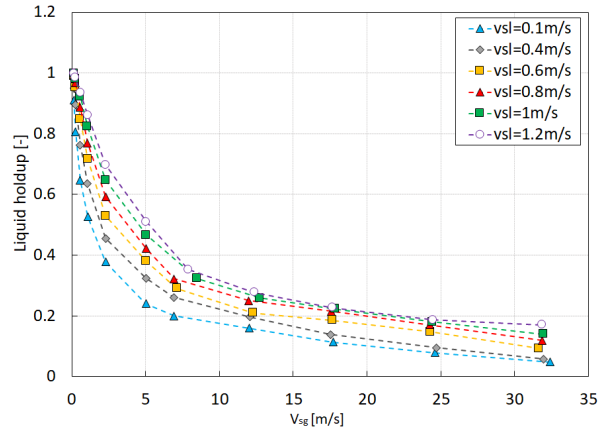
(a) 10°



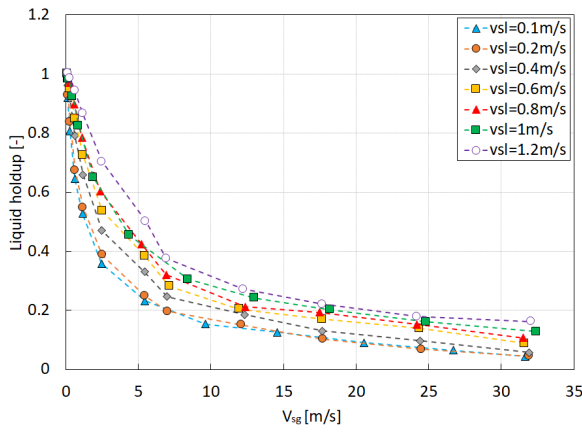
(b) 15°



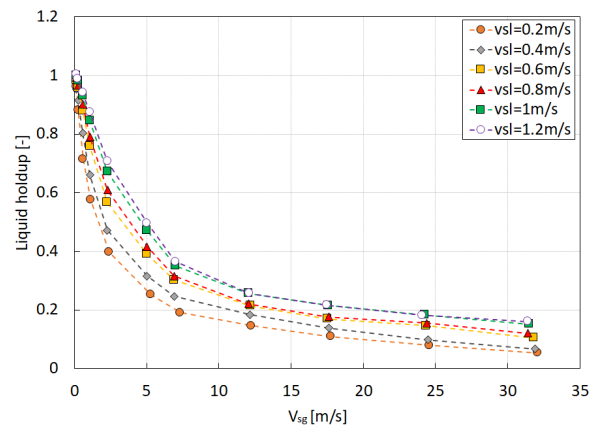
(c) 20°



(d) 25°

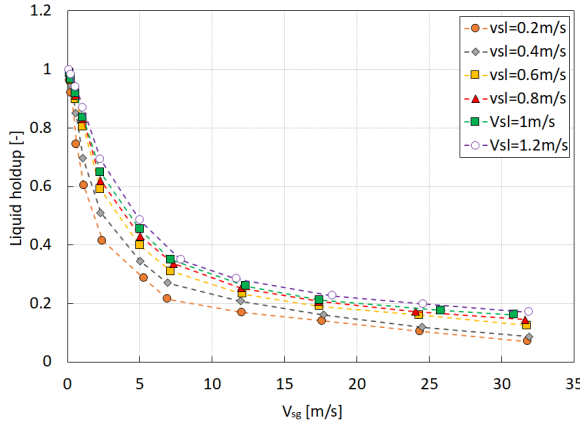


(e) 30°

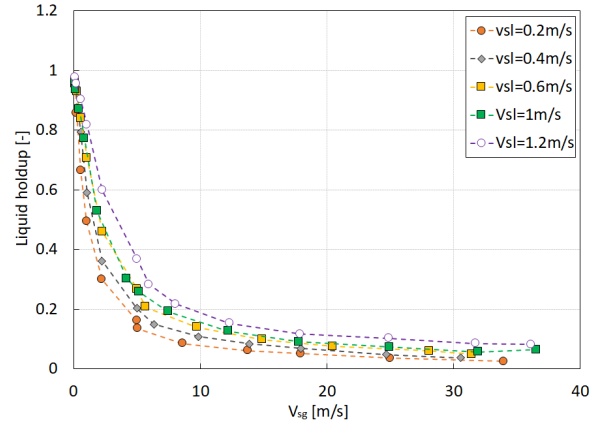


(f) 45°

Figure 3.17. Liquid Holdup vs. superficial gas velocity for air-mixed oil system at STP conditions for different inclination angles (from horizontal)



(g) 60°



(h) 70°

Figure 3.17. (cont.) Liquid Holdup vs. superficial gas velocity for air-mixed oil system at STP conditions for different inclination angles (from horizontal)

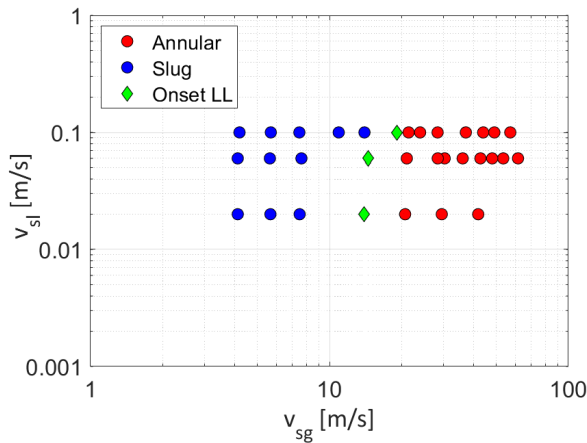
Overall, the change in flow pattern and pipe inclination had no significant impact on the liquid holdup behaviour with superficial gas velocity as observed in Figure 3.17.

### 3.6.2 Air-water system

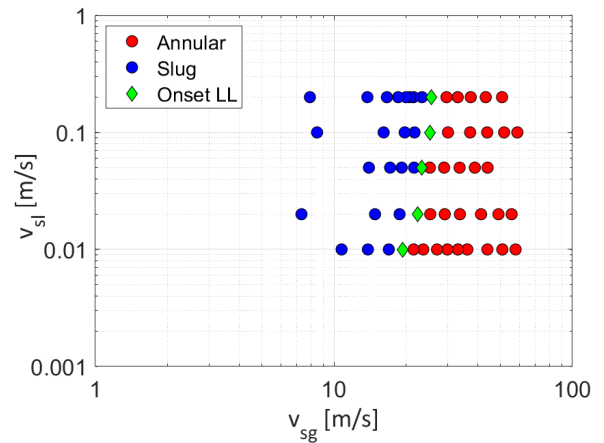
Result from experiments performed for air-water flow system are presented in this subsection. The experiments were aimed to evaluate the annular-slug transition boundary for inclined test section. Thereafter liquid loading was related to flow pattern transition.

#### 3.6.2.1 Flow regime transition

Observed flow pattern transition from slug to annular flow and the onset of liquid loading is presented in Figure 3.18.



(a) 20°



(b) 30°

Figure 3.18. Experimental tests on transition boundary of annular-slug for air-water system at STP condition for different inclination angles (from horizontal)

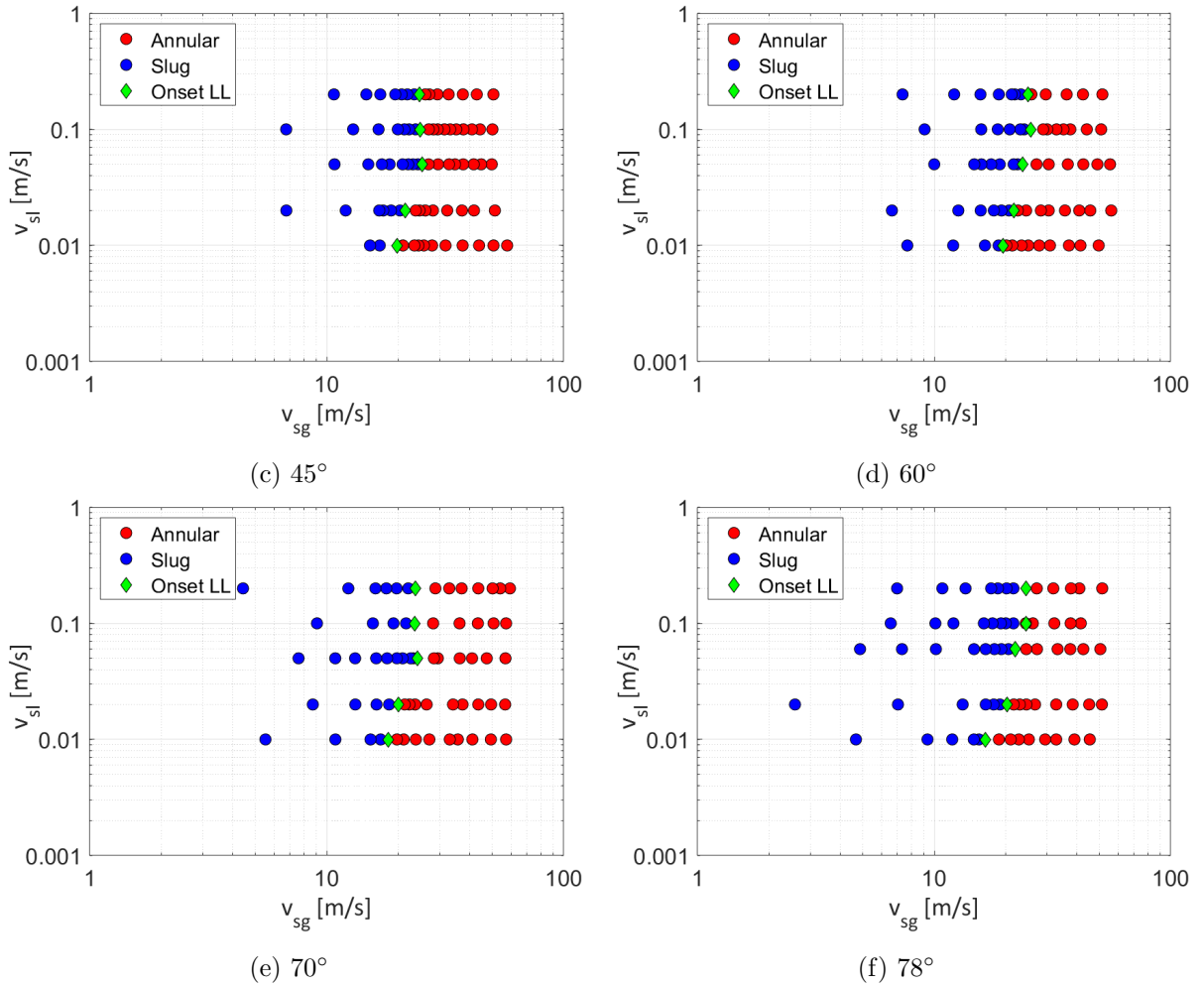


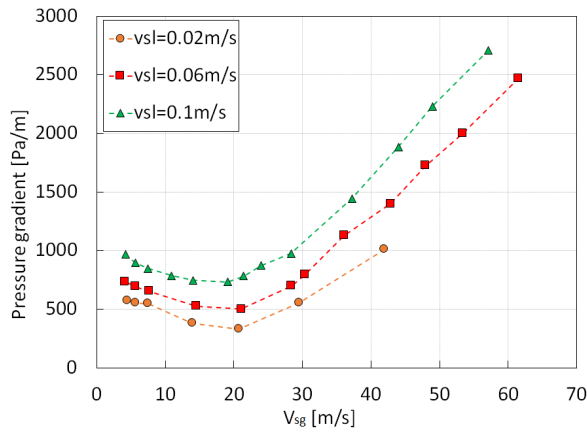
Figure 3.18. (*cont.*) Experimental tests on transition boundary of slug-annular for air-water system at STP condition for different inclination angles (from horizontal)

For this experimental study, a refined interval was used so that the transition from annular to slug could be identified. In addition, slow motion video was recorded and used in the identification. For a constant superficial liquid velocity, the reduction of superficial gas velocity was irregular, since the valve controlling the gas injection into the test section was operated manually.

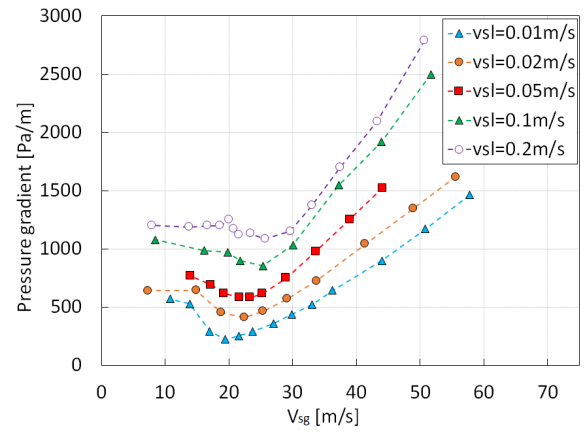
### 3.6.2.2 Pressure gradient

Figures 3.19a–3.19f shows the change in pressure gradient vs. superficial gas velocity for all the pipe inclinations for air-water flow system.

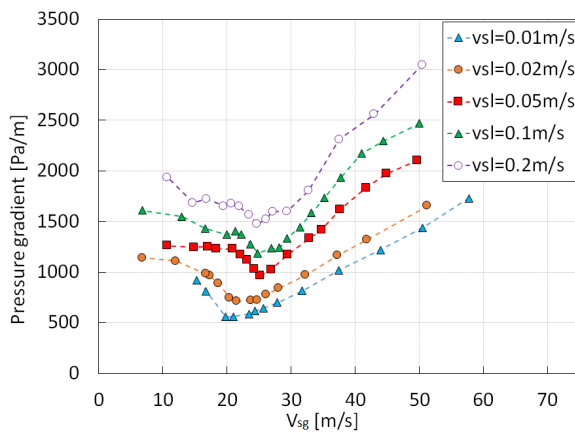
For all the pipe inclination, measured pressure gradient reached a minimum. To the left of the minimum, Shoham (2006) explained that the reduction of pressure drop can be due to the fact that with the increase of the gas flow rate, the liquid holdup reduces, resulting in a lower gravitational pressure gradient and that the velocities encountered in slug flow are not high enough to cause high frictional pressure gradient. To the right of the minimum in the curve the friction component of the pressure gradient starts to be dominant increasing the pressure drop.



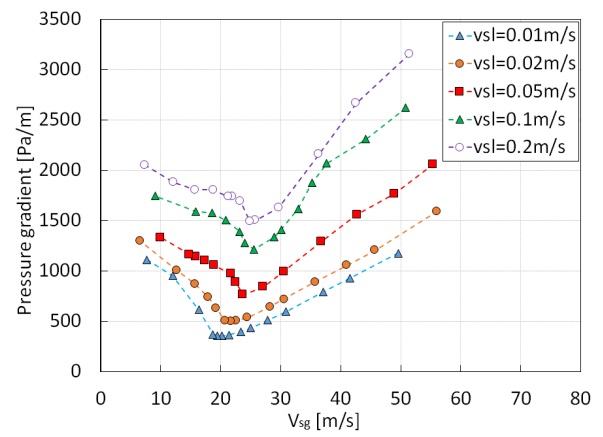
(a) 20°



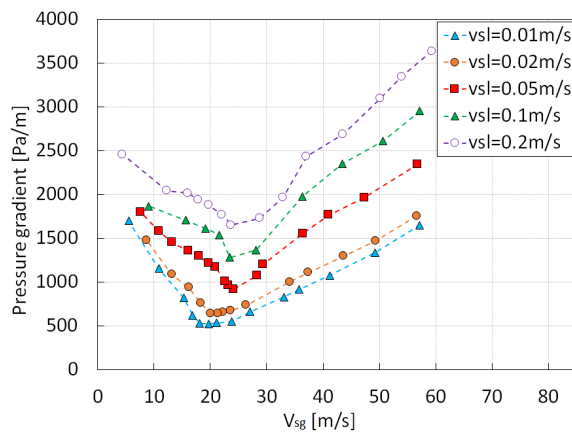
(b) 30°



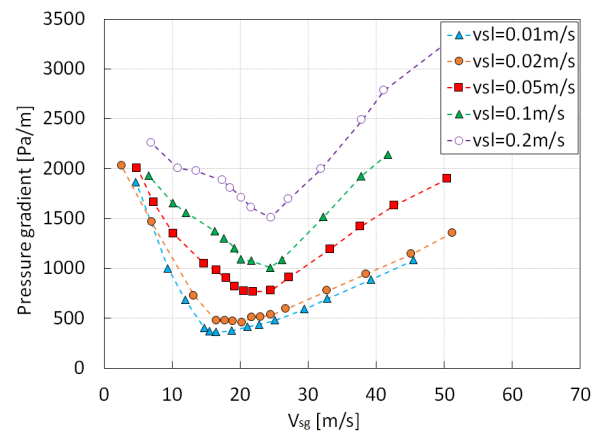
(c) 45°



(d) 60°



(e) 70°



(f) 78°

Figure 3.19. Pressure gradient variation vs. gas superficial velocity for air-water system at STP conditions for different inclination angles (from horizontal)

### 3.6.2.3 Liquid holdup

Figures 3.20a–3.20f presents the liquid holdup vs. superficial gas velocity for air-mixed oil flow system, for a given constant superficial liquid velocity and pipe inclinations. Liquid holdup at flow regime transition was calculated with the average values and the S-curve of the impedance probe (Figure 3.12a).

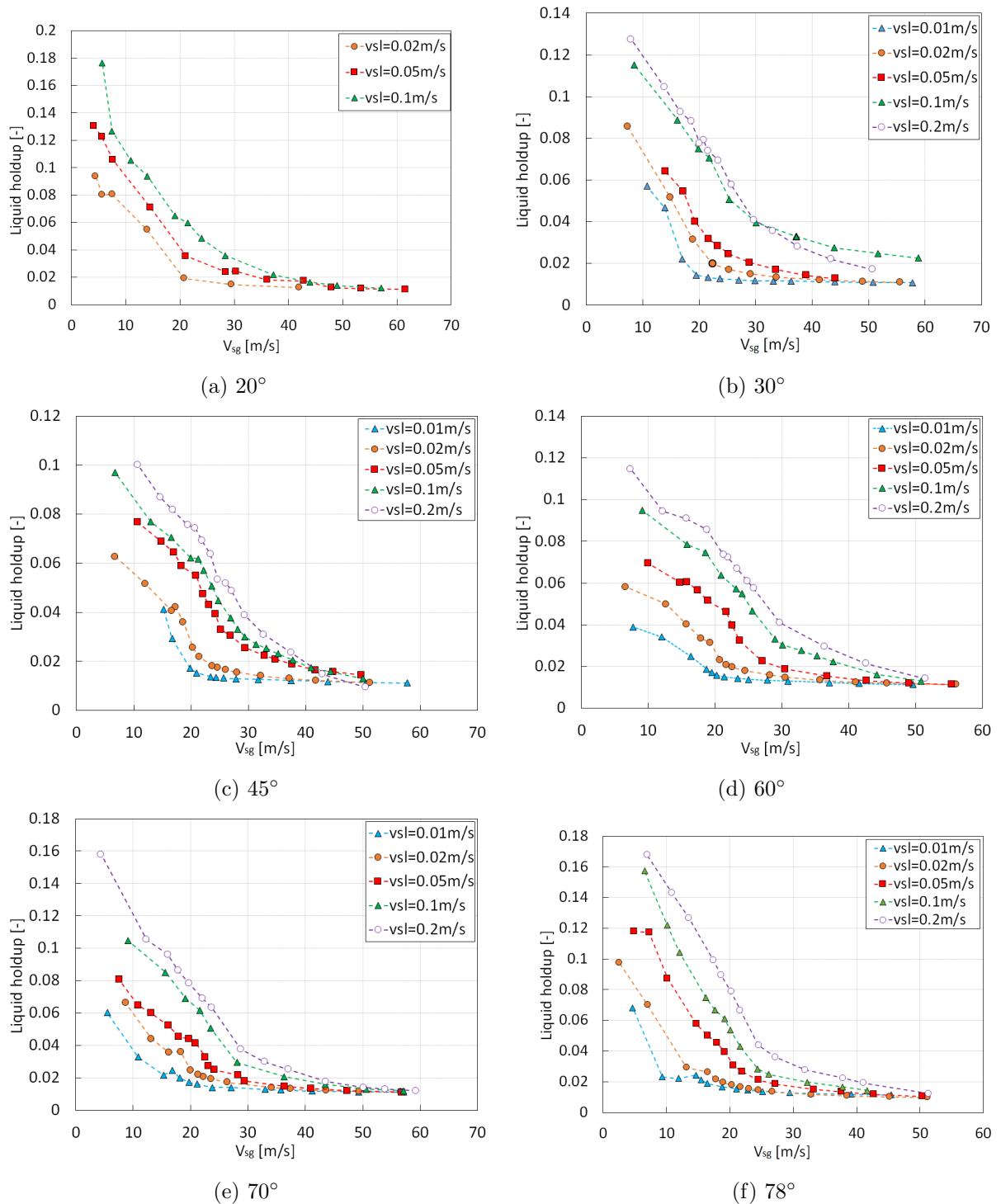


Figure 3.20. Liquid holdup vs. gas superficial velocity for air-water system at STP conditions for different inclination angles (from horizontal)

### 3.6.3 Air-Exxsol D80 system

Result from experiments performed for air-Exxsol D80 flow system are presented in this subsection. The experiments were performed aimed to evaluate the annular-slug transition boundary for inclined test section. The acquired data would then be compared with air-water experimental results to evaluate the effect of liquid viscosity on the annular-slug transition. Liquid loading study was also performed for this set of data.

#### 3.6.3.1 Flow regime transition

Flow pattern transition from slug to annular flow observed experimentally is presented in Figure 3.21.

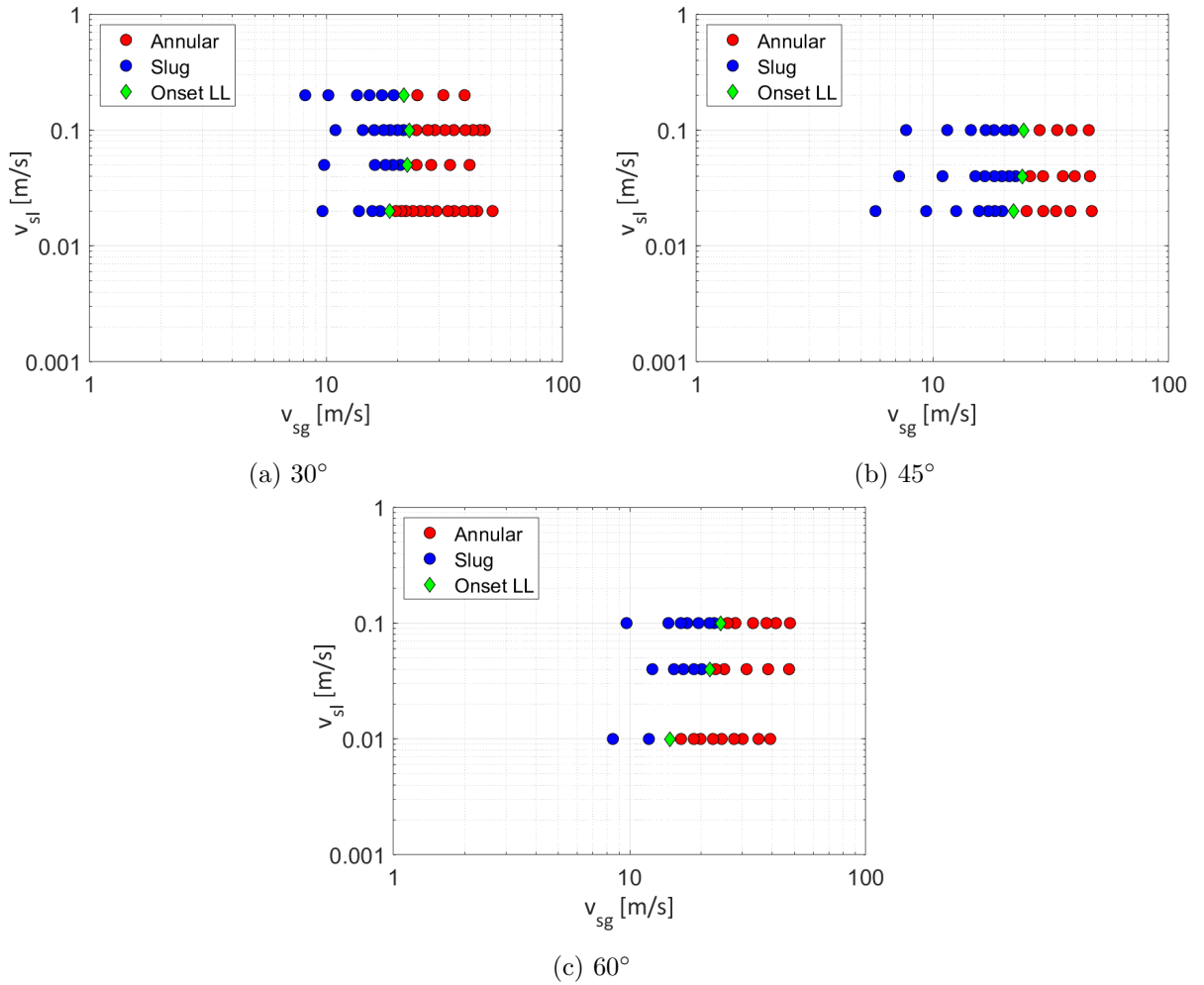


Figure 3.21. Boundary of slug-annular transition for air-Exxsol D80 system for different inclination angles (from horizontal)

The interval of variation of superficial gas and liquid velocity are not equally distributed for tested pipe inclinations, due to insufficiency of liquid available in the lab and to manual injection of the gas flow into the test section.

### 3.6.3.2 Pressure gradient

Figure 3.22 shows the change in pressure gradient vs. superficial gas velocity for all tested pipe inclinations for air-Exxsol D80 flow system.

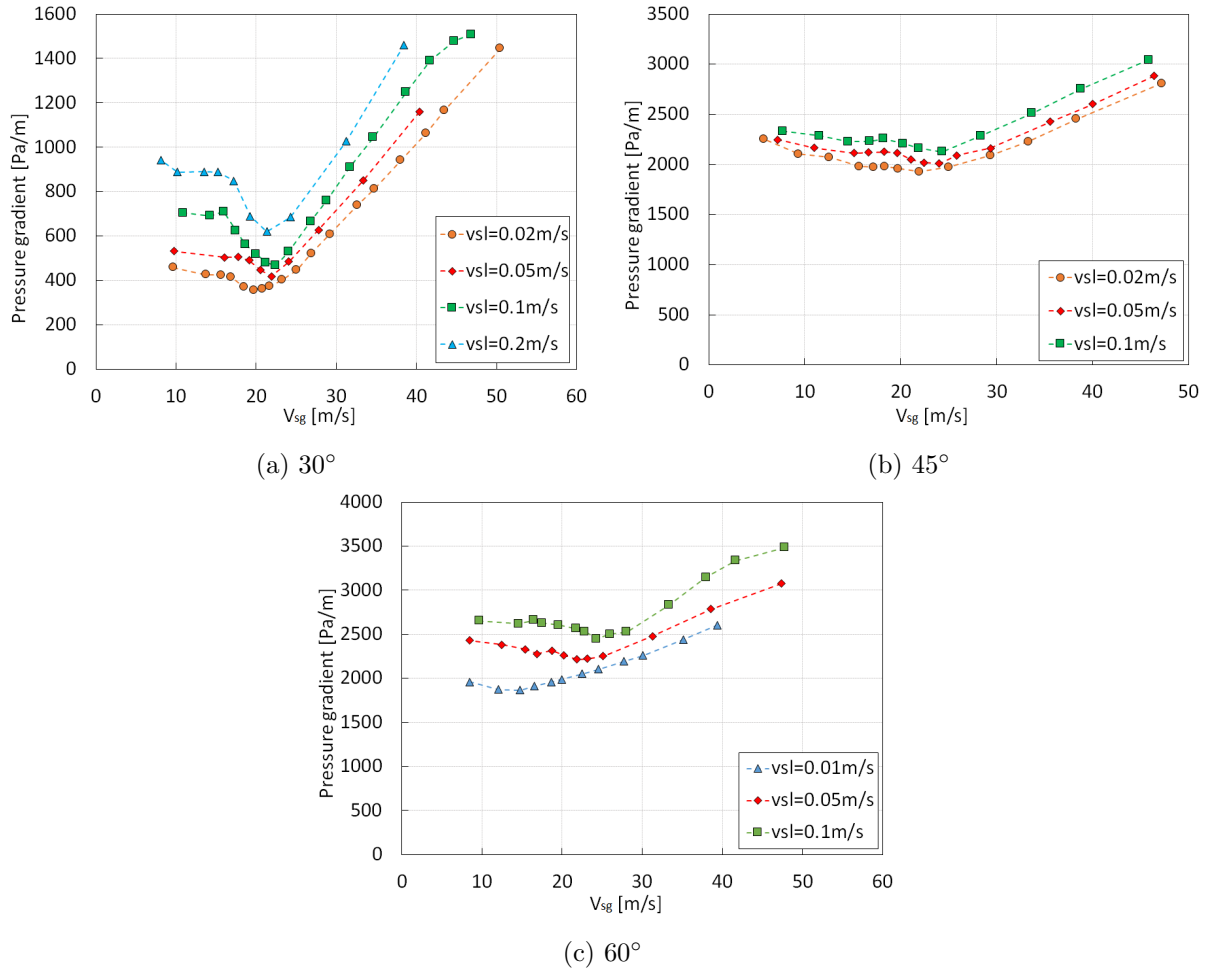


Figure 3.22. Pressure gradient variation with gas superficial velocity for air-Exxsol D80 system at STP conditions for different inclination angles (from horizontal)

It can be observed that as in air-water system, the pressure gradient reached a minimum value as the superficial gas velocity reduced, which meant an increase in liquid content inside the pipe section.

Liquid holdup was not measured for this experimental campaign due to poor quality of the values measured by the capacitance probes.

# Chapter 4

## Numerical study on two-phase gas-liquid flow

In this chapter the data acquired for two-phase gas-liquid flow inclined pipe were analysed and compared against models available in the literature, as well as a dynamic simulator. The goal of the present studies was to:

- Investigate the effect of viscous fluid on flow regime map for inclined pipe.
- Evaluate the accuracy of models available in the literature used for prediction of the onset of liquid loading by comparing them against experimental data.
- Investigate the effect of entrainment droplets in gas core in liquid film models.
- Develop a new liquid loading onset model with more predictability.
- Quantify the variability of gas liquid loading onset rates, for different loading criteria and pressure drop.



## 4.1 Effect of fluid viscosity on two-phase flow in inclined pipe

From literature survey presented in Section 2.1 and summarised in Table 2.1, it was observed that most experimental studies on two-phase flow pattern for inclined section were carried out using water as liquid phase. Few researchers such as Stanislav et al. (1986) and Kokal and Stanislav (1989*a,b*) performed experiments for slightly inclined pipe (maximum  $9^\circ$  inclination) using viscous liquid (7 mPa.s and 6.5 mPa.s). Other examples are Gokcal et al. (2008) and Jeyachandra et al. (2012) who performed experiments with higher liquid viscosity, ranging from 0.585 Pa.s to 0.181 Pa.s, in lower pipe inclination ( $\pm 2^\circ$  from horizontal). Therefore, the availability of data to evaluate the performance of multiphase flow models on flow pattern predictions for viscous liquid is limited.

The experimental work carried out in this thesis and presented in Section 3.6.1 was used to evaluate the performance of the unified model proposed by Barnea (1987) and the dynamic multiphase flow simulator (OLGA<sup>®</sup> 7.3 - hereafter referred to as OLGA).

Barnea (1987) model was chosen to be evaluated being the most used model for flow pattern predictions. Pressure gradient values from OLGA simulations for a certain liquid velocity and different pipe inclinations were compared with pressure gradient acquired experimentally.

### 4.1.1 Flow pattern

Experiments were performed in a steady-state conditions according to methodology presented in section 3.5. The flow regimes observed experimentally were:

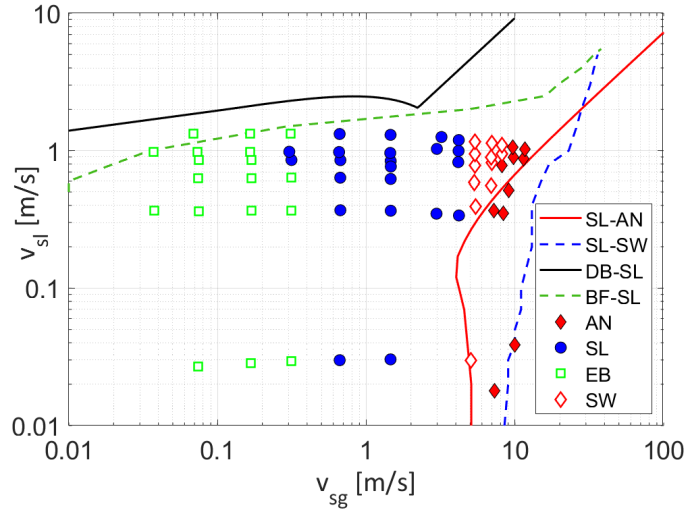
- stratified-wavy flow (SW);
- elongated-bubble flow (EB);
- cap-bubble flow (CB);
- slug flow (SL);
- churn flow (CH);
- annular flow (AN).

A complete flow regime mapping such as the example shown in Figure 2.2 was not possible to achieve, due to limitations of the laboratory facility, such as pump capacity, volume of liquid available in the main separator and limited range of flow meters.

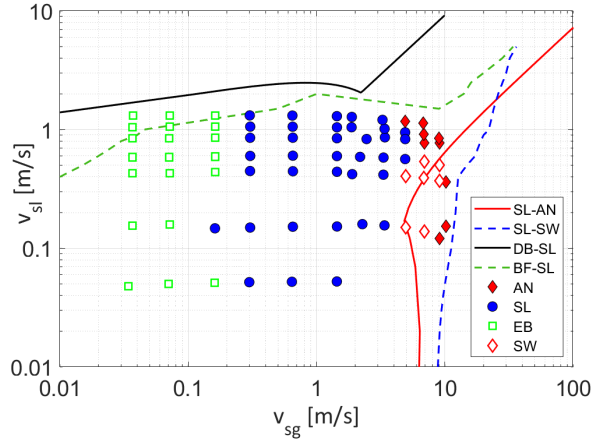
The identification of flow regime present in the pipe was sometimes questionable due to visual similarity of some regimes, for example the case of stratified-wavy to annular flow transition for low inclination angles, and churn to annular flow transition for high inclination angles. This brought some uncertainty into flow pattern classification in present study.

Figures 4.1a–4.1i show flow pattern boundaries obtained from the transition model of Barnea (1987) (solid lines), OLGA (discontinuous line) and the data measured in the present work (colour points).

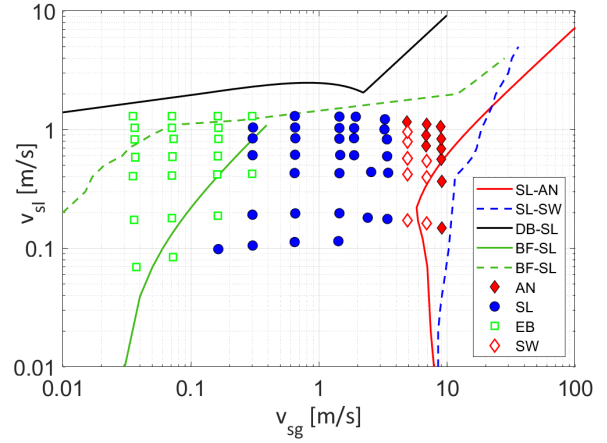
|   |                  |    |
|---|------------------|----|
| ◊ | Stratified-wavy  | SW |
| □ | Elongated-bubble | EB |
| ■ | Cap-bubble       | CB |
| ● | Slug             | SL |
| ○ | Churn            | CH |
| ◆ | Annular          | AN |



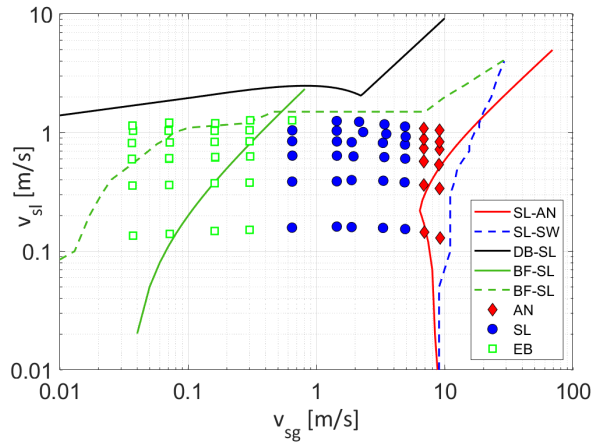
(a) 10°



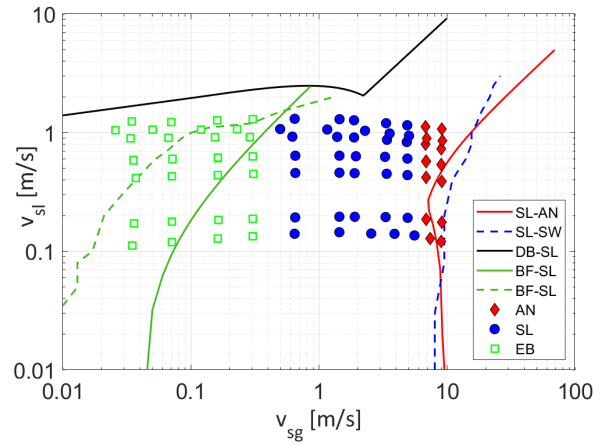
(b) 15°



(c) 20°



(d) 25°



(e) 30°

Figure 4.1. Experimental flow pattern vs. Barnea (1987) model (—) and OLGA simulation (---) for air-mixed oil system in upwards inclined pipes

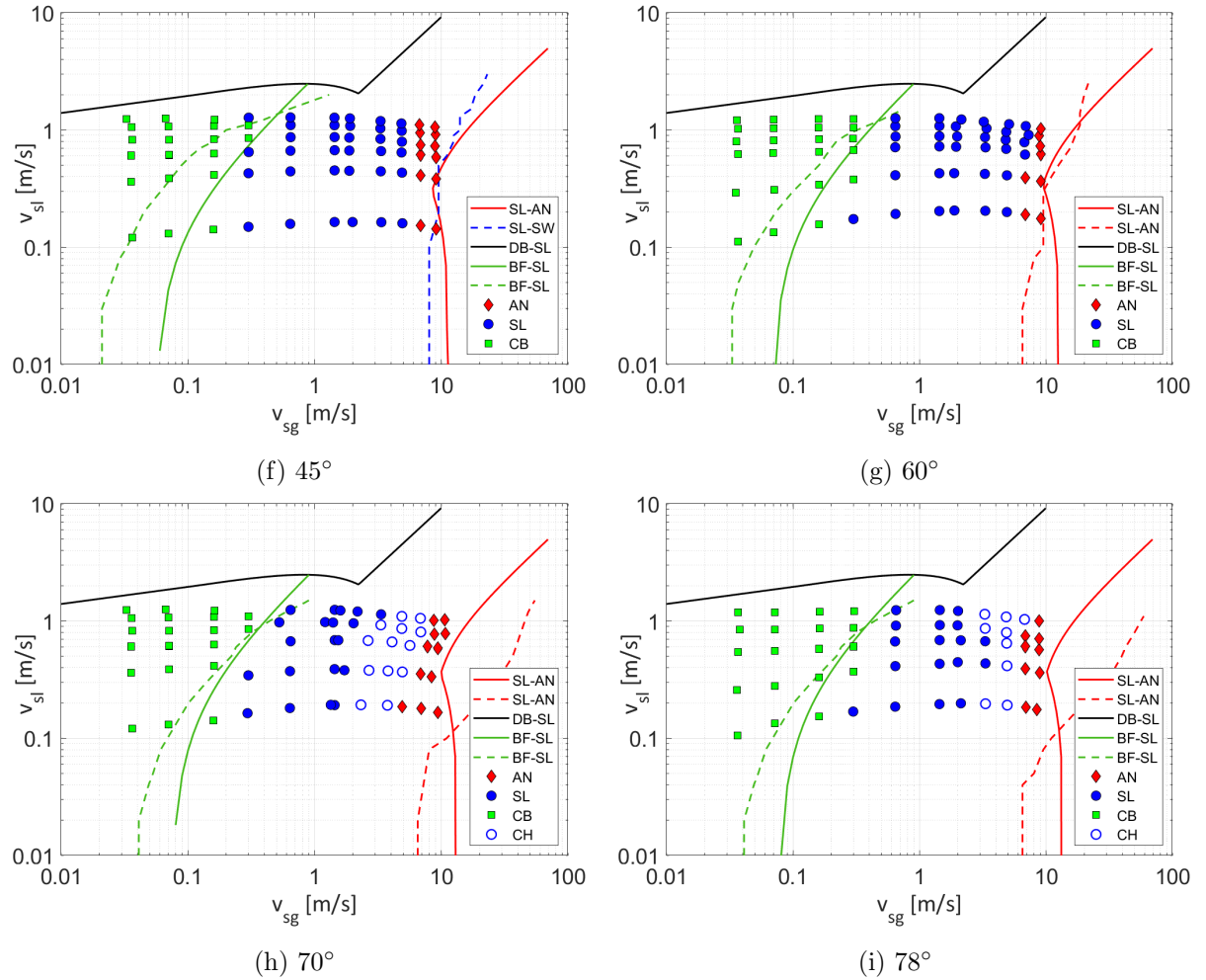


Figure 4.1. (cont.) Experimental flow pattern vs. Barnea (1987) model (—) and OLGA simulation (---) for air-mixed oil system in upwards inclined pipes

It was mentioned in Section 2.1 that Shoham (1982) classified two-phase flow into four main regions: *Stratified*, subdivided into stratified-smooth and stratified-wavy; *intermittent*, with elongated-bubble, slug and churn flow; *annular*, with annular and annular wavy and finally *dispersed bubble* region (see Figure 2.1). However, In OLGA (according to Bendiksen et al. (1991)) the flow regime identification is based on two flow regime classes, namely *distributed* and *separated*. The distributed class is where the contribution of bubble and slug flow are present, while the separated class include stratified either as smooth or wavy and annular flow. Therefore, OLGA only distinguishes between four flow regimes: stratified, bubble, slug and annular.

Starting from stratified region, it is notable in Figures 4.1 that stratified-smooth flow could neither be observed experimentally nor predicted numerically due to  $10^\circ$  being the minimum inclination angle tested. Barnea et al. (1985) stated that such flow regime would be possible to observe for inclination angles less than  $0.25^\circ$ . Stratified-wavy flow (SW) on the other hand was shown to increase when pipe diameter increased and reduced as the upward inclination increased. Experimentally the SW was not observed for inclinations greater than  $20^\circ$ . However, an transition region predicted by the model was expected to appear, yet could not be displayed on the plot due to the minimum liquid velocity used in this study. In Barnea (1987) model the transition region appeared at low inclination

angles, liquid velocity ranging from 0.001 to 0.01 m/s. It should be mentioned that due to differences in naming between annular-wavy and stratified-wavy, the stratified-wavy to annular transition region was not clear, which mean that experimentally flow pattern could be misinterpreted.

The OLGA simulation results indicated that for inclination angles lower than 60° stratified-wavy to slug flow transition was predicted instead of annular to slug flow as experimentally observed or predicted by the model. Bendiksen et al. (1991) explained that the transition between stratified and annular flow is based on wetted perimeter, where annular flow can appear when the wetted perimeter becomes equal to the film inner circumference, i.e., when the wave height reaches the top of the pipe. The average wave height may be obtained by assuming that the mass flow forces in the gas balance the gravitational and surface tension forces (Bendiksen et al., 1991).

Experimentally, through visual inspection, it was observed that for lower pipe inclinations high gas velocities was required in order to see an uniform liquid film around the pipe. Barnea et al. (1980*b*) mentioned that annular flow regime could be classified as annular-wavy which is characterised by an unstable liquid film wave around the pipe circumference.

For the intermittent region, it was observed experimentally and confirmed from the data published by Barnea et al. (1985) that the elongated-bubble flow area is reduced with increasing pipe diameter and inclination angles. In elongated-bubble flow the gas phase had a smooth bullet-formed shape, while the liquid phase did not contain any dispersed bubble and the flowing of the fluid was slowly approaching slug flow. For inclinations above 30°, small bubbles flowing at the top of the pipe were observed and classified as cap-bubble flow. The appearance of small bubbles were due to the air injection point, that protrudes into the test section (see Figure 3.1), which was located at the top of the test section. Barnea et al. (1985) and Barnea (1987) observed that for inclinations above 30°, elongated-bubble disappeared and dispersed flow took place. Therefore, for low gas and liquid velocity and high inclinations, a cap-bubble was identified instead of dispersed-bubbles.

Churn flow in the experimental data had a similar behaviour as the one verified by Barnea et al. (1985), where the first appearance of this pattern occurred at 70° inclination (Figure 4.1h). In Barnea et al. (1985) the range of  $v_{sl}$  at which churn flow was observed, increased with pipe diameter. Thus for the test section diameter and liquid velocity test it was possible to experimentally observe churn flow.

Slug flow was observed through all the tested inclination angles, and transition to annular flow occurred at high gas velocities. The tested gas velocity was lower than the boundary velocity required for numerical and simulated slug-annular flow transition (SL-AN) as shown in Figure 4.1. In OLGA for instance SL-AN transition was observed only for inclinations above 60° as explained previously. Simulations were performed for 30° pipe inclination, aiming to estimate at which gas velocity annular flow could be found. However, no transition could be found, even for gas velocities above 200m/s (see Figure 4.2).

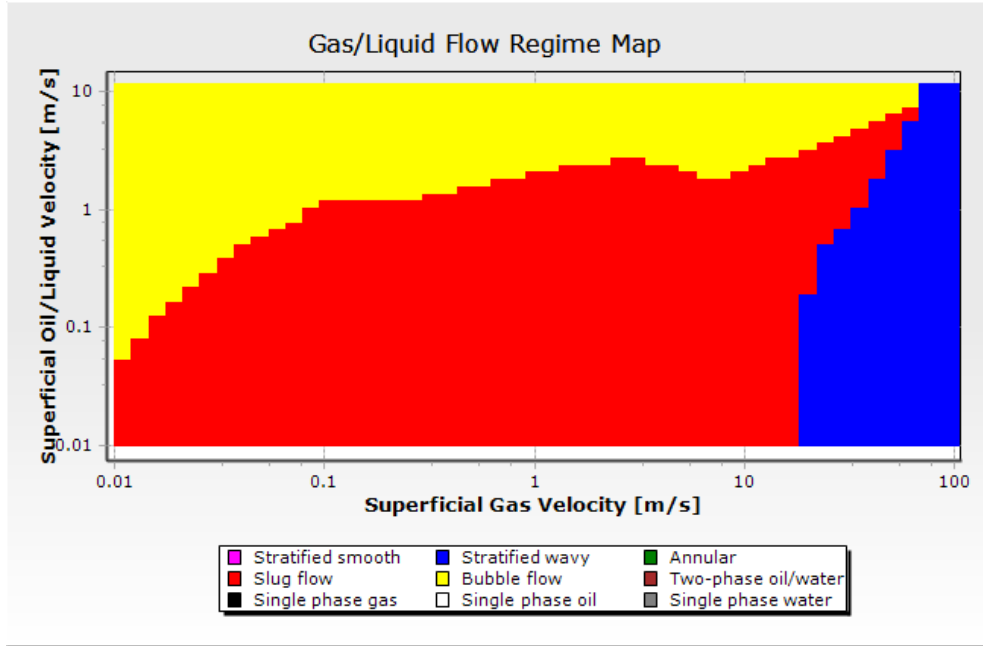


Figure 4.2. OLGA simulation results for flow pattern transition in 30° upward inclined pipe for air-mixed oil system at STP condition

For high liquid velocities the dispersed-bubble region was not achieved experimentally since available liquid volume was limited by the capacity of the main separator. Dispersed-bubble to slug transition (DB-SL) predicted through the Barnea’s model was located above the maximum applicable liquid velocity, which showed good agreement with observations. Barnea (1987) defined the bubble flow region for low liquid and gas velocities and high inclination angles instead of dispersed-bubble flow. Experimental data for inclination angles above 60° showed good agreement with predicted bubble to slug flow transition (BF-SL). In OLGA, the BF-SL transition curve moved downwards to the right as the inclination angle increased, hence the experimental bubble flow region was better represented by inclination above 30°. This conclusion was based on the fact that cap-bubble flow existed in the dispersed-bubble region.

Overall, the flow pattern map for viscous fluid predicted using Barnea (1987) unified model presented a good agreement with the experimental data. Most the flow pattern regions identified experimentally could also be identified by the model with acceptable accuracy, except for annular flow. It seemed to be too offset from the numerical and simulated results. OLGA did not manage to reproduce satisfactorily the experimental flow pattern map measured.

#### 4.1.2 Pressure gradient

Pressure gradients in two-phase flow are more complicated and difficult to predict compared to single phase flow. As mentioned in Section 2.1.1, pressure gradients are strongly dependent on flow pattern. This was also observed experimentally, where for a certain flow regime present in the pipe section, recorded pressure drop and capacitance presented different readings. Figures C.1 to C.6 present total pressure drop and capacitance probe signal against superficial gas velocities at given constant superficial liquid velocity for different pipe inclination angles.

Figure 4.3 presents measured pressure gradient compared to OLGA simulations, given a constant superficial liquid velocity, varying superficial gas velocities and pipe inclinations.

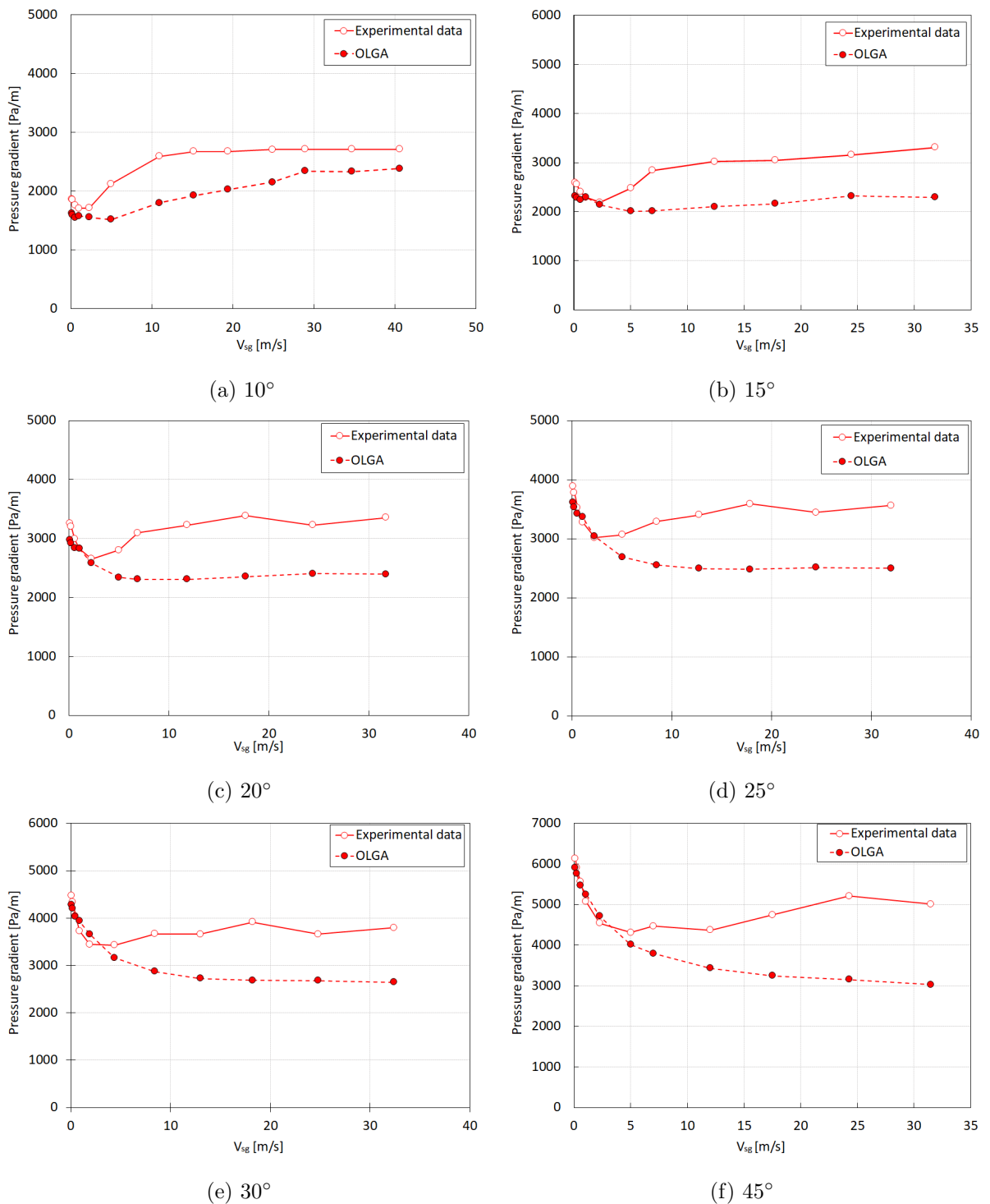
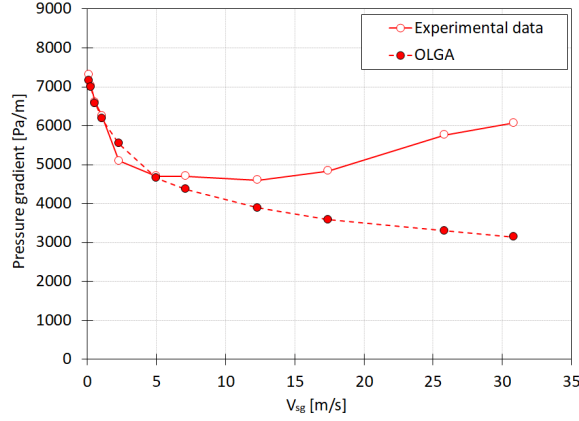


Figure 4.3. Recorded pressure gradient in upward inclined pipes compared to OLGA simulation for  $v_{sl}=1\text{m/s}$



(g) 60°

Figure 4.3. (*cont.*) Recorded pressure gradient in upward inclined pipes compared to OLGA simulation for  $v_{sl}=1\text{m/s}$

Experimentally, it was observed that for a given constant superficial liquid velocity as gas velocity increases, total pressure gradient reached two minimum points in the curve. For lower values of superficial gas velocity the minimum was reached during the transition between bubble to slug flow and at high gas velocities on intermittent to annular flow transition. Bubble flow can exist at low superficial gas and liquid velocities, exhibiting high gravitational pressure gradient due to high liquid content. As superficial gas velocities increases up to moderate values towards the slug flow or intermittent region, the liquid content reduces, resulting in lower gravitational pressure drop. Simultaneously, frictional pressure gradient increases leading to a minimum pressure gradient. Further increase of superficial gas velocity causes the existence of annular flow, where frictional losses are more dominant.

Figure 4.3 have shown that both experimental and the simulation results presented a similar trend. However, there was a significant discrepancy at high superficial gas velocities. A reason for these discrepancies could be due to the difference between the flow regimes predicted in OLGA compared to the regimes experimentally observed. At high superficial gas velocity OLGA predicted slug or stratified-wavy flow, while stratified-wavy or annular flow were observed. For superficial gas velocities above 5 m/s OLGA underestimated the total pressure drop compared to measured total pressure drop.

In order to quantify how the measured data differ from the OLGA simulation, experimental and calculated results were compared and presented in Figure 4.4

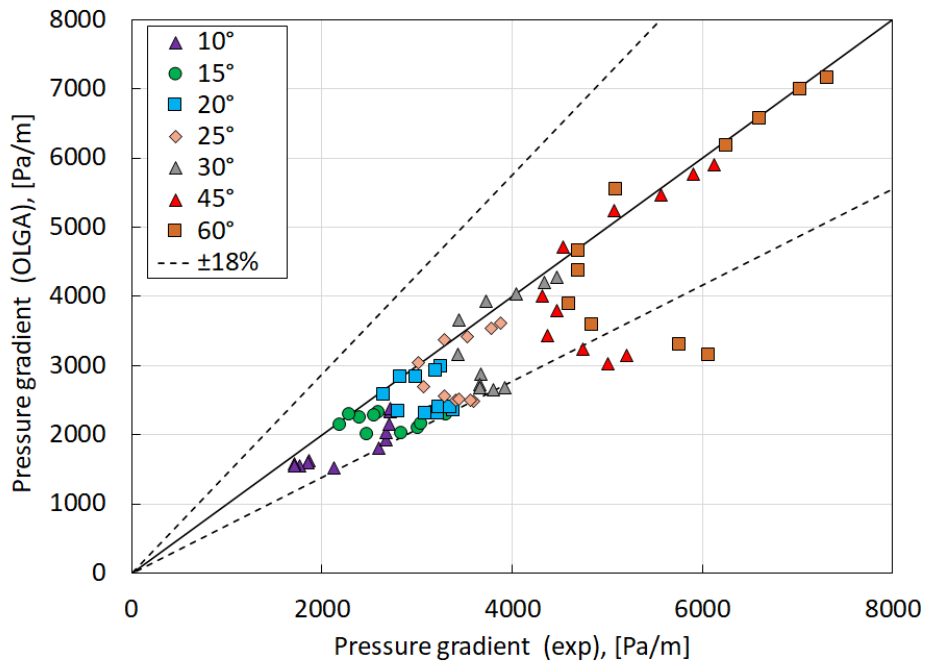


Figure 4.4. Comparison of measured pressure gradient with OLGA values for all pipe inclinations at constant  $v_{sl}=1\text{m/s}$

Figure 4.4 shows that most values predicted with OLGA are within  $\pm 18\%$  error with respect to the measured data values except for some data point for  $45^\circ$  and  $60^\circ$  inclinations due to the large gap on high gas velocities previous presented in Figures 4.3f and 4.3g.



## 4.2 Applicability of existing models for liquid loading prediction

The literature review in Section 2.2 revealed that most of the proposed models for onset of liquid loading prediction were empirical correlations developed based on field and experimental data. Therefore, it is expected that such models will perform good for operational conditions close to the conditions for which the correlations are derived, but it could exhibit significant deviations for conditions different from those. Hence, each model provided different indications on the critical gas velocity at which the onset of liquid loading might exist.

The goal of this section is to quantify and evaluate the performance of the available models used for liquid loading onset prediction. Prediction results from the most relevant and currently used models, such as droplet model by Turner et al. (1969) and Belfroid et al. (2008), along with liquid film models by Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017) and results from a dynamic simulator (OLGA), were evaluated through comparison with experimental data acquired in this work.

Model performance was quantified by calculating an absolute error for each data point, following a calculation of relative error by using Equations B.30 and B.31, respectively. Relative errors were presented as bar plot and summarised in Tables B.3 and B.4.

### 4.2.1 Air-water system

Discrete data points representing the critical gas velocity ( $v_{sg,critical}$ ) at which the onset of liquid loading occurs were taken from the experimental data presented in Section 3.6.2.1.

Figures 4.4a–4.4f presents the measured critical gas velocity plotted in logarithmic scale with the models and OLGA predicted transition boundary values for critical gas velocity. Prediction from liquid film model were shown as continuous lines and the prediction from liquid droplet models as well as OLGA were shown as dashed lines.

In addition, to represent the variability of the measured critical gas velocity, an error bar was added to the data points (Onset LL) where the right length of the horizontal error bars represented the last full stable production (annular flow) and left length the first full unstable production (slug flow), both flows were identified by visual inspection.

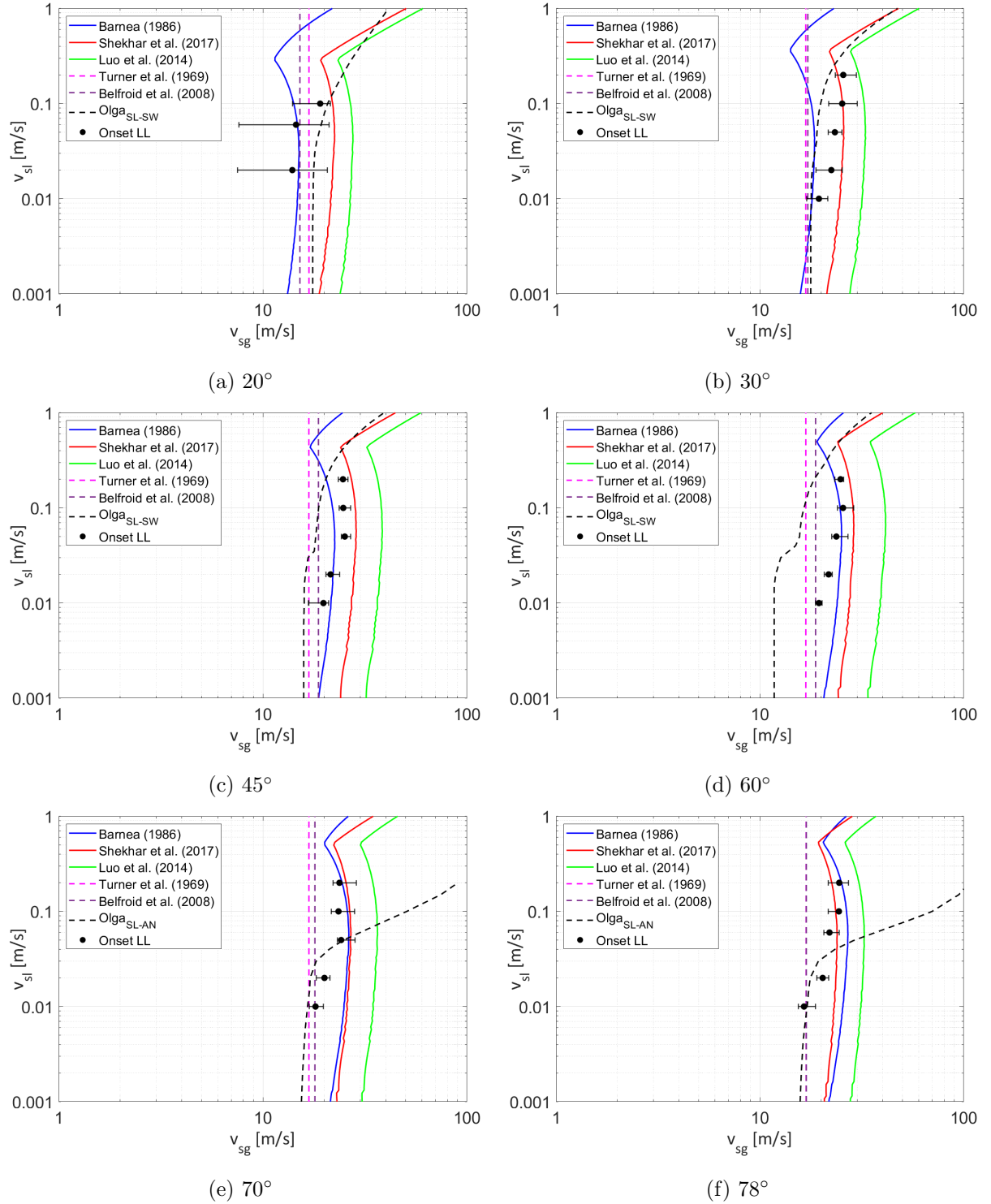


Figure 4.4. Comparison between experimental data, models prediction and OLGA results for an inclined pipe and air-water system at STP condition

In general, the proposed liquid film models represented the critical gas velocities measured experimentally better than the liquid droplet model and OLGA simulations results. The poor performance of Turner et al. liquid droplet model could be related to the fact that no inclination effect or liquid film was taken into consideration during critical gas velocity prediction. However, for the model proposed by Belfroid et al. (2008) in which

pipe inclination effects were considered, also performed poorly. This revealed that liquid droplet model may not be a good approach to predict the onset of liquid loading in inclined pipes.

Among all the liquid film models evaluated in this study it was consistently found that the model proposed by Luo et al. (2014) had a poor performance. Such deficiency was also highlighted by Shekhar et al. (2017). To overcome this problem Shekhar et al. (2017) corrected the Luo et al. (2014) model and proposed a new set of equations. The performance of the models proposed by Barnea (1986) and Shekhar et al. (2017), on the other hand, was similar, except for inclination angles lower than  $45^\circ$ , in which the models predicted poorly for the annular-slug transition line.

Regarding OLGA simulation, it was mentioned in Section 4.1.1 that flow regime transition distinguished between four main regions: stratified (smooth or wavy), annular, slug and bubble flow. In this study, the identification of annular-to-slug flow transition was desired, and such transition occurred only for inclination angles greater than  $60^\circ$ . For lower inclinations annular-to-stratified-wavy transition was predicted instead. Figure 4.4a to Figure 4.4c showed that the transition line predicted by the simulator was close to the experimental data, even-though slug to stratified-wavy was estimated. It is worth mentioning that for lower pipe inclination annular flow could also be classified as stratified-wavy or annular-wavy. Visual classification during the experiments to differentiate between those flows was challenging, thus only annular flow was presented.

An error quantification was performed by estimating relative errors between measured and calculated critical gas velocities. Figure 4.5 presents the relative error for each tested pipe inclination.

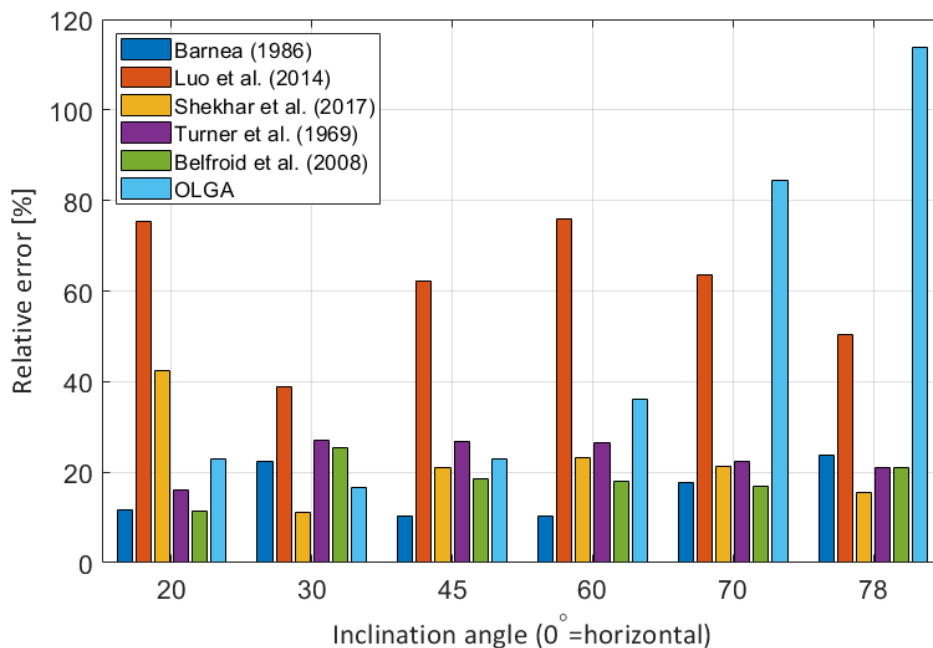


Figure 4.5. Comparison between experimental data with models prediction for all inclined pipe tested of air-water system at STP condition

From Figure 4.5 we can confirm the visual observation previously discussed. Among the evaluated liquid film models, Luo et al. (2014) presented higher relative error for all the pipe inclinations. In case of OLGA, the relative error tended to increase with increasing pipe inclination, reaching higher values for inclination greater than  $60^\circ$ . This could be due to the fact that at higher inclinations the predicted transition from annular-slug flow at moderate superficial liquid velocity were given at very high superficial gas velocities. This behaviour was not experimentally observed for inclinations where annular-stratified wavy transition was predicted.

For liquid droplet models it was observed that the error calculated with the prediction from Belfroid et al. (2008) model, did not present a wide range of variation with increase of inclination and in some cases were close to the liquid film model error. The same was not observed for Turner et al. (1969) model where the relative error appeared mostly to be higher than the liquid film model.

In general, liquid film models from Barnea (1986) and Shekhar et al. (2017) presented relative lower errors compared to the rest of the evaluated models. It was expected that the Shekhar et al. (2017) model would present better performance for lower inclination compared to Barnea (1986) model, since the model took into account the effect of enlarged film thickness at the bottom of the pipe. However, such behaviour was not observed.

To evaluate further the performance of the models, especially for Barnea (1986) and Shekhar et al. (2017), every individual observed onset LL data point was plotted against predicted results, as shown in Figure 4.6, and relative errors using all data points for every inclination was estimated and presented in Table 4.1.

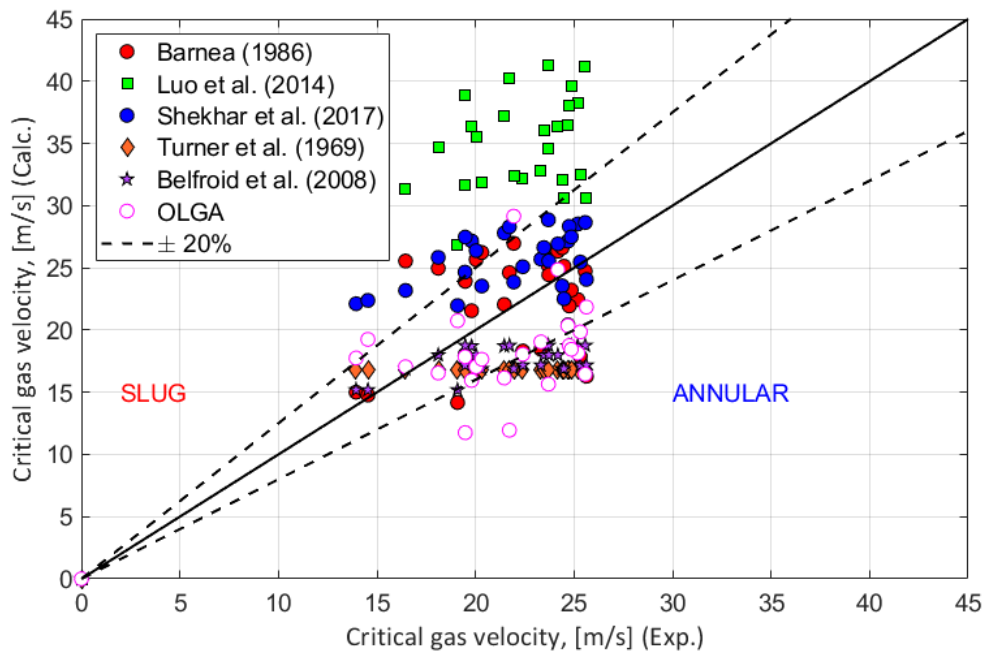


Figure 4.6. Comparison between experimental data vs. predicted results for air-water systems

Table 4.1. Model prediction error using all the data measured experimentally for air-water system

| <b>model</b>           | <b>number of data correctly predicted</b> | $err_{rel}(\%)$ |
|------------------------|---|-----------------|
| Barnea (1986)          | 17/28                                     | 16.9            |
| Luo et al. (2014)      | 28/28                                     | 60              |
| Shekhar et al. (2017)  | 25/28                                     | 20.9            |
| Turner et al. (1969)   | 3/28                                      | 23.8            |
| Belfroid et al. (2008) | 3/28                                      | 19.0            |
| OLGA                   | 10/28                                     | 54.7            |

In Figure 4.6 the  $45^\circ$  line in the plot represents the annular-slug transition boundary. This boundary divides the plot into an unloaded region which is the lower part (full annular flow) and a loaded region (full slug flow). The onset LL data points corresponded to the stage at when the unstable flow started to be visible. Therefore, the model's prediction values were considered to be accurate if the data point fell close to the  $45^\circ$  line or into the slug region. For liquid film models most of the data point fell above the line, except the model of Luo et al. (2014) which overestimate the transition. On the other hand, the liquid droplet model and OLGA seemed to underestimate the critical gas velocity during the transition.

After close analyse of the performance of Barnea (1986) and Shekhar et al. (2017), it can be seen on Figure 4.6 and Table 4.1 that Shekhar et al. (2017) shows a good match for the numbers of data correctly predicted (25 out of 28 correct predictions). However, it present a higher relative error (20.9%) compared to 16.9% given by Barnea (1986) predictions.

Overall for air-water systems the predictions of liquid loading onset in inclined pipes were better predicted by the liquid film model proposed by Barnea (1986) followed by the model of Shekhar et al. (2017).

#### 4.2.2 Air-Exxsol D80 system

Experiments were performed for air-Exxsol D80 system to evaluate the performance of models used on prediction of liquid loading in gas wells. It is important to mention that most of the liquid loading models presented earlier were developed and evaluated for experimental data acquired for air-water flow systems. Discrete data points representing the critical gas velocity at which the onset of liquid loading exists were taken from the experimental data presented in Section 3.6.2.2.

Figures 4.7a–4.7c presents the measured critical gas velocity plotted in a logarithmic scale with the models and OLGA predicted transition boundary values for critical gas velocity. Prediction from liquid film model is shown as continuous lines and the prediction from liquid droplet model as well as OLGA are shown as dashed lines.

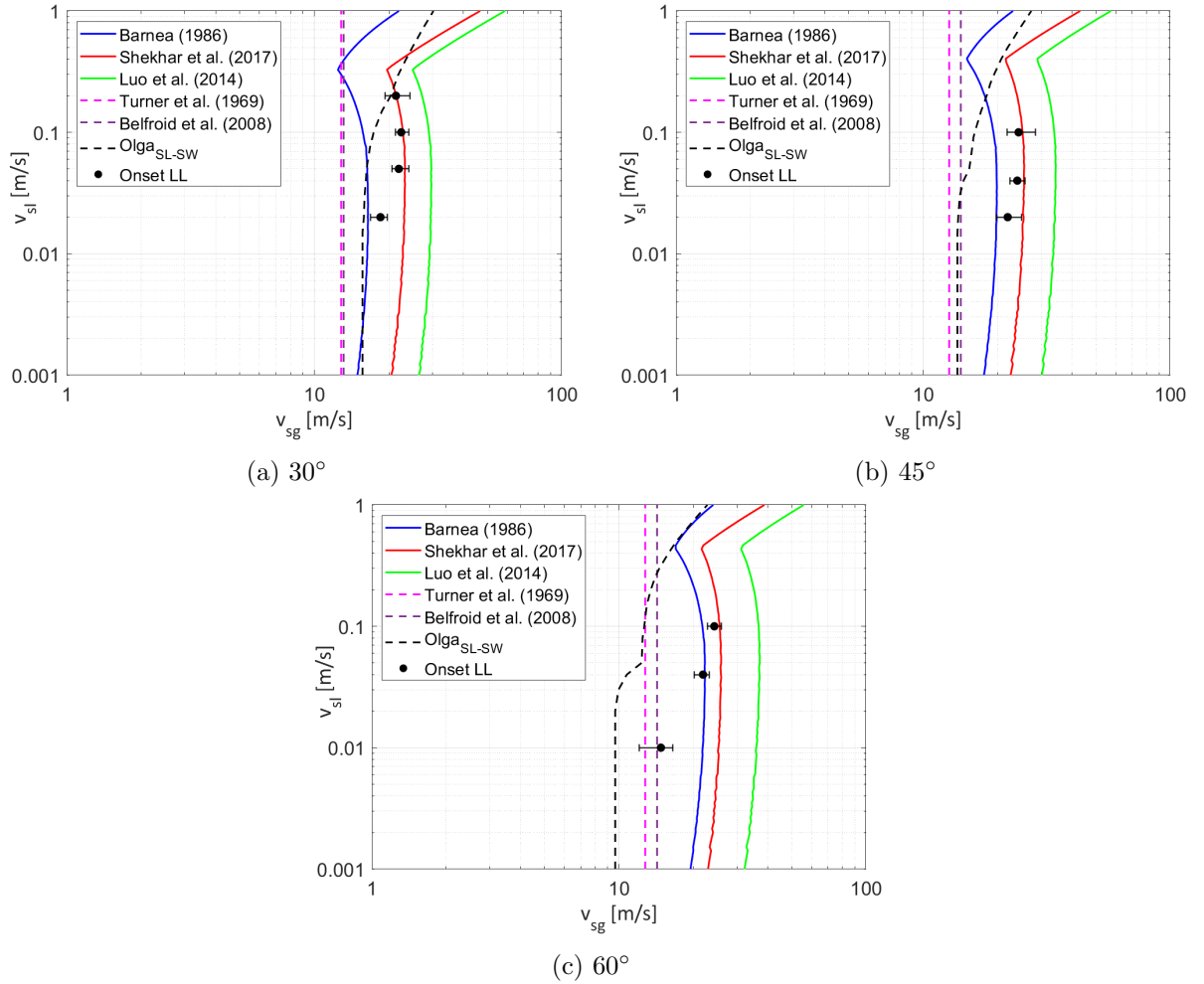


Figure 4.7. Comparison between experimental data, models prediction and OLGA results an inclined pipe and air-Exxsol D80 system at STP condition

In general, the same behaviour as seen in air-water systems (Figure 4.4) was observed. The liquid film models gave a good agreement with the experimental critical gas velocities, while the liquid droplet by Turner et al. (1969) and Belfroid et al. (2008) models and OLGA under-estimated the critical gas velocity for all the inclination angles.

The predictions using the model of Luo et al. (2014) overestimated the critical gas velocity. On the other hand, the models proposed by Barnea (1986) and Shekhar et al. (2017) showed a reasonable match with the experimental data. However, considerable difference between annular-slug flow transition predicted by the models was detected for 30° pipe inclination.

Regarding OLGA simulation results, annular to stratified-wavy flow transition was observed for all pipe inclinations. Figure 4.7a showed that the predicted transition line was near the experimental data. Similar behaviour was observed for air-water system (Figure 4.4).

To evaluate the model's performance quantitatively, relative errors were estimated using measured and calculated critical gas velocities. Figure 4.8 presents the relative error for each pipe inclination.

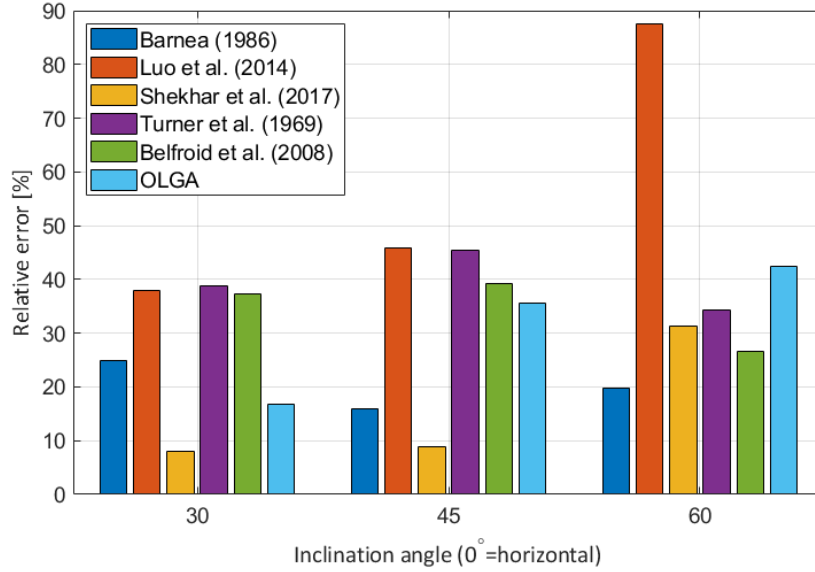


Figure 4.8. Comparison between experimental data with model predictions for all pipe inclinations for air-Exxsol D80 system at STP conditions

From Figure 4.8 we can confirm the visual observations discussed previously. Among the evaluated liquid film models, Luo et al. (2014) presented higher relative error for all pipe inclinations. For OLGA the relative error tended to increase with increasing inclination, reaching the highest values for 60° inclination.

Liquid droplet models exhibited higher relative error when compared to the liquid film models.

It is known that the model of Shekhar et al. (2017) was proposed to account for the inclination effect on the film thickness, which at the bottom of the pipe increases with decreasing inclination. Analysing the error for 30° and 45° inclinations, Shekhar et al. (2017) model provided a better prediction, which might be due to the fact that for such inclination the film thickness had high influence on the critical gas velocity estimation.

To get a better interpretation of the model's performance, for every individual observed onset of LL, data points were plotted against predicted results, as shown in Figure 4.9 and the relative error, using all data points for every inclination, was estimated and presented in Table 4.2

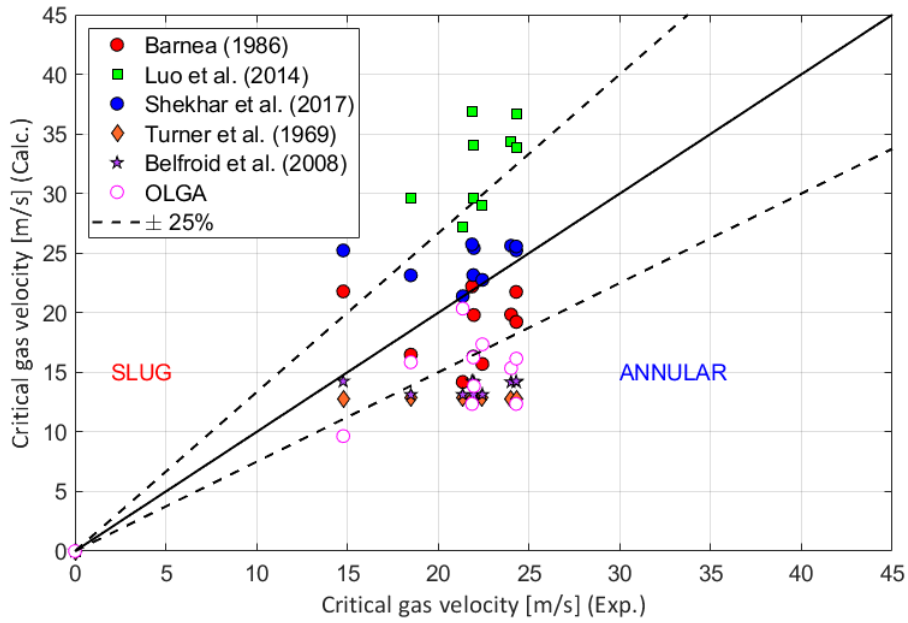


Figure 4.9. Comparison between experimental data vs. predicted results for air-Exxsol D80 system

Table 4.2. Model prediction error using all the data measured experimentally for air-Exxsol D80 system

| model                  | number of data correctly predicted | $err_{rel}(\%)$ |
|------------------------|------------------------------------|-----------------|
| Barnea (1986)          | 2/10                               | 20.8            |
| Luo et al. (2014)      | 10/10                              | 55.2            |
| Shekhar et al. (2017)  | 10/10                              | 15.2            |
| Turner et al. (1969)   | 0/10                               | 39.4            |
| Belfroid et al. (2008) | 0/10                               | 34.7            |
| OLGA                   | 0/10                               | 30.1            |

In Figure 4.9 the 45° line represents the annular-slug transition boundary. It can be seen that for liquid film models most data fall on the slug region except for the Barnea (1986) model. Although Luo et al. (2014) model predicted that the pipe will be in unstable flow, the values over-estimate the critical gas velocities, which is not the case for Shekhar et al. (2017); all the data points are close to the 45° line and having a variation of approximately 25%. For liquid droplet models and the OLGA simulator all the data points fell into the annular region, which did not made the predictions accurate.

Table 4.2 shows a good match for number of data correctly predicted (10 out of 10 correct predictions) for Shekhar et al. (2017) when compared to Barnea (1986) (2 out of 10 correct predictions) as well as the relative error of 15.2% estimated from the Shekhar et al. (2017) model, which proved to be the lowest error.

Overall, for air-Exxsol D80 system, the predictions of onset of liquid loading in inclined pipes were better interpreted by the liquid film model proposed by Shekhar et al. (2017), especially for pipe inclinations lower than 45°.



### 4.2.3 Air-mixed oil system

Experiments were performed for air-mixed oil systems to evaluate flow regime mapping for two-phase flow system in inclined pipes when high viscosity fluid (32cP) was used. Since flow pattern was the primary goal of the experimental study, an accurate annular-slug flow transition boundary was not covered. Therefore, slug flow and annular flow data were used to create an annular-slug transition region (shown in yellow in the plot below). Discrete data points representing both flows were taken from the experimental data presented in Section 3.6.2.3.

Figures 4.10a–4.10f presents the experimental data in logarithmic scale with the models predicting transition values for critical gas velocity. Prediction from the liquid film model were shown as continuous lines while prediction from the liquid droplet models were shown as dashed lines.

In the study performed in Section 4.1 it was observed that the Barnea (1986) model showed a good agreement with the data for the flow pattern mapping prediction. However, an additional study to evaluate Barnea (1986) model on predicting the annular-slug transition was performed, and likewise for models proposed by Luo et al. (2014) and Shekhar et al. (2017).

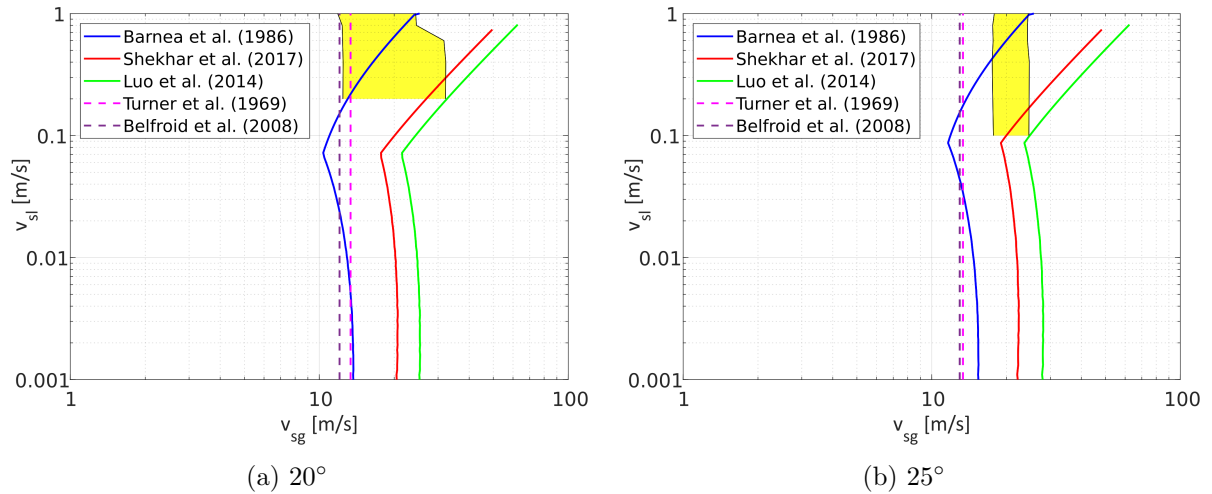


Figure 4.10. Comparison between experimental data and models prediction results for an inclined pipe and air-mixed oil system at STP condition

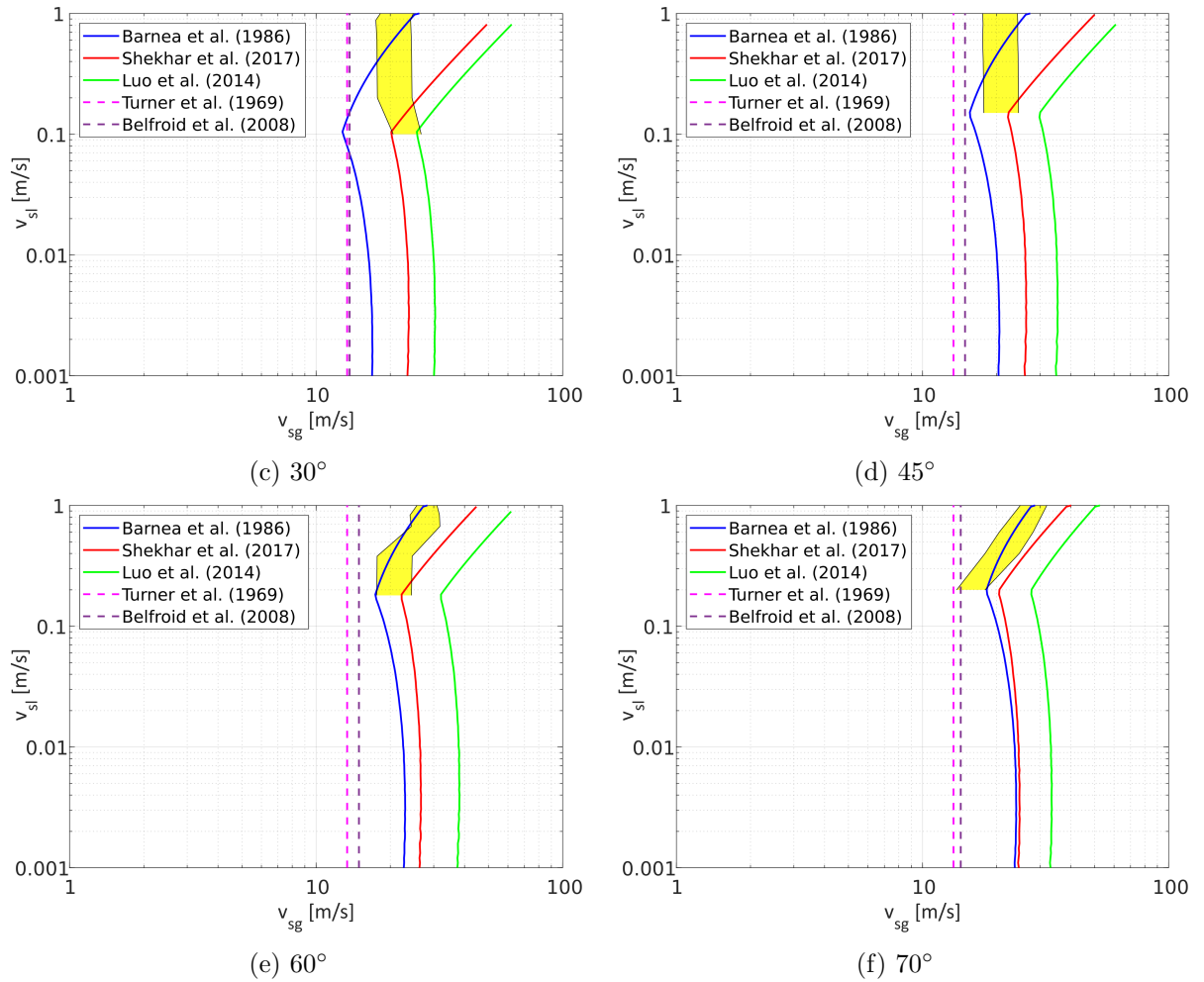


Figure 4.10. (cont.) Comparison between experimental data and prediction model results in inclined pipes and air-mixed oil system at STP condition

Figure 4.10a through Figure 4.10f shows the comparison between the experimental data for air and viscous oil with the models. To evaluate the models, the transition line predicted by the models were compared with the transition area, i.e., if the transition line from the model is located in the transition region it means that the model had a better chance of predicting the correct critical gas velocity.

It can be observed from Figure 4.10 that the Barnea's model predicted better than the Shekhar et al. (2017) and Luo et al. (2014) model, since the annular-slug flow transition boundary line passed through a larger part of the region.

### 4.3 Effect of entrainment on the annular-slug flow regime transition for liquid loading prediction

In section 4.2 it was shown that the onset of liquid loading was better predicted when liquid film models were used. However, literature review in Section 2.2.2 revealed that all the liquid film models were developed based on the assumption that the liquid present in the well was only transported in the film, neglecting the droplets entrainment in the gas core. This assumption could overestimate the film thickness and therefore affect the prediction of critical gas velocity for a gas well with risk of liquid accumulation.

The objective of the present section was to evaluate the effect of droplet entrainment in liquid film models for the prediction of liquid loading in gas wells. Thus, an empirical equation that takes into account the fraction of liquid droplet entering the gas core ( $E$ ) i.e, liquid transported as droplets was added to the model. The model proposed by Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017) were evaluated. A study done by Enos (2018) on the evaluation of the model to predict liquid loading have shown that an equation proposed by Oliemans et al. (1986) predicted better the fraction of droplet entering the gas core. Oliemans et al. (1986) empirical correlation was developed from a regression analysis using the Harwell data bank. The correlation model proposed was:

$$\frac{E}{1-E} = 10^{-2.52} \rho_l^{1.08} \rho_g^{0.18} \mu_l^{0.27} \mu_g^{0.28} \sigma^{-1.80} D^{1.72} v_{sl}^{0.70} v_{sg}^{1.44} g^{0.46} \quad (4.1)$$

where  $E$  is the fraction of liquid droplet entering the gas core. The exponent values in Equation 4.1 were chosen such that the right-hand side of the equation formed a dimensionless group. The parameters were compiled both for the whole Harwell data bank and for subgroups after dividing the data bank into a number of intervals based on the film Reynolds number (Oliemans et al., 1986).

Experimental data acquired in present work and in field data from Turner et al. (1969), Belfroid et al. (2008) and Veeken et al. (2010) were used to evaluate the ability of the liquid film models to predict the onset of liquid loading, considering and neglecting the entrainment of droplets in the gas core. The absolute error for every individual well or data point was estimated by Equation B.30 and then the relative error was estimated for the whole set of data by Equation B.31. For the case of experimental data, the relative errors were presented as bar plot (summarised in Tables B.1 and B.2) while for field data the results were presented in tables.

In addition, for a better interpretation on the model's performance, assuming droplet entrainment, for every individual observation, the critical gas velocity was plotted against predicted results.

### 4.3.1 Experimental data evaluation

Experimental data for the onset of liquid loading transition for air-water and air-Exxsol D80 system, were used to evaluate the liquid film model when droplet fraction was considered. Section 4.2.1 states that models proposed by Barnea (1986) and Shekhar et al. (2017) could correctly predict the onset of liquid loading for air-water two-phase flow in inclined pipes. While Section 4.2.2 have shown that in air-exxsol D80 two-phase flow in inclined pipes, the onset of liquid loading was better predicted by the Shekhar et al. (2017) model. Overall, it is observed that the model proposed by Luo et al. (2014) overestimates the annular-slug flow transition for all inclinations in both systems.

Figure 4.11 and Figure 4.12 presents the relative error between measured and calculated critical gas velocity with and without droplet entrainment in gas core, estimated for all pipe inclinations for air-water and air-exxsol D80 system, respectively.

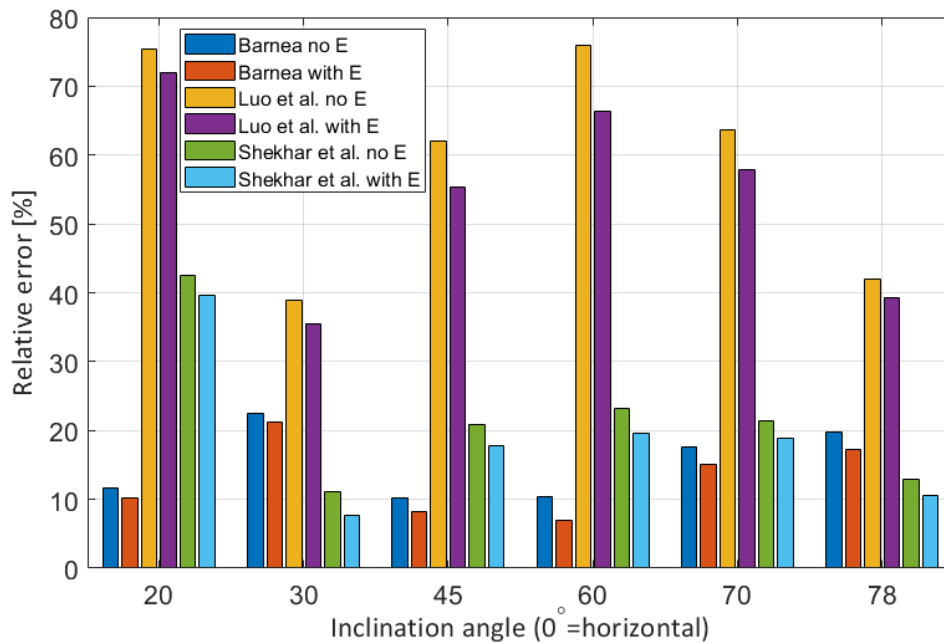


Figure 4.11. Comparison between experimental data with liquid film models prediction with and without entrainment for air-water system at STP conditions

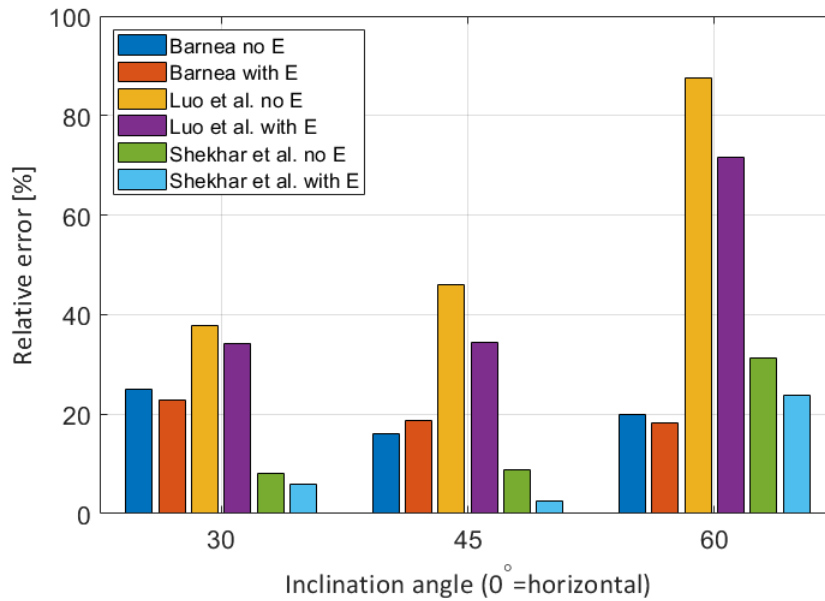


Figure 4.12. Comparison between experimental data with liquid film models prediction with and without entrainment for air-Exxsol D80 system at STP conditions

Overall, the model including the entrainment in the liquid film model improved the prediction of the flow pattern transition by presenting lower relative error compared to the liquid film model that neglected the presence of liquid in form of droplet in the gas core.

From Figure 4.11 it is observed that for 45° inclination Shekhar et al. (2017) model without (no E) droplet fraction, predicted the critical gas velocities with 20.9% relative error versus 14.4% for prediction with droplet fraction (with E). For higher inclinations the relative error reduced substantially.

In Figure 4.12 the relative error was estimated for 45° pipe inclination, and exhibit the same behaviour; the error reduced from 8.8% to 3.4% when Shekhar et al. (2017) model was used. Likewise, for 60° pipe inclination the relative error reduced from 31.2% to 20.7%.

It was observed that for higher pipe inclinations, there was an insignificant difference between the relative error for liquid film models predicting the onset of liquid loading taking into account the liquid entrained in gas core as droplet. This could be related to the rates of droplet deposition and droplet entrainment, being equal at steady-state condition as stated on Shoham (2006).

Figure 4.13 and 4.14 present every individual observed critical gas velocity plotted against the results from the model's prediction with and without droplet entrainment.

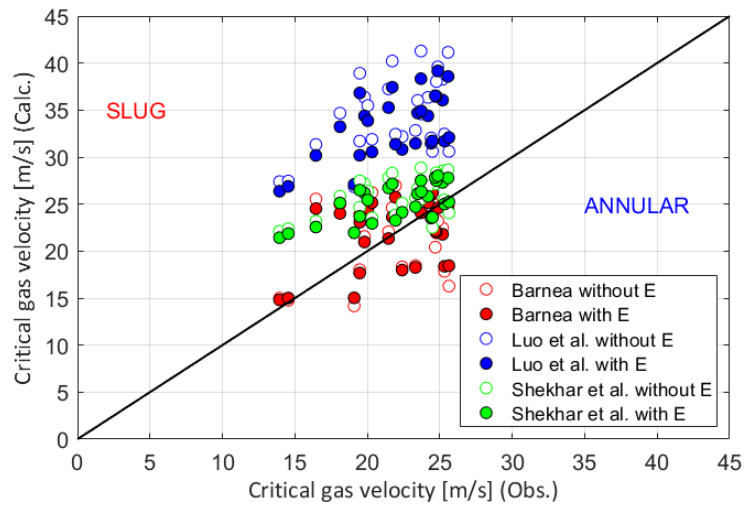


Figure 4.13. Experimental data vs. predicted results for air-water system

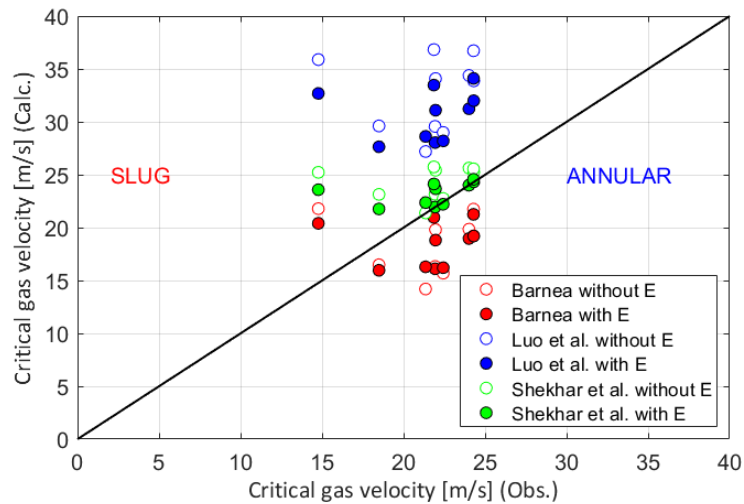


Figure 4.14. Experimental data vs. predicted results for air-Exxsol D80 system

The 45° line in the plot represent the annular-slug transition boundary. This boundary divides the plot into unloaded region at the lower part (full annular flow) and loaded region (full slug flow). The critical gas velocity data points were measured when the unstable flow started to be visible. Therefore, the model's prediction values are considered to be accurate for data point close to the 45° line or in the slug region. It can be seen that for Shekhar et al. (2017) and Luo et al. (2014) models, most of the data points fall above the line. However, Luo et al. (2014) seems to overestimate the transition. On the other hand, the Barnea (1986) model seem to underestimate the critical gas velocity at which the onset of liquid loading was observed. Predicted results seems to be closer to the 45° line when the empirical correlation for the liquid droplet fraction was used.

A relative error using all data points for every tested pipe inclination for air-water and air-Exxsol D80 system were estimated and presented in Table 4.3. A close analysis of the performance between Barnea (1986) and Shekhar et al. (2017) show that for air-water system both models show a good match with the data by presenting similar relative error.

Table 4.3. Model prediction (With E) relative error using all the data measured experimentally for air-water and air-Exxsol D80 system

| model                 | Air-Water                |                 | Air-Exxsol D80           |                 |
|-----------------------|--------------------------|-----------------|--------------------------|-----------------|
|                       | data correctly predicted | $err_{rel}(\%)$ | data correctly predicted | $err_{rel}(\%)$ |
| Barnea (1986)         | 16/28                    | 14.0            | 1/10                     | 20.3            |
| Luo et al. (2014)     | 28/28                    | 54.5            | 10/10                    | 45.5            |
| Shekhar et al. (2017) | 24/28                    | 17.9            | 5/10                     | 10.3            |

However, Shekhar et al. (2017) presented higher number of data correctly predicted (24 out of 28 correct predictions). Comparing with Table 4.1, the relative error of Shekhar et al. (2017) reduced from 20.9% to 17.9%. For air-Exxsol D80 system a good agreement with the data was estimated for Shekhar et al. (2017) model, were 5 out of 10 data were correctly predicted and the relative error proved to be the lowest.

Overall, the Shekhar et al. (2017) model predicted better the liquid loading phenomenon in inclined pipes for air-water and air-Exxsol D80 system when liquid droplet fraction was taken into account.

### 4.3.2 Field data evaluation

Three different sets of field data were used to evaluate the importance of droplet entrainment for predicting the onset of liquid loading.

The first field data used in the study was the one published by Veeken et al. (2010). They published data from 67 gas wells from North Sea that were starting to experience liquid loading. The gas wells had tubing diameter from 2–6 inches and included vertical and inclined pipe geometry ( $0^\circ$  to  $64^\circ$  inclination angles from vertical). The liquids produced were condensate and water. Liquid gas ratio was assumed to be 5 bbl/MMcf in the calculation as recommended by Luo et al. (2014). In their paper the reported test gas rate was converted to superficial gas velocity.

Figure 4.15 to 4.17 observed gas velocities of Veeken et al., 2010 were compared with critical gas velocities predicted by Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017) models, with and without the correlation of liquid droplet fraction present in the gas core. The  $45^\circ$  line in the plot represent the unload and loaded transition boundary. Veeken et al. (2010) reported the gas rate after the onset of liquid loading, which means that all the data should be located slight above the  $45^\circ$  line (loaded region) in the plot of calculated critical gas velocity and the observed critical gas velocity.

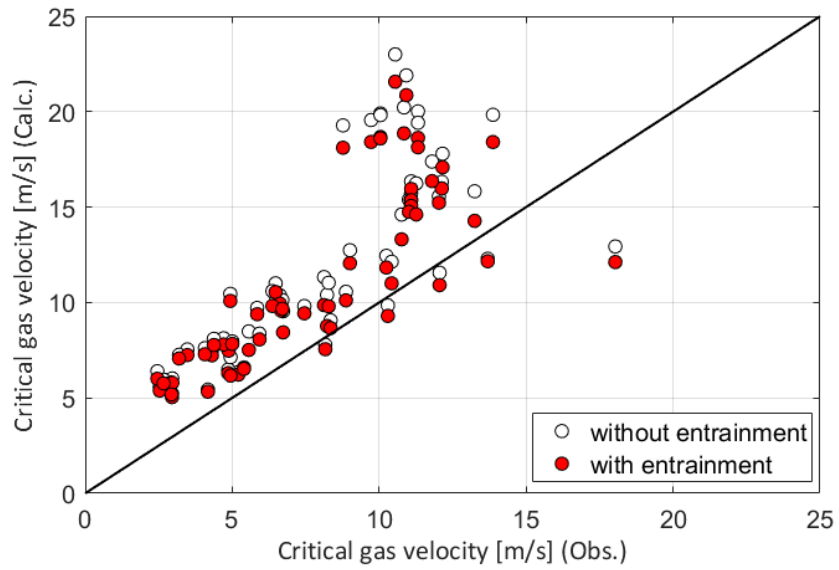


Figure 4.15. Veeken et al. (2010) data vs. the Barnea (1986) model prediction

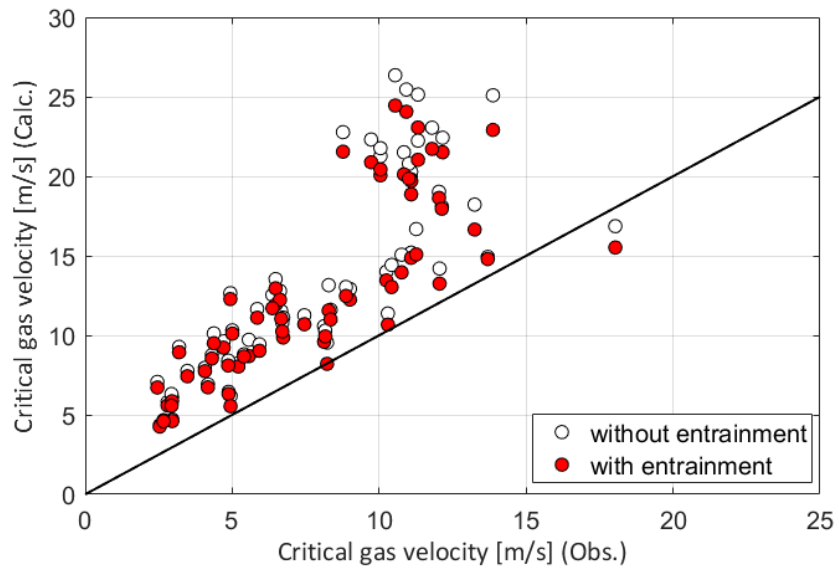


Figure 4.16. Veeken et al. (2010) data vs. the Luo et al. (2014) model prediction

Table 4.4. Critical gas velocity prediction for Veeken et al. (2010) data

| model                 | No Entrainment           |                 | Entrainment              |                 |
|-----------------------|--------------------------|-----------------|--------------------------|-----------------|
|                       | well correctly predicted | $err_{rel}(\%)$ | well correctly predicted | $err_{rel}(\%)$ |
| Barnea (1986)         | 62/67                    | 59.07           | 62/67                    | 51.28           |
| Luo et al. (2014)     | 66/67                    | 78.84           | 65/67                    | 69.82           |
| Shekhar et al. (2017) | 57/67                    | 35.73           | 54/67                    | 32.56           |

It can be seen that most of the wells were in the loaded region. It is also observed



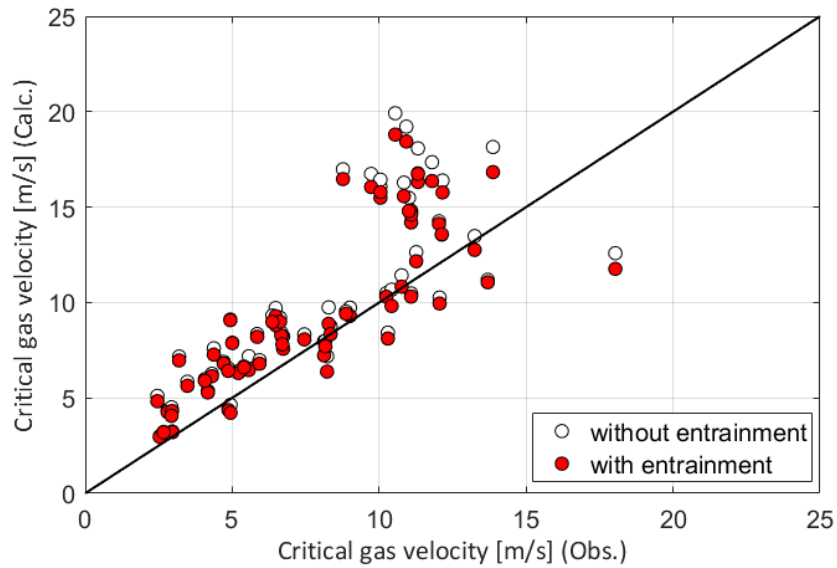


Figure 4.17. Veeken et al. (2010) data vs. the Shekhar et al. (2017) model prediction

that when droplet entrainment was considered during critical gas velocity prediction, the results were close by the 45° line, suggesting that the well had just started to load.

For an ideal model, the points have to be slightly above the 45° line and the relative error as low as possible. From Table 4.4 result, it is clear that Shekhar et al., assuming entrainment, exhibits the best result, although the number of wells predicted correctly is almost the same.

The second field data used for model evaluation was the wells published by Belfroid et al. (2008). They published data for two gas wells. Both wells had an inclined pipe geometry of 40° (from vertical). One well had a tubing diameter of 0.112 m and observed critical gas rate of 90 000 Sm<sup>3</sup>/d, and the other well 0.074 m tubing diameter and 45 000 Sm<sup>3</sup>/d critical gas rate. Calculations were performed using data given in their publications. As the wells were also reported at critical condition, the predicted results were expected to be above the 45° line, as seen in Figure 4.18. Like for the Veeken et al. (2010) data, Table 4.5 shows that critical gas velocity prediction improved by showing smaller relative error when the model assumed droplet entrainment.

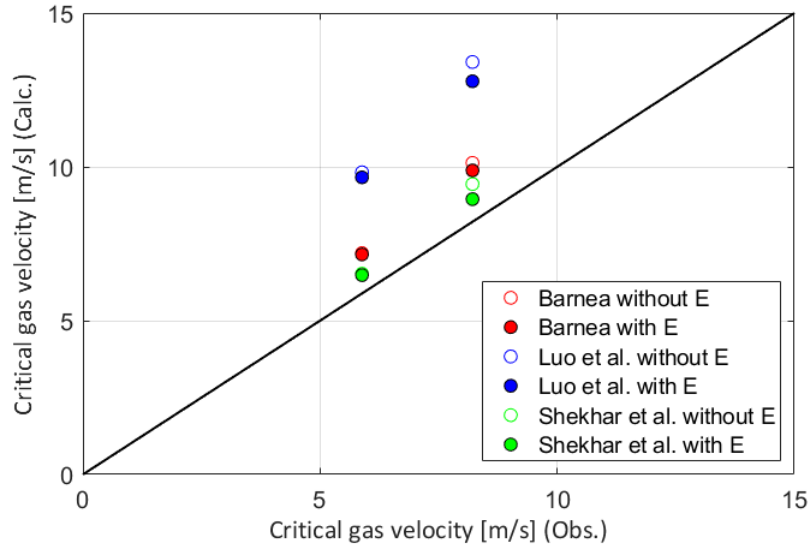


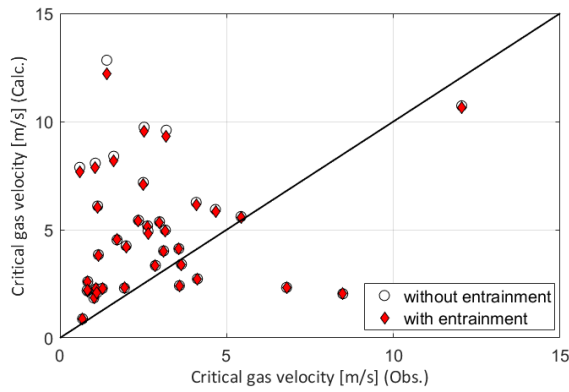
Figure 4.18. Belfroid et al. (2008) data vs. liquid film models prediction

Table 4.5. Critical gas velocity prediction for Belfroid et al. (2008) data

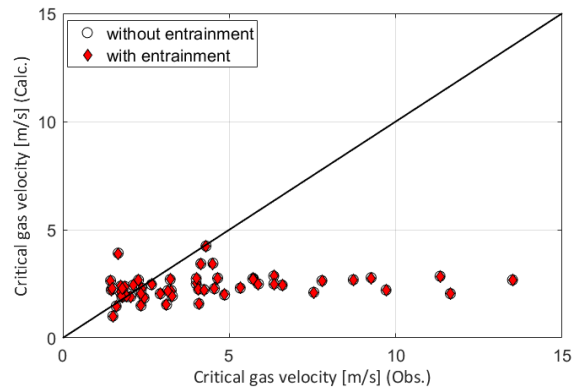
| model                 | No Entrainment           |                 | Entrainment              |                 |
|-----------------------|--------------------------|-----------------|--------------------------|-----------------|
|                       | well correctly predicted | $err_{rel}(\%)$ | well correctly predicted | $err_{rel}(\%)$ |
| Barnea (1986)         | 2/2                      | 22.82           | 2/2                      | 20.95           |
| Luo et al. (2014)     | 2/2                      | 65.10           | 2/2                      | 59.9            |
| Shekhar et al. (2017) | 2/2                      | 12.91           | 2/2                      | 9.56            |

The third field data set used for evaluation of the model was the wells production data published by Turner et al. (1969). They published field data for 90 gas wells, where 37 were experiencing liquid loading and 53 were producing at stable conditions, meaning no liquid accumulation in the wellbore (unloaded). All the wells were vertical ( $0^\circ$  inclination angle). Gas rate tested and reported by Turner were converted to superficial gas velocities, which were then used to compare with calculated critical gas velocity using the model with and without entrainment. The comparison was performed for every individual well, as shown in Figures 4.19 to 4.21.

When the calculated velocity was higher than the observed, the well was considered loaded. If the calculated critical gas velocity was lower than the observed, the well was defined as unloaded. In case of unloaded wells, the well data were located slightly below the  $45^\circ$  line in the plot. It can be seen that for Turner et al. (1969) field data, entrainment fraction of droplets did not influence the prediction of critical gas velocity. This behaviour could be explained by the observations given by Shoham (2006) that, the film thickness variation result in variation of the deposition and the entrainment rate. Since the published well had vertical geometry, film thickness was considered constant, therefore deposition and entrainment was considered constant.

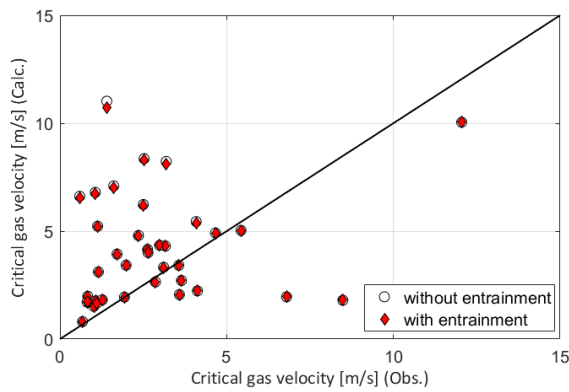


(a) Loaded wells

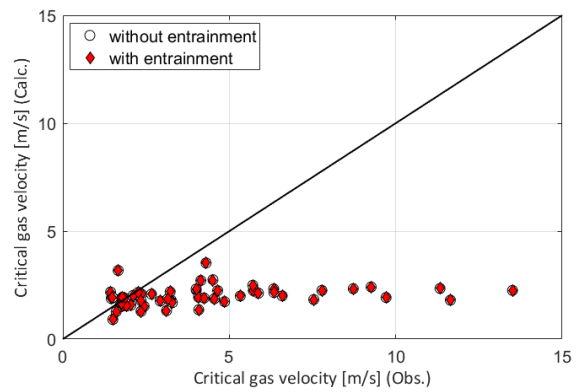


(b) Unloaded wells

Figure 4.19. Turner et al. (1969) data vs. Barnea (1986) model prediction

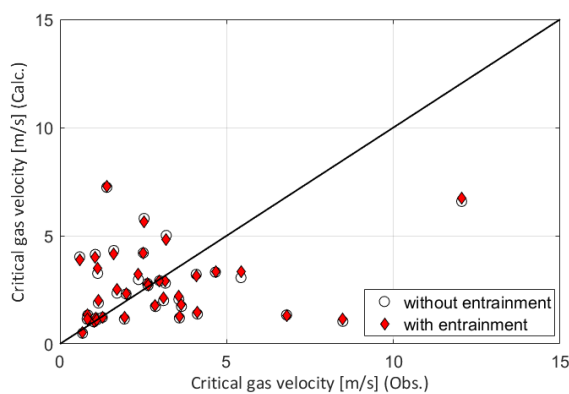


(a) Loaded wells

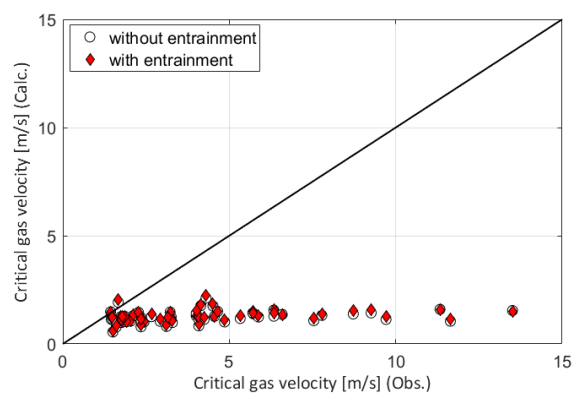


(b) Unloaded wells

Figure 4.20. Turner et al. (1969) data vs. Luo et al. (2014) model prediction



(a) Loaded wells



(b) Unloaded wells

Figure 4.21. Turner et al. (1969) data vs. Shekhar et al. (2017) model prediction

For all models the prediction of unloaded wells was conservative i.e., the well data were located below the 45°-line. However, the relative error was highest in the case of Luo et al. (2014) and Shekhar et al. (2017) as shown in Table 4.6. Although the film

thickness correlation was introduced in both models to account for the effect of inclination, no improvement was observed. To mention that the interfacial friction factor suggested by both researchers influence on the prediction by overestimating the critical gas velocity in gas well with a vertical geometry. On the other hand, Barnea (1986) model showed better prediction in both number of wells and in percentage deviation.

Table 4.6. Critical gas velocity prediction for Turner et al. (1969) data

| <b>Well at loaded condition</b>   |                                 |                              |                                 |                              |
|-----------------------------------|---------------------------------|------------------------------|---------------------------------|------------------------------|
| <b>model</b>                      | <b>no Entrainment</b>           |                              | <b>Entrainment</b>              |                              |
|                                   | <b>well correctly predicted</b> | <i>err<sub>rel</sub></i> (%) | <b>well correctly predicted</b> | <i>err<sub>rel</sub></i> (%) |
| Barnea (1986)                     | 31/37                           | 176.72                       | 31/37                           | 172.54                       |
| Luo et al. (2014)                 | 28/37                           | 137.39                       | 28/37                           | 135.93                       |
| Shekhar et al. (2017)             | 20/37                           | 78.09                        | 20/37                           | 77.27                        |
| <b>Well at unloaded condition</b> |                                 |                              |                                 |                              |
| Barnea (1986)                     | 41/53                           | 42.03                        | 40/53                           | 42.07                        |
| Luo et al. (2014)                 | 46/53                           | 44.29                        | 46/53                           | 44.28                        |
| Shekhar et al. (2017)             | 51/53                           | 60.64                        | 51/53                           | 58.90                        |

Overall, it was observed that for deviated wells, Shekhar et al. (2017) model presented a good agreement with tested gas velocities. On the other hand, the model failed to predict the gas velocity for stable production gas wells with vertical geometry.

## 4.4 Effect of liquid film distribution on the determination of liquid loading onset

Many investigators have proposed models consisting of correlations based on field and experimental data, equations from physical properties, aiming at predicting when liquid accumulation in the wellbore would start to be a problem in a gas well. Most models are often inaccurate for estimating the liquid loading onset when used at different conditions for which the models were evaluated. Most of these models assume that the liquid removal in gas wells resulted from liquid being transported as droplets entrained in the gas core (liquid droplet models) or as liquid film attached to the pipe wall (liquid film models). Earlier studies performed in this thesis have revealed that liquid film models presented a better prediction of liquid loading onset.

The liquid film model, also known as liquid film reversal, assumes that liquid is transported as film moving with the gas along the wall of the conduit and liquid accumulation occurs once the film flows counter-current to the gas core. The model was developed based on empirical correlations and mechanistic modelling of multiphase flow in pipe.

As mentioned in Section 2.2.2, several researchers relate the onset of liquid loading with the flow regime transition from annular to intermittent flow. Most of this research followed after the work performed by Zabaras et al. (1986), who concluded that at low gas flow rates the film motion was controlled by a switching mechanism coupled to the instability of the liquid film due to decreasing of both film-thickness and the interfacial friction. Thereafter, the two-phase flow annular to slug transition model, started to be used for predictions of the critical gas velocity for example the model proposed by Barnea (1986).

The annular-slug transition boundary model proposed by Barnea (1986) has been widely used and related to liquid loading onset predictions. The model was developed to cover the transition boundary for whole range of pipe inclinations, assuming that liquid film thickness distribution around the pipe is constant. Details of the model derivation are presented in Appendix B.1.

Recently, the Barnea (1986) model have been improved by Shekhar et al. (2017) by taking into account non-uniform film thickness distribution due to pipe inclination. The changes were proposed after the results of Paz (1994) who proved that pipe inclination had an effect on the liquid film thickness distribution (Figure 4.22).

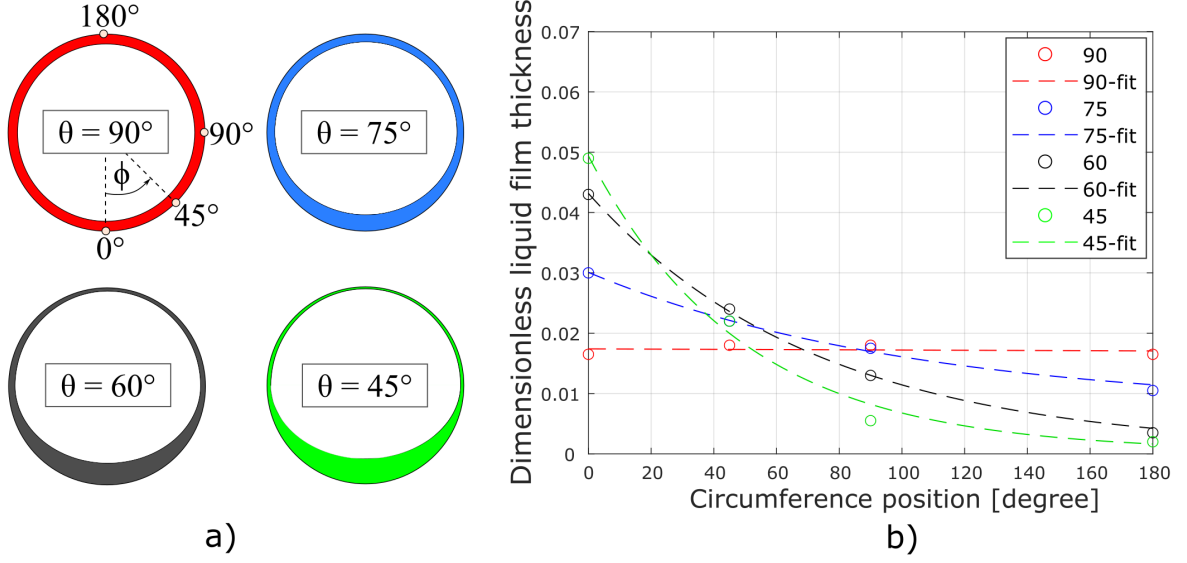


Figure 4.22. Illustration of liquid cross-section for various inclinations a) and for liquid film distribution fitting (Paz (1994),  $v_{sl}=0.006$  m/s,  $v_{sg}=18.29$  m/s) b)

The prediction of annular-slug transition boundary by Barnea (1986) is based on estimation of uniform liquid film thickness ( $\tilde{\delta}_L$ ) that satisfies the interfacial shear stress at given superficial liquid velocity (Equation B.8). Then the value is used to determine the critical superficial gas velocity. Shekhar et al. (2017) based their model following the same criterion. However, they assumed that the critical film thickness occurred at the bottom of the pipe, i.e., the liquid loading would begin when the thicker film at the bottom can no longer be carried by the gas phase. Thus, they estimated the maximum film thickness that satisfied the required shear stress (Equation B.8) as ( $\tilde{\delta}_{max}$ ), and used a relation (Equation 2.11) to convert into  $\tilde{\delta}_{avgL}$ . The corrected value was then used back in Barnea (1986) equation (Equation B.8) for determination of the critical superficial gas velocity.

It is worth to mention that Equation B.8 was derived assuming uniform film thickness (Figure B.3 and Equations B.7).

Although the Shekhar et al. (2017) model was proposed to take into account the non-uniform film thickness, it still calculates critical superficial gas velocity to uniform liquid film thickness concept by using the equation provided by Barnea (1986). Thus, in this research work a new approach was suggested, assuming liquid loading would start at a position in the pipe of maximum liquid film thickness ( $\delta_{maxL}$ ), and that the maximum liquid film thickness would be one that satisfy Equation B.8 similar to Shekhar et al. (2017). However, in contrast to them, the model predicts the critical superficial gas velocity by employing liquid holdup ( $H_L = A_L/A$ ) caused by non-uniform liquid film thickness distribution due to pipe inclination in the momentum balance equation instead of the liquid thickness directly. The momentum balance equation for gas-liquid two-phase flow (Equation B.3) can then be re-written as

$$\tau_i S_i \left( \frac{1}{H_L} + \frac{1}{(1 - H_L)} \right) - gA(\rho_l - \rho_g) \sin \theta - \tau_{wl} \frac{S_L}{H_L} = 0 \quad (4.2)$$

The model is based on Paz's measured circumferential film thickness for various in-

clinations and liquid velocities  $v_{sl}$ . Film thickness distribution changes with decreasing inclination from uniform to non-uniform, when thickness at the top of the pipe becomes thinner, while thickness at the bottom increases (Figure 4.22a). The dimensionless liquid film thickness at several angular positions ( $\phi$ ) in the pipe cross section was computed from measured values by Paz (1994) and plotted versus pipe inclination angle ( $\theta$ ) for different liquid superficial velocities. The data was fitted to an exponential function (Equation 4.3)

$$\tilde{\delta}_L(\phi, \theta) = ae^{(-b\phi)} + c \quad (4.3)$$

The function was numerically integrated in  $\phi$  in order to obtain the area under the curve, which represents the cross-sectional area of liquid in the pipe from position  $0^\circ$  to  $180^\circ$  (Figure 4.22b). The same analysis was performed for the other liquid velocities of similar behaviour as shown in Figs. B.7 through B.11.

The liquid holdup was calculated from the cross section area occupied by the liquid estimated above, and plotted versus the maximum dimensionless liquid film thickness (occurring at the bottom of the pipe), presented in Figure 4.23.

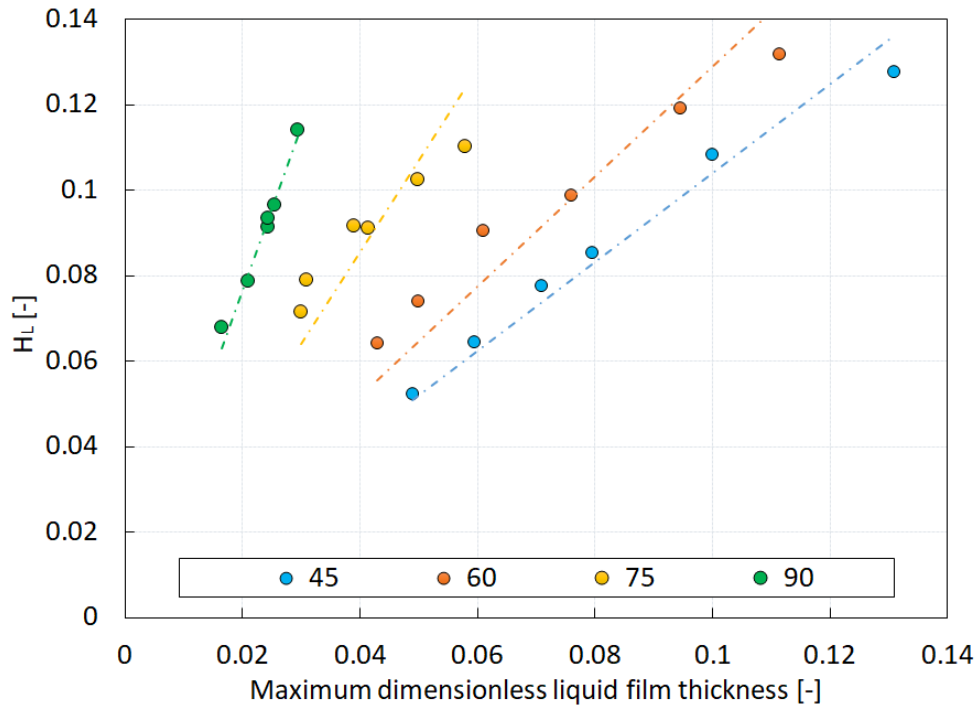


Figure 4.23. Liquid holdup vs. maximum dimensionless liquid film thickness (measured at the bottom of the pipe)

There is a fairly linear relationship between these two variables, thus the liquid holdup can be used to determine the maximum film thickness and can be described by a simple linear function of the single variable  $\mathbf{a}$ .

$$H_L = a\tilde{\delta}_{maxL} \quad (4.4)$$

The slope of the fitting lines (**a**) increases with increasing pipe inclination ( $\theta$ ). Both of these variables were plotted in Figure 4.24.

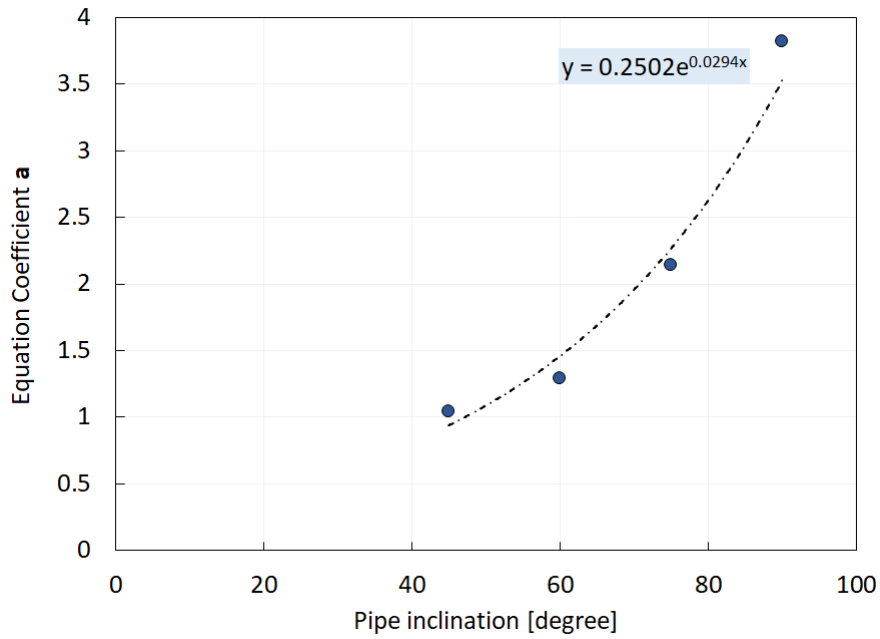


Figure 4.24. Estimation of liquid holdup equation vs. pipe inclination (from horizontal)

As it can be seen, the coefficient  $a$  increases exponentially with increasing pipe inclination and their relationship is described by:

$$a = 0.25e^{0.0294\theta} \quad (4.5)$$

The change of liquid area (liquid holdup) due to pipe inclination also causes a change in the perimeter of the liquid-gas interface ( $S_i$ ). From the functions created by fitting the Paz (1994) data, the perimeter  $S_i$  was computer from Equation 4.3 and plotted against liquid holdup (Figure 4.25). Equation 4.6 is proposed to fit the data.



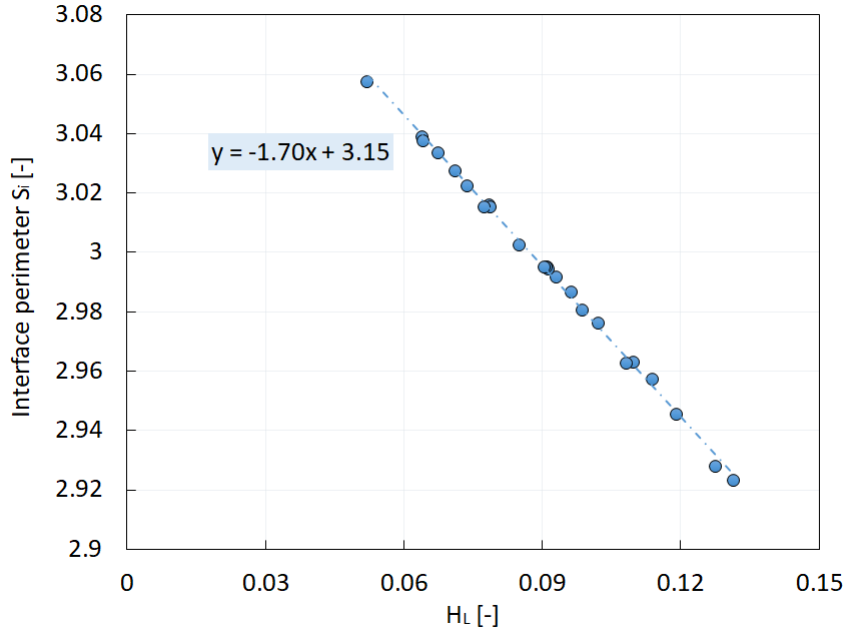


Figure 4.25. Estimation of interface perimeter against liquid holdup

$$S_i = (\pi - 1.7H_L)D \quad (4.6)$$

The perimeter of the wall-liquid interface was calculated by  $S_L = \pi D$  and wall shear stress by Equation 4.7, which was related to the local liquid velocity at the bottom of the pipe, similar to what is presented by Barnea (1986).

$$\tau_{wl} = \frac{1}{2}C_l\rho_l\left(\frac{\rho_l D v_{sl}}{\mu_l}\right)^{-n} \frac{v_{sl}^2}{4\left(\overbrace{\delta_{maxL}}^2 - \overbrace{\delta_{maxL}}^2\right)} \quad (4.7)$$

where  $C_l$  and  $n$  are constants in the friction factor correlation, where  $C_l = 0.046$ ,  $n = 0.2$  for turbulent liquid film and  $C_l = 16$ ,  $n = 1$  for laminar liquid film.

Substituting the relationship of  $S_L$ ,  $S_i$ ,  $H_L$  and the wall shear stress expression into Equation 4.2 and solving for interfacial shear stress yields

$$\tau_{i,liquid} = \frac{\tau_{wl} \frac{S_l}{H_L} + gA(\rho_l - \rho_g) \sin \theta}{S_i \left[ \frac{1}{H_L} + \frac{1}{(1 - H_L)} \right]} \quad (4.8)$$

Then the supplied interfacial shear stress provided by gas-phase was estimated by Equation 4.9

$$\tau_{i,gas} = \frac{1}{2}f_i \frac{\rho_g v_{sg}^2}{(1 - 2\overbrace{\delta_{maxL}}^2)} \quad (4.9)$$

In addition, a new equation for calculating the interfacial friction factor developed based on the experimental data of Paz (1994) data was proposed. The steps used for the development are presented below:

1. Calculate the liquid friction factor using Equation B.5.
2. Calculate the liquid cross section area by multiplying liquid holdup (Figure 4.23) with pipe area.
3. Calculate liquid shear stress ( $\tau_{wl}$ ) using Equation B.4 where the actual liquid velocity was estimated using Equation B.6.
4. Determine pressure drop from Equation 4.10. The equation was obtained by adding the momentum equation of liquid (Equation B.1) with the gas core (Equation B.2)

$$-\frac{dp}{dL}A = g(A_l\rho_l + A_g\rho_g)\sin\theta + \tau_{wl}S_l. \quad (4.10)$$

5. Determine the interface shear stress using either Equation B.1 or Equation B.2
6. Calculate the interface friction factor

$$f_i = \frac{2\tau_i}{\rho_g v_g^2} \quad (4.11)$$

where  $v_g = v_{sg} \frac{A}{(1 - A_l)}$

7. Plot the relation interfacial friction factor given in terms of dimensionless parameter  $I$  against liquid holdup ( $H_l$ )

$$I = \frac{f_i}{\sin\theta f_g} \quad (4.12)$$

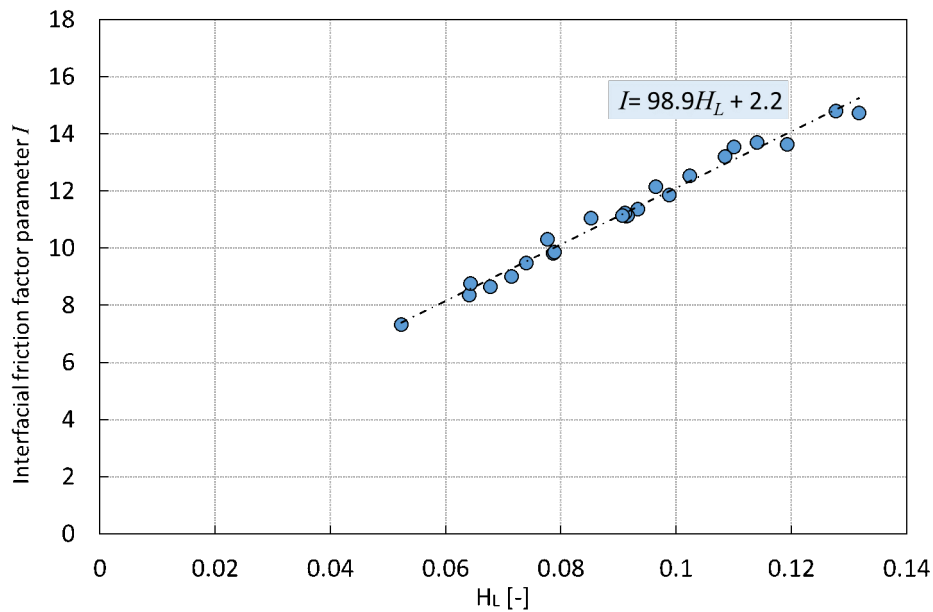


Figure 4.26. Interface friction factor relationship with the liquid holdup estimated from Paz (1994) data

From Figure 4.26 the new interfacial friction factor is determined by:

$$f_i = f_g(98.87H_L + 2.2) \sin \theta \quad (4.13)$$

Here the superficial gas friction factor ( $f_g$ ) was assumed to be 0.005 and the pipe inclination ( $\theta$ ) is expressed in radians.

Using the experimental data of Paz (1994), interfacial friction factor was estimated using the new proposed correlation (Equation 4.13), Wallis (1969) (Equation B.12), Fore et al. (2000) (Equation 2.6) and Shekhar et al. (2017) (Equation 2.12). The comparison is presented in Figure 4.27.

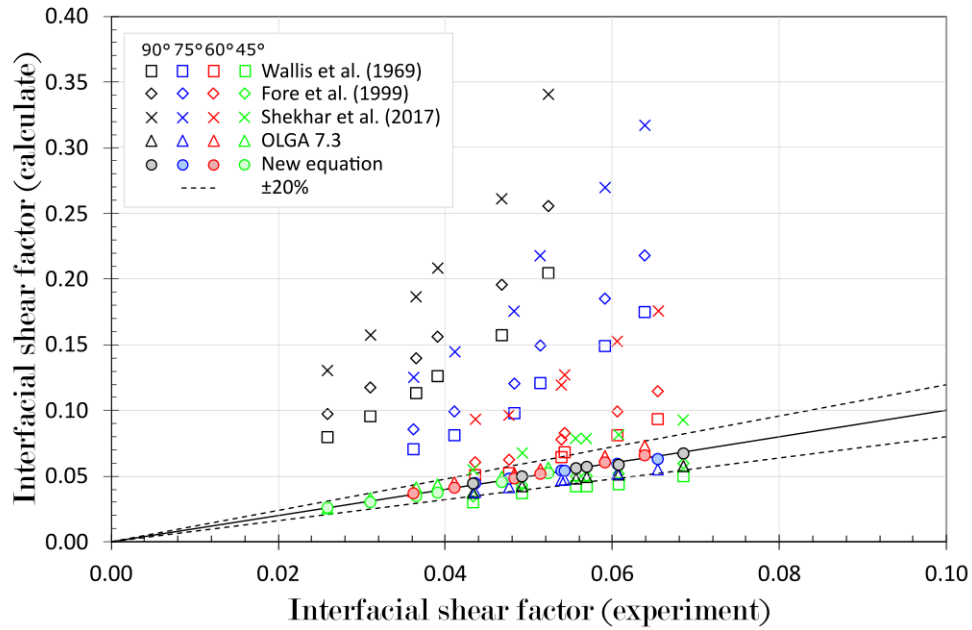


Figure 4.27. Comparison of interfacial friction factor estimated from experimental Paz (1994) data with Wallis (1969), Fore et al. (2000), Shekhar et al. (2017) and OLGA prediction values of interfacial friction factor

It can be seen that for inclination above  $45^\circ$ , equations proposed by Wallis (1969), Fore et al. (2000) and Shekhar et al. (2017), overestimate the interfacial friction factor. On the other hand, OLGA predicted values close to the experimental estimation, similar to the new equation predictions.

Figure 4.28 shows an overall flow chart for the annular-intermittent transition boundary (critical gas velocity) for inclined pipe. Critical gas velocity is first determined from on the input parameters. Then the momentum and continuity equation is used to calculate the hydrodynamic behaviour of the two-phase flow.

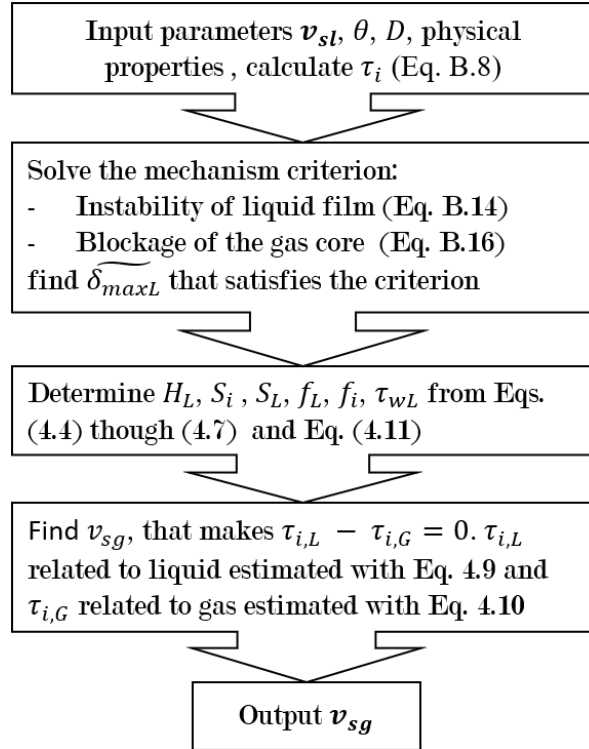


Figure 4.28. Flow chart for calculating annular-slug flow transition boundary calculation

#### 4.4.1 Model validation

Experimental critical gas velocities acquired for air-water and air-Exxsol D80 system (Section 3.6.2 and 3.6.3 respectively) were used to evaluate the applicability of the proposed model on the prediction of liquid loading in gas wells.

Figures 4.29a–4.29f, discrete experimental points from air-water system were plotted on logarithmic scale with the continuous-line representing the annular-slug transition boundary for the new model. The transition estimated with the models of Barnea (1986) and Shekhar et al. (2017) are also plotted using dashed-lines.

Figure 4.30a–4.30c presents the same analysis where air-Exxsol D80 discrete data point were used instead.

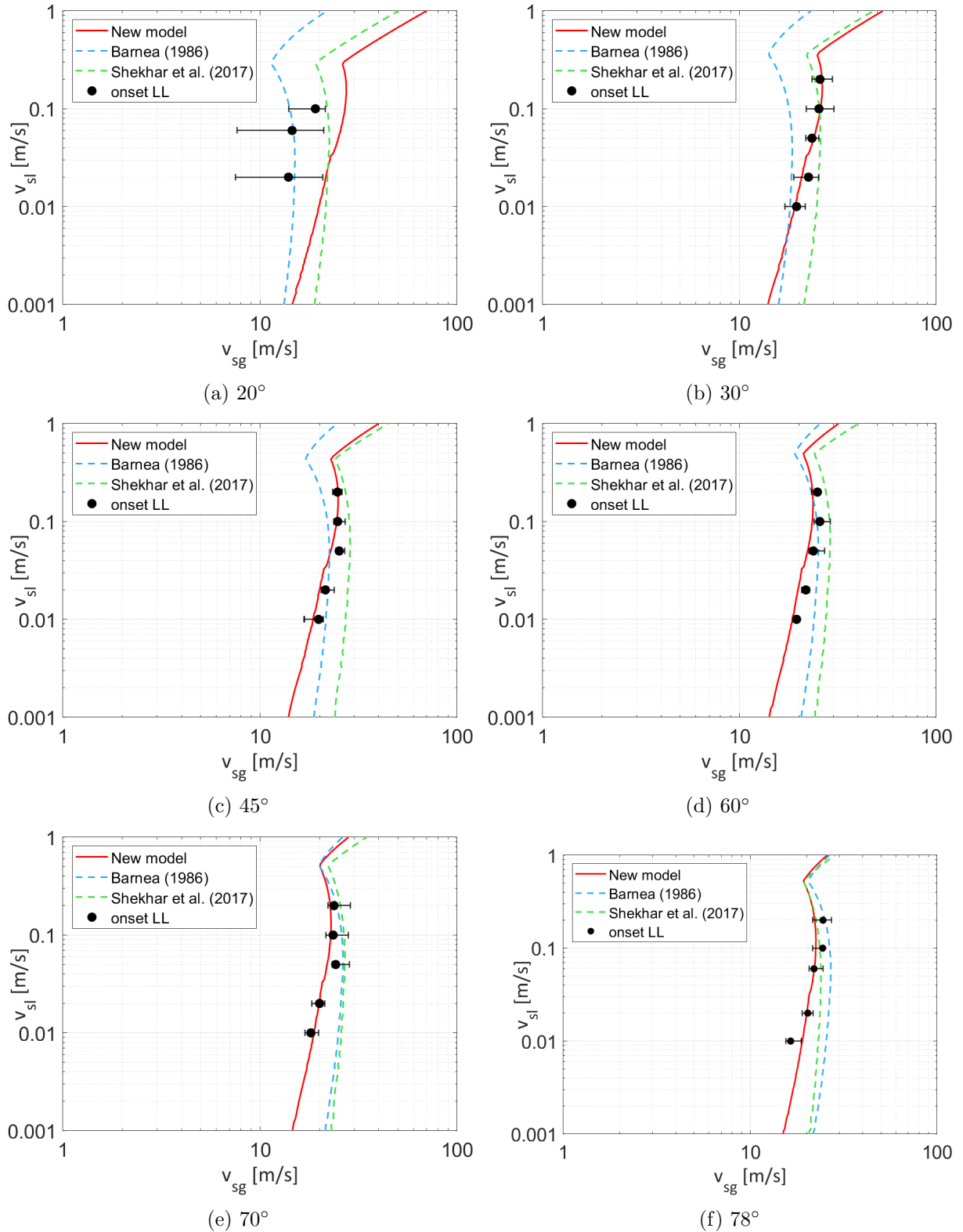


Figure 4.29. Comparison between experimental data and the transition boundary prediction by the new model, the model by Barnea (1986) and the model by Shekhar et al. (2017), for air-water system at STP condition

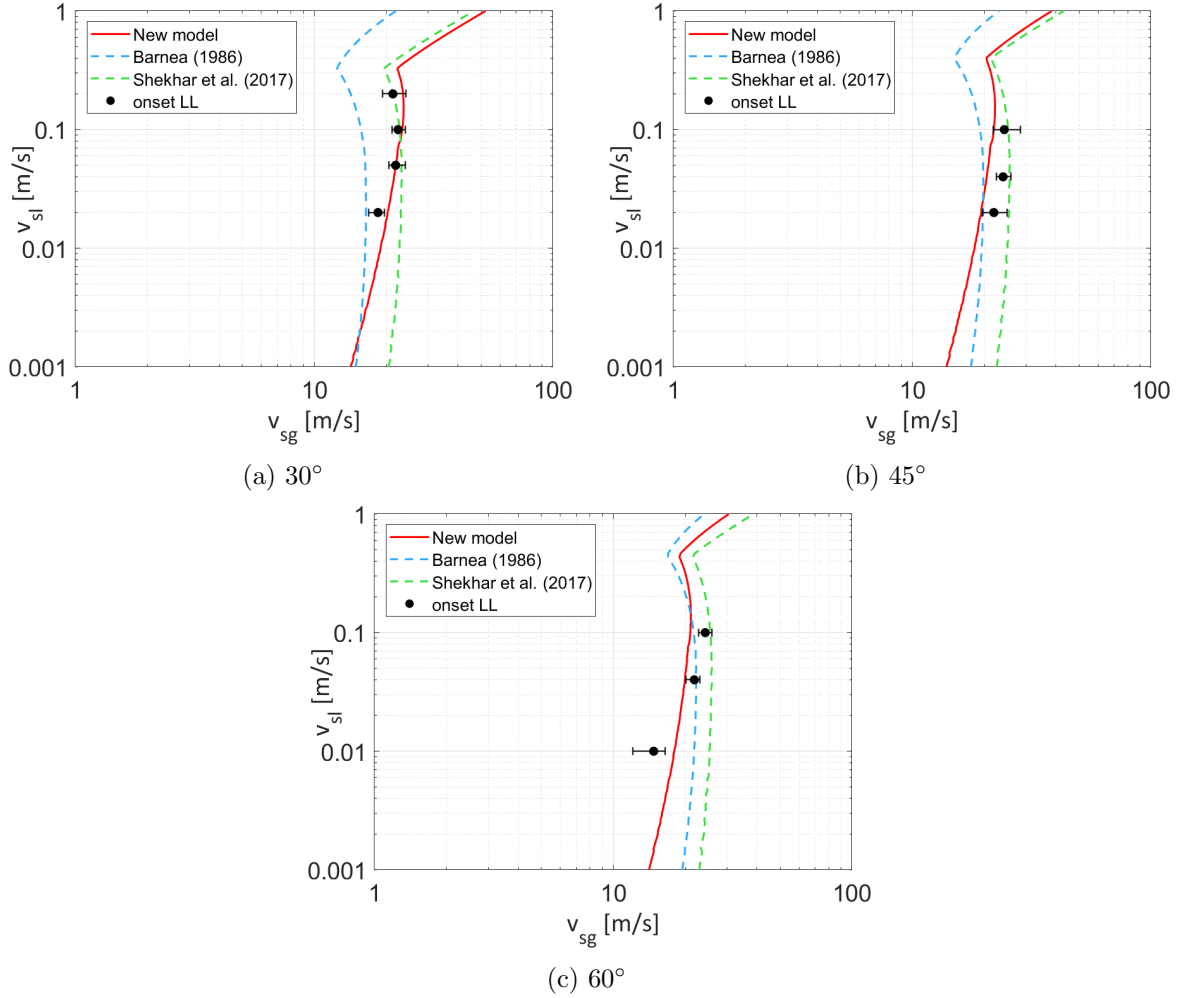


Figure 4.30. Comparison between experimental data and the transition boundary prediction by the new model, the model by Barnea (1986) and the model by Shekhar et al. (2017) for air-Exxsol D80 system at STP condition

The agreement between the predictions using the new model and experimental measurements is fairly good for most cases. This could indicate that the model is generic and can be extrapolated to other operational conditions different than the ones from which it was derived (experimental data of Paz (1994)). However, the model has poor performance for the lowest inclination in air-water flow (Figure 4.29a). This could be because the data of Paz does not include inclinations below  $45^\circ$ . Figure 4.29b and 4.30a shows that even though the pipe inclination is below  $45^\circ$ , the model agreed with the experimental measurements. This could be due to the fact that at  $30^\circ$  inclination the conditions are not significantly different as presented in  $45^\circ$  (Figure 4.22a). However, for an inclination of  $20^\circ$  the difference might be significant as the liquid film might not reach the top of the pipe.

Figure 4.31 shows the comparison between every individual observed critical gas velocities predicted by the present model and the measured data.

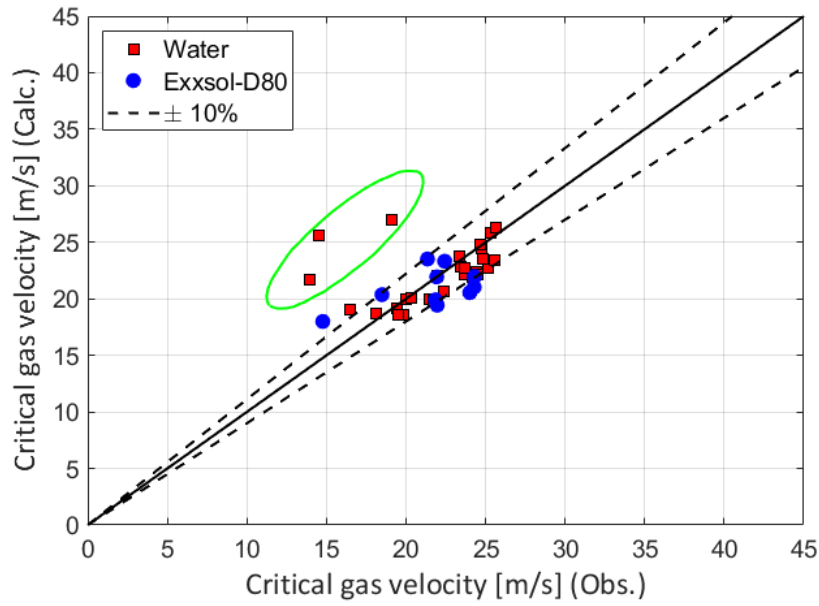


Figure 4.31. Comparison between experimental data vs. predicted values by the new model

In Figure 4.31 the 45° line in the plot represents the annular-slug transition boundary. It can be seen that the predicted critical gas velocities lays close to the line, having a variation of approximately 10%. It was also noticed that the model overestimates the values for the critical gas velocity at 20° pipe inclination (points surrounded by the green ellipse).

Table 4.7 presents the relative error calculated for each pipe inclination and using all the data points for air-water and air-Exxsol D80 system, respectively.

Table 4.7. Relative error for the air-water and air-Exxsol D80 system

|                             | <b>Air-Water</b>             | <b>Air-Exxsol D80</b>        |
|-----------------------------|------------------------------|------------------------------|
| <b>pipe inclination</b> [°] | <i>err<sub>rel</sub></i> (%) | <i>err<sub>rel</sub></i> (%) |
| 20                          | 57.50                        | -                            |
| 30                          | 3.22                         | 6.10                         |
| 45                          | 4.91                         | 11.85                        |
| 60                          | 6.68                         | 14.73                        |
| 70                          | 4.14                         | -                            |
| 78                          | 7.01                         | -                            |
| all data                    | 10.8                         | 10                           |

Comparing the results presented in Table 4.7 for air-water system its was possible to see that the new model had an improvement on prediction of critical gas velocity with an average accuracy for all inclinations of 10.8% against the 20.9% from Shekhar et al. (2017) and 16.9% from Barnea (1986) (see Table 4.1). For air-Exxsol D80 a similar trend is observed, the new model has a lower error of 10% against 15.2% and 20.8%, for Shekhar et al. (2017) and Barnea (1986) respectively (see Table 4.2).

To evaluate further the performance of the new proposed model, experimental data publish by Guner (2012) on two-phase air-water system was used. He performed experiments in 3-in ID pipe at inclination angles of  $90^\circ$ ,  $75^\circ$ ,  $60^\circ$  and  $45^\circ$  from horizontal, using superficial liquid velocity of 0.01, 0.05 and 0.1 m/s and superficial gas velocity ranging from approximately 40-2m/s.

The set of discrete data points define by (Guner, 2012) as the onset of film reversal, complete film reversal (critical  $v_{sg}$ ) and no loading were used. The complete film reversal data points were used as the left length of the horizontal error bars while the no loading as the right length the first full unstable production.

Figure 4.32a to 4.32d shows the comparison of the discrete data with the prediction from the new model, Barnea (1986) and Shekhar et al. (2017).

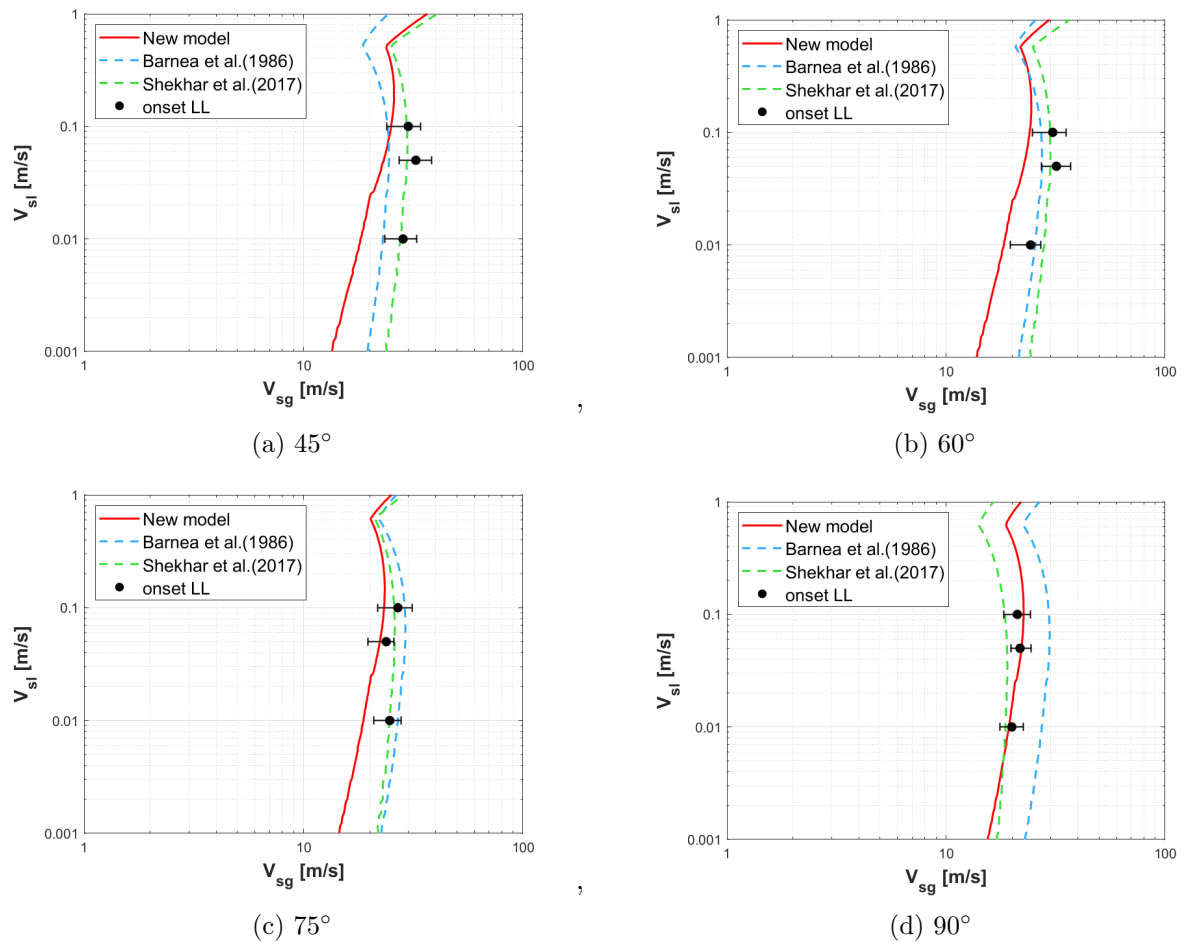


Figure 4.32. Comparison between Guner (2012) experimental data and the transition boundary prediction by the new method, Barnea (1986) and Shekhar et al. (2017)

Overall, the agreement between the prediction using the new model and Guner (2012) experimental data is fairly good for most cases. However, comparing to Shekhar et al. (2017) model performance the new model predicted poorly with more than 25% of error (Figure 4.33).



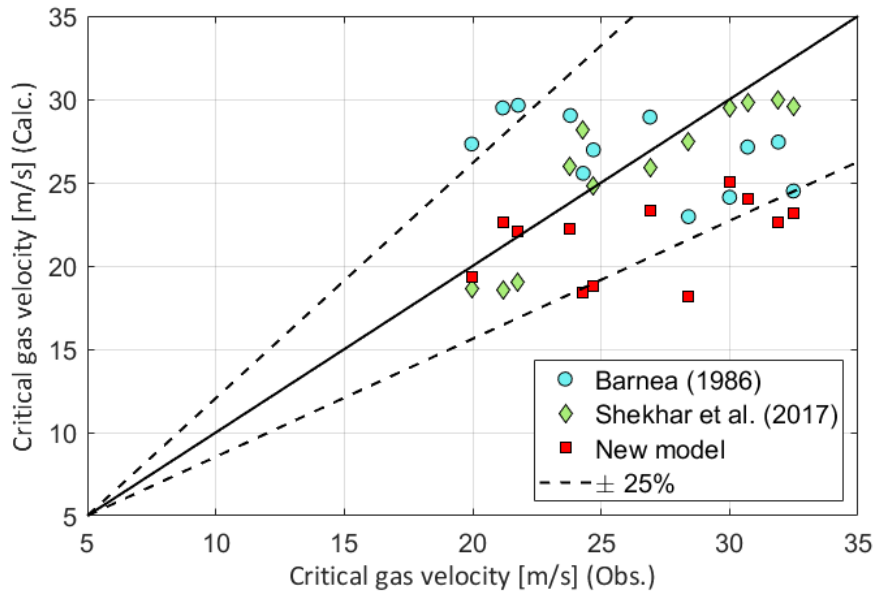


Figure 4.33. Comparison between Guner (2012) experimental data vs. predicted values by the new model, Barnea (1986) and Shekhar et al. (2017)

It is worthwhile to mention that the same set of data was published by Guner et al. (2015), where the values of critical superficial gas velocity are the same as the values presented earlier as loaded conditions, past the onset point. The author has therefore assumed that the values published are the critical onset velocities, but if otherwise, results will vary.

### Application to field data

Field data previously studied on section 4.3.2 was used to evaluate the performance of the new method for the prediction on liquid loading onset.

Analysis of the field data revealed that for an accurate prediction, the model required an upwards adjustment of approximately a factor of 0.4 on the interfacial friction factor for cases of low liquid holdup. Therefore, a coefficient was added to Equation 4.13 resulting in Equation 4.14

$$f_i = 0.4f_g(98.87H_L + 2.2) \sin \theta \quad H_L < 0.05 \quad (4.14)$$

When this modification is introduced, the prediction accuracy for the datasets described above worsened from 10% to 50% relative error. However, the model prediction is conservative (i.e. lower critical gas velocities are predicted) see Figure 4.34). A similar behaviour was observed when applied for Guner (2012) experimental data (Figure 4.35).

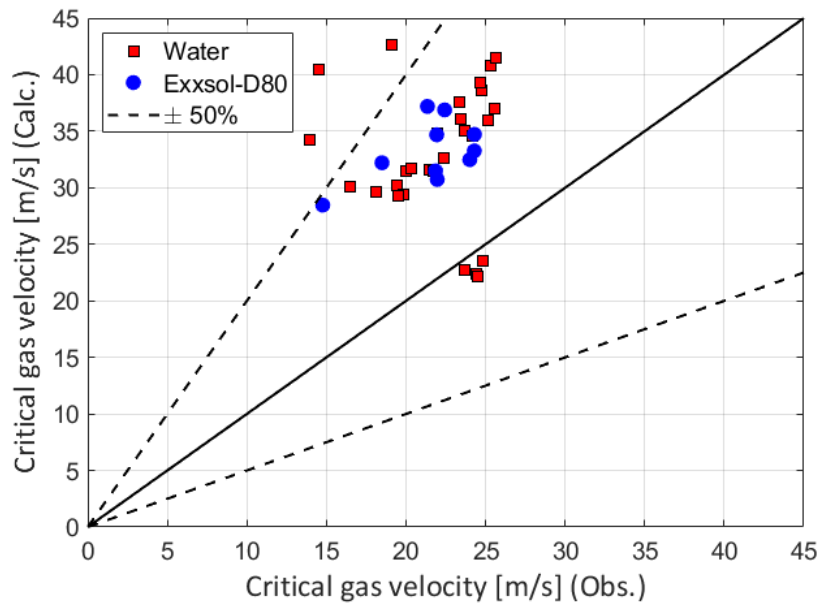


Figure 4.34. Comparison between experimental data vs. predicted values by the new model with adjustment factor

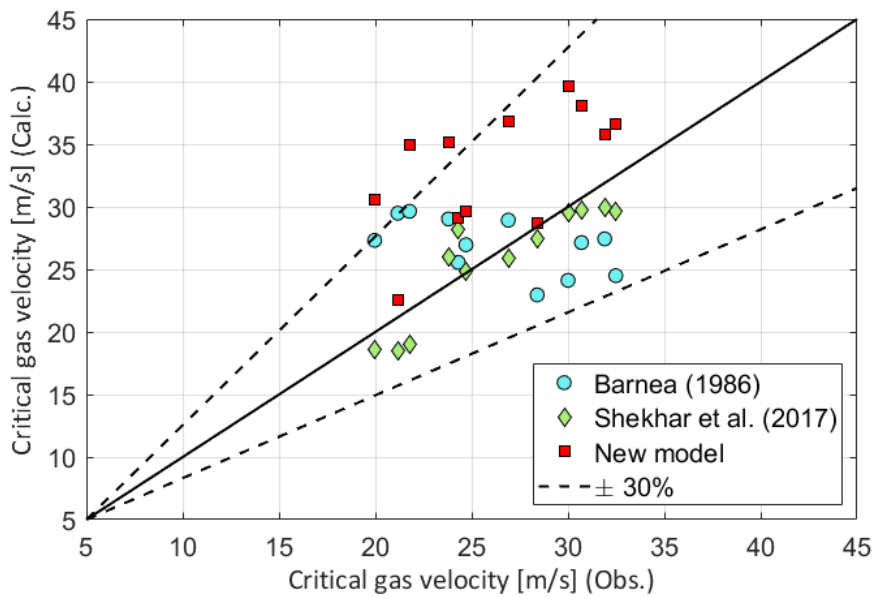


Figure 4.35. Comparison between Guner (2012) experimental data vs. predicted values by the new model with adjustment factor

In Figure 4.36 through Figure 4.39, measured field data were plotted in a 45° line plot and compared with the new model prediction and for the other studied models.

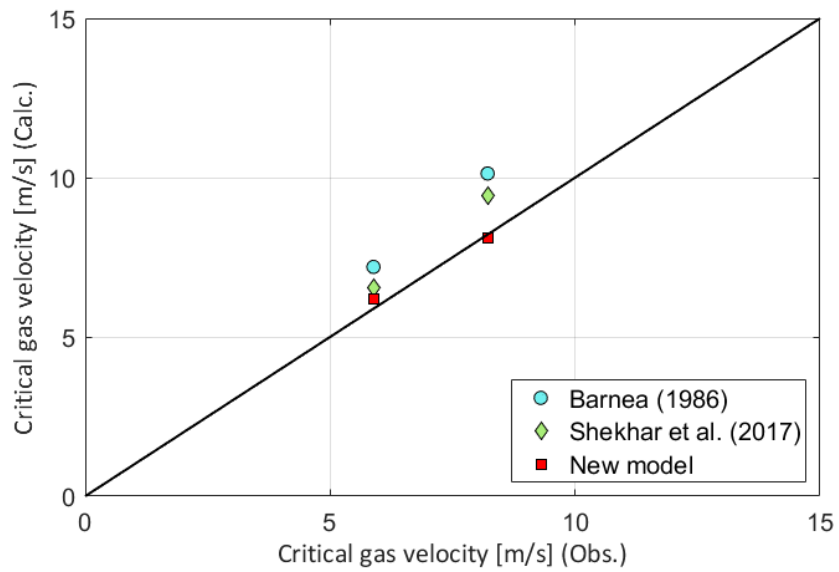


Figure 4.36. Comparison between Belfroid et al. (2008) data vs. predicted values from new model

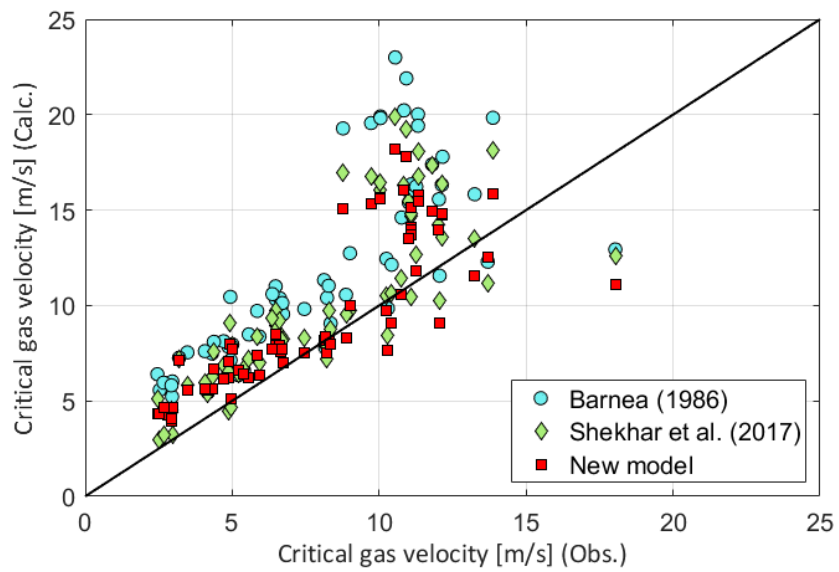


Figure 4.37. Comparison between Veeken et al. (2010) data vs. predicted values from new model

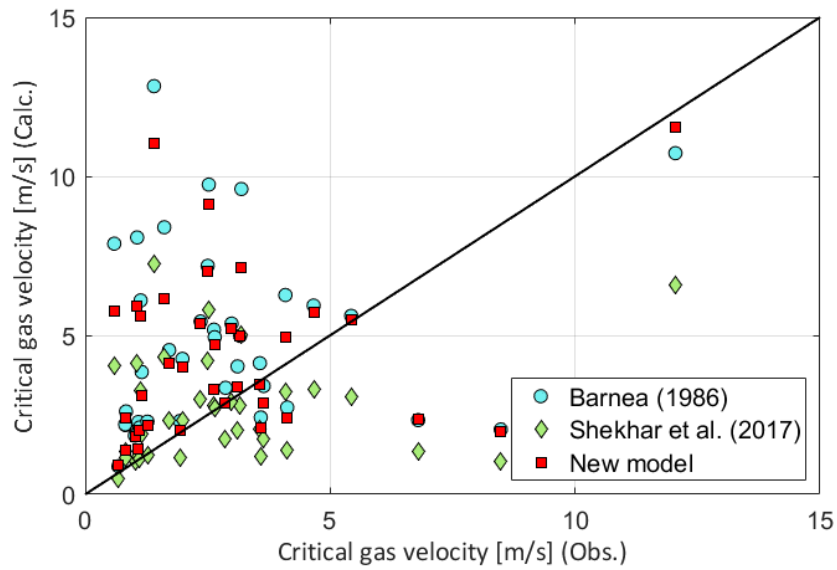


Figure 4.38. Comparison between Turner et al. (1969) data (loaded) vs. predicted values from new model

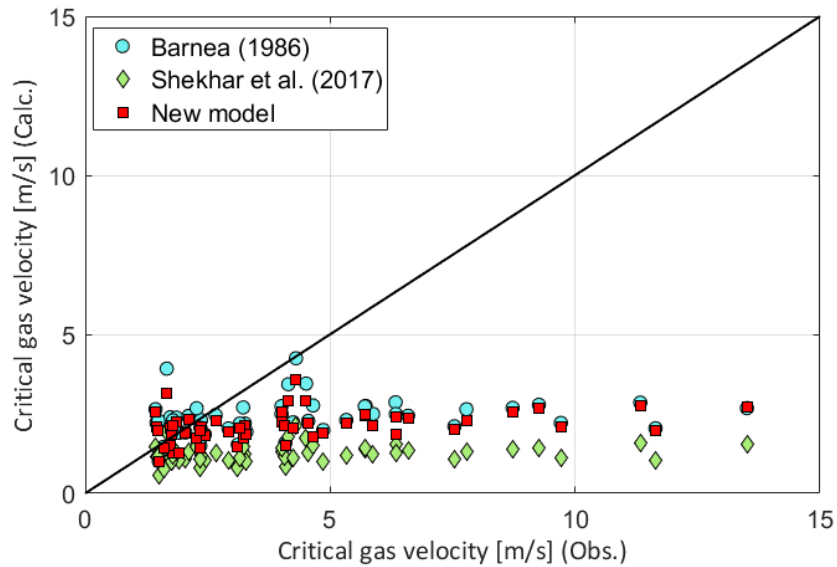


Figure 4.39. Comparison between Turner et al. (1969) data (unloaded) vs. predicted values from new model

The new model exhibits a slightly better prediction when compared to Barnea (1986) and Shekhar et al. (2017) by given the prediction results close to the actual measured gas velocity, i.e., more data points were close to the 45° line. Although, the suggested model performed well, it is recommended as further and future work to investigate methods to verify the applicability of the equations developed (and improve them if necessary) with experimental data for other pipe diameter, test fluids and extended liquid holdup ranges.

Overall, the new proposed model performed better for our experimental data when compared against models of Barnea (1986) and Shekhar et al. (2017), and similar was for the field data, which constitutes an improvement.

## 4.5 Study on liquid accumulation along the wellbore

In the previous sections the analysis of the liquid loading onset was performed considering one location in the pipe. However, in reality a well is a long pipe of a few thousand meters divided in several sections. Thus, there are some spatial aspects of liquid loading that are important to look into, namely:

- The changes of superficial velocities of gas and liquid along the wellbore will cause liquid loading to have its onset usually in one location. Then as gas rate is reduced further, there will be other locations in the well that will start also to experience loading. Therefore, a study was performed to evaluate how does the wellbore transitions from unloaded to fully loaded and quantify the increase in pressure drop and the fraction of the wellbore that is loaded.
- Additionally, a comparison between different liquid loading criteria such as droplet model (Turner et al., 1969), film model (annular to slug transition) and minimum in the pressure drop curve were performed. This with the objective to quantify the variability in the critical gas rate values predicted with different criteria.

Due to the fact that it was not feasible to do field testing on this issue, numerical study was performed. To carry out the pressure drop study in the tubing as a function of gas rate, three numerical simulators were employed a dynamic flow simulator (OLGA), a well performance simulator tool (PROSPER) and Gray (1978) (model described in Appendix B.2) pressure correlation, programmed in Excel VBA. The reason of choosing the models and simulation listed was such that OLGA is able to capture and model flow transients, if any. PROSPER on the other hand is a steady state tool commonly used by the industry for liquid loading studies, as well as Gray correlation. To determine either or not a point on the wellbore is experiencing liquid loading three methods were used:

- The gas velocity (actual) was compared against the critical gas velocity computed with Turner et al. correlation (Equation 2.2).
- The flow pattern was checked, if different than annular flow, the point is considered to be loaded.
- The minimum pressure drop in the vertical performance lift curve was identified.

The study case consist of a vertical 1.625-inches inner diameter gas well, 3468 ft long production tubing, with constant wellhead pressure of 25 psia and temperature of 100°F. Dry gas and free water were used as fluid which entered at the same point at the bottom of the well. Figure 4.40 shows the schematic of the simulated well.

Gas rates ranging from 0.00625 to 1.5 MMscf/d and water-gas ratio (WGR) of 1, 16.67, 100 and 300 stb/MMscf, estimated from a constant flow rate of 15 Mscf/d, were simulated. Results obtained from the simulators were bottom flowing pressure ( $p_{wf}$ ), wellbore pressure profile, fluid properties and superficial velocities.

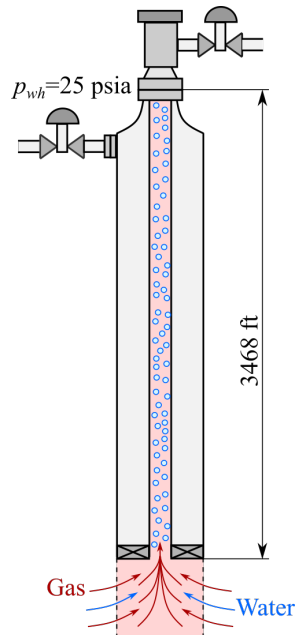


Figure 4.40. Simulated well dimension and operational conditions

To simplify the simulations and to remove the effect of the formation temperature distribution, isothermal ambient conditions were assumed. However, due to the Joule-Thomson effect and the pressure drop experienced by the fluid, the fluid exhibited a temperature variation along the wellbore.

The change in pressure influenced some of the fluid properties such as gas density and surface tension. Therefore, a curve of surface tension and gas density varying with pressure at constant temperature was obtained from the PVT file in OLGA (Figure 4.41 and 4.42). A fitting equation was determined and used to correct the value of surface tension for all the simulated scenarios.

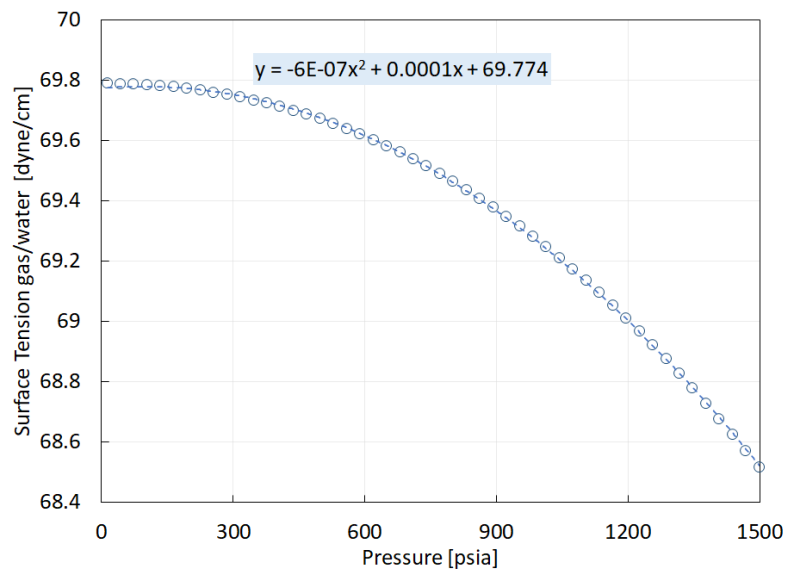


Figure 4.41. Surface tension as function of pressure from OLGA at 100°F

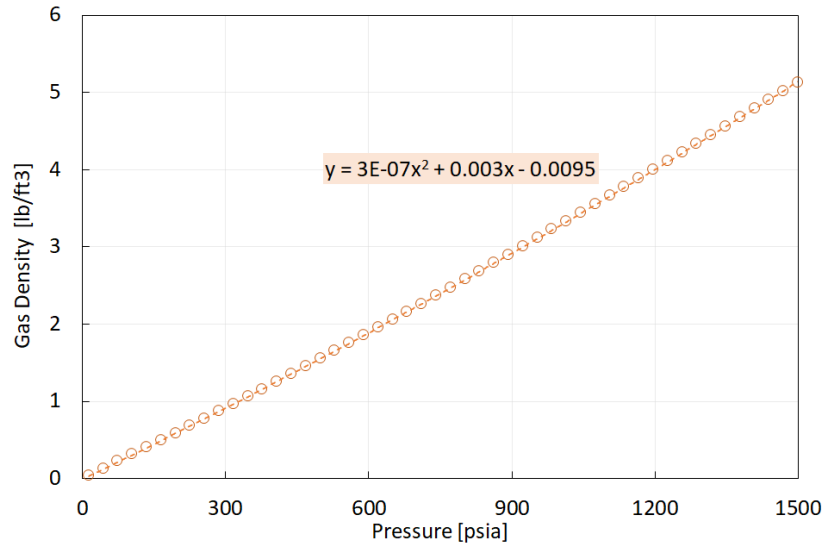


Figure 4.42. Gas density as function of pressure from OLGA at 100°F

### 4.5.1 Simulation results

In this section the simulation results are presented. Figure 4.43 to Figure 4.45 presents the bottom flowing pressure varying with gas flow rate obtained from Gray (1978), OLGA and PROSPER at constant wellhead pressure and various gas rate and water-gas ratio.

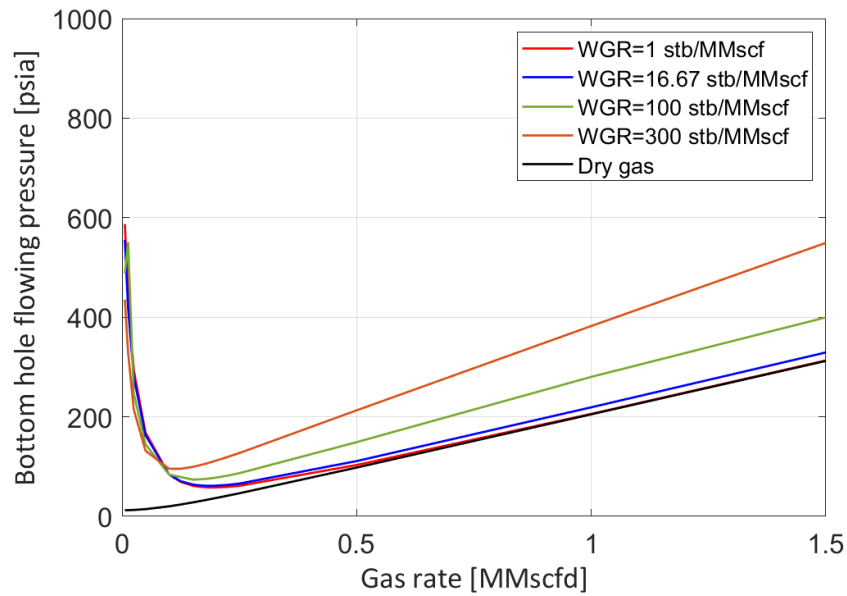


Figure 4.43. Pressure drop for vertical well with 1.625-inches inner diameter using Gray correlation model

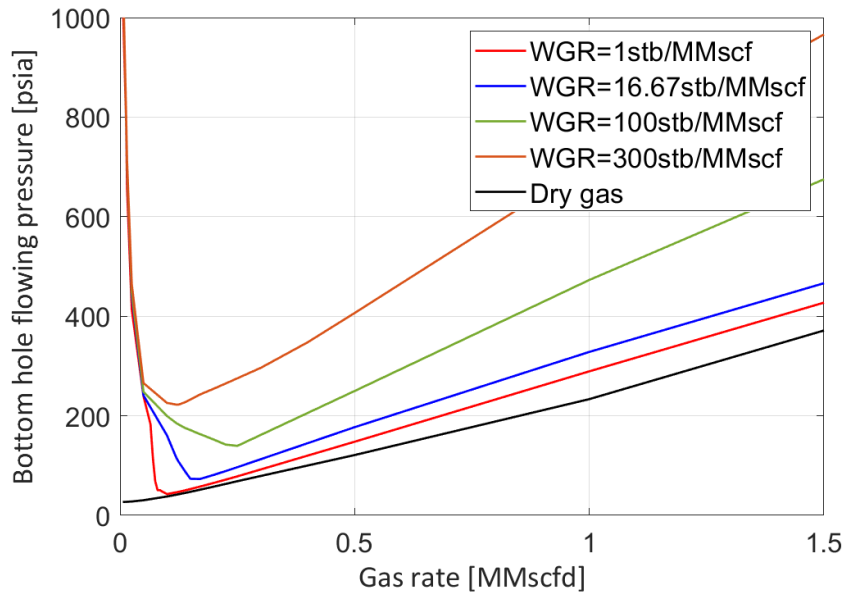


Figure 4.44. Pressure drop for vertical well with 1.625-inches inner diameter using OLGA model

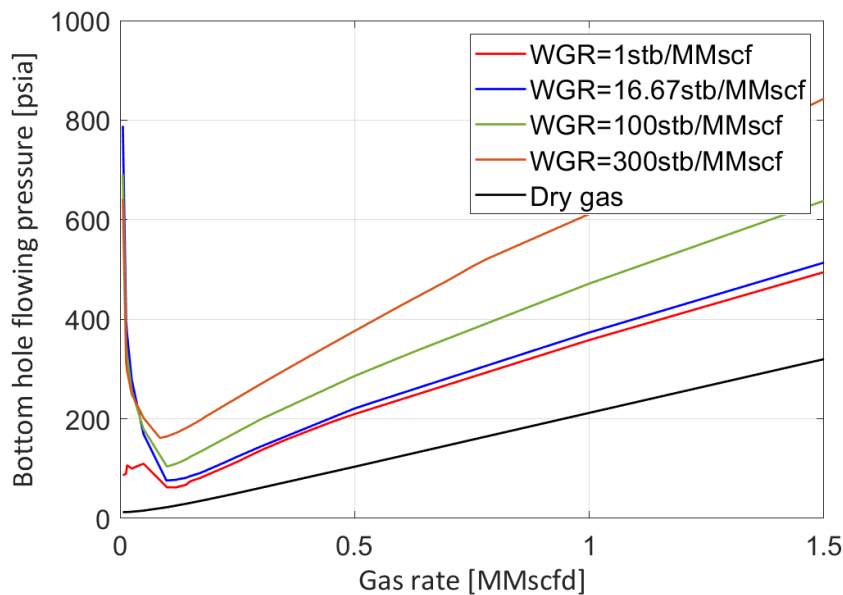


Figure 4.45. Pressure drop for vertical well with 1.625-inches inner diameter using PROSPER model

Overall, the curves presented in Figure 4.43–4.45 show a similar behaviour. As the gas flow rate decreases the bottom hole flowing pressure ( $p_{wf}$ ) decreases until a minimum pressure point. A further decrease of gas flow rate the  $p_{wf}$  increases rapidly, where the curves tend to overlap. For the case of pressure predicted by OLGA (Figure 4.44) the minimum pressure point exhibits a sharp curvature at the minimum pressure point and below those rates, the curves tend to overlap. This could be due to limitation of the PVT data table inserted in the simulator that does not allow simulations to continue at very low gas flow rates. When using PROSPER, it was noticed that, for WGR=1 stb/MMscf, for low gas rates, the curve has different trends depending on the model employed. This



is shown in 4.46 where the vertical lift performance curve is estimated using 4 models, VBA, Gray, GRE models and Petroleum Experts (PE). VBA and GRAY are the model described by Gray (1978). GRAY refers to the results obtained with PROSPER and VBA the results obtained with Excel. PE uses the Gould et al. flow map and various flow regimes model, while GRE is a model developed in house research by petroleum experts, result of several models including Gray (1978) correlation.(Experts, 2019)

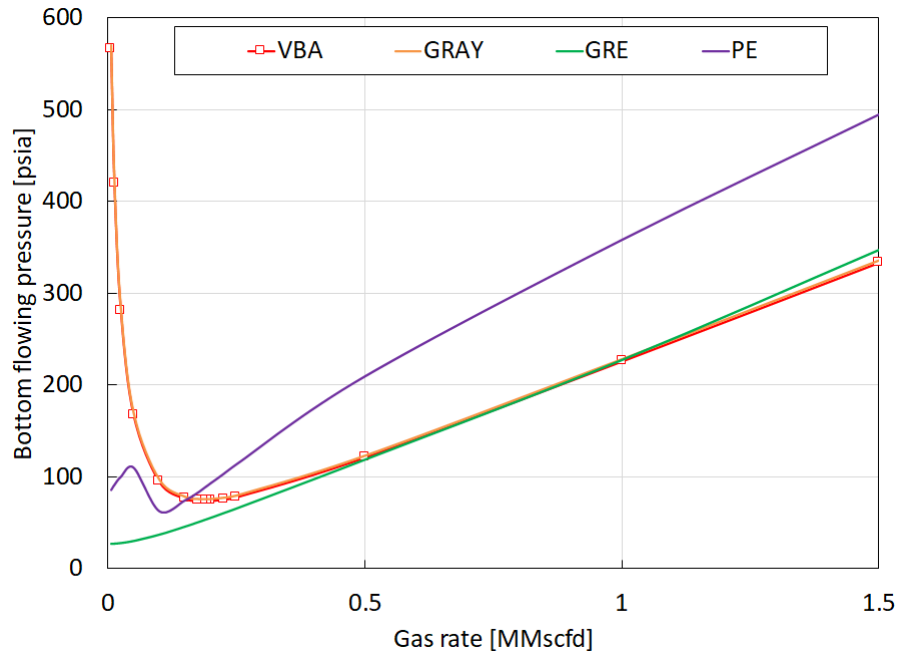


Figure 4.46. Relationship between bottom hole pressure and gas flow rate for different tubing flow correlation for WGR=1 stb/MMscf

Such difference on the vertical lift performance curve predicted by PROSPER was reported by Nymoer (2017). He stated that Gray correlation cannot be used to calculate the static pressure. since with reduction of the gas flow rate the in-situ volume fraction of gas,  $\alpha$ , (see Equation B.20) approaches zero, meaning that the gravitational component approaches the liquid density, which could overestimate the pressure drop in gas wells. He also mentioned that the problem could be solved by using the no-slip density (Equation B.28) on the determination of the gravitational component instead of the average density.

Gray and VBA present the same results as expected since is the same model. GRE as mention in the simulator is the modification of PE which is a correlation result of the combination of several existing correlations. In the present study the PE correlation was used. It is also worth to mention that the vertical lift relationship curve predicted by PROSPER was also dependent of the version of the simulator.

For each gas flow rate given a constant WGR, wellbore pressure profile was determined. Figure 4.47 shows the wellbore pressure profile calculated by the models. In order to obtain pressure at different locations, the wellbore was divided into section. The number of wellbore section varied according to the models used. In the case of PROSPER for example the maximum number of section was 14, which was automatically estimated. OLGAs and Gray's for instance was 50 since the number of sections could be manually introduced prior to the calculations.

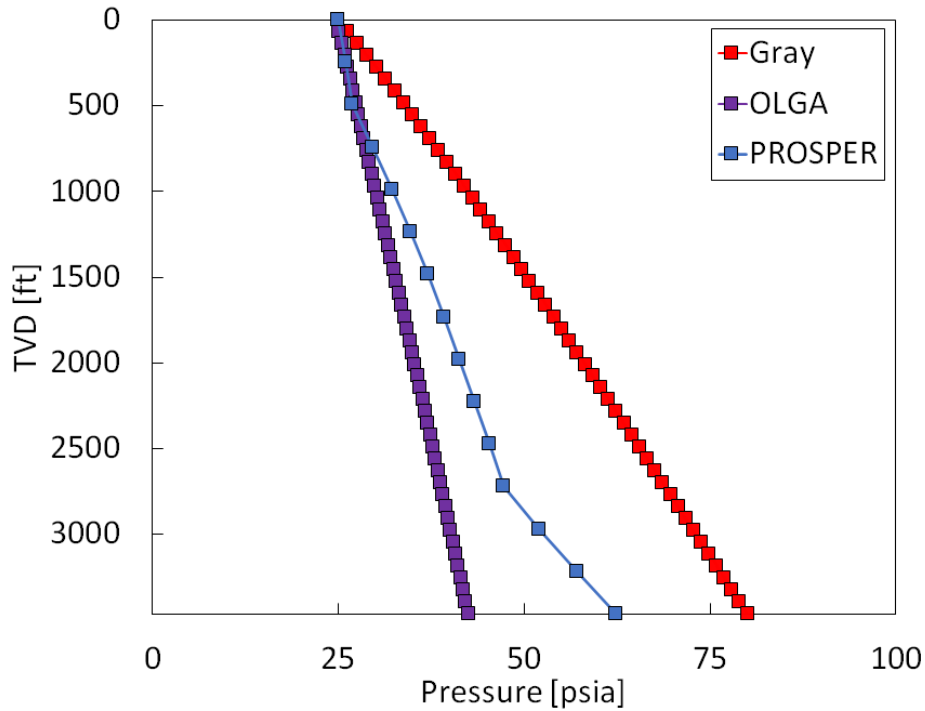


Figure 4.47. True vertical Depth (TVD) vs. wellbore pressure profile for Gray correlation, OLGA and PROSPER for WGR=1 stb/MMscf and  $v_{sg}=0.1$  MMscfd

After the wellbore pressure profile was calculated, three criteria/methods used on the identification of liquid loading onset such as 1. droplet model from Turner et al. (1969), 2. film model (annular to slug transition) and 3. minimum pressure in the vertical lift performance curve were evaluated.

From the Excel VBA (Gray correlation) only the droplet and minimum pressure critical gas flow rate were estimated.

In this study the liquid loading accumulation in all the simulated scenarios start at the bottom of the well, because the local superficial gas rate is smallest at that point due to high pressure.

Figure 4.48 present the vertical lift performance relationship curves and in addition each curve present the critical gas flow rate determine by the different methods. The critical gas flow rates were determined as follow:

- Droplet model: when the local superficial gas velocity was lower than the superficial gas velocity determined ( $v_g < v_{gc}$ ).
- Film model: when the flow pattern at the bottom of the well was different than annular flow.
- Minimum pressure: rate at which the vertical performance lift curve displaced a minimum.

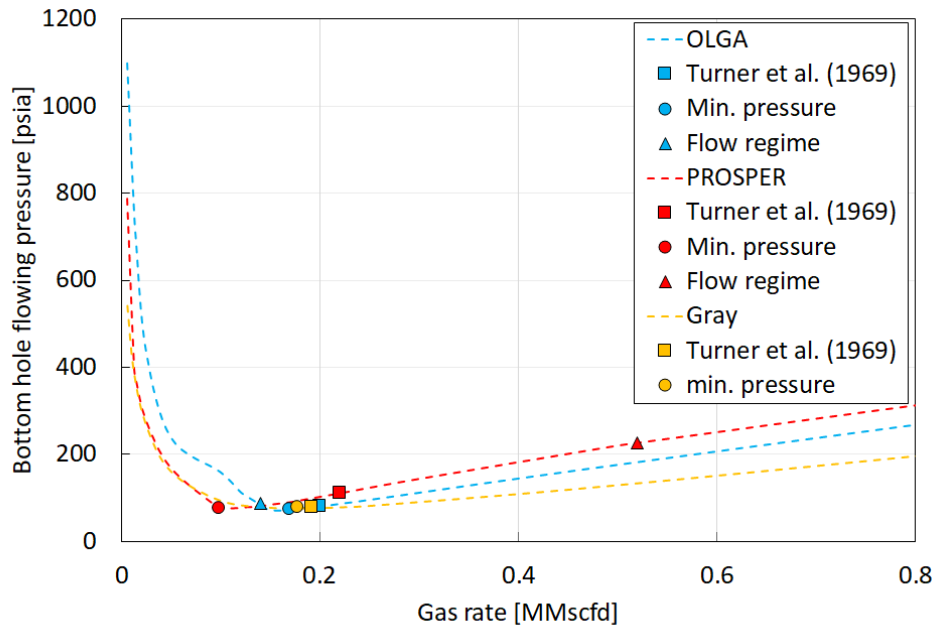


Figure 4.48. Simulation results on liquid loading onset using three different criteria given WGR=16.7 stb/MMscf and constant wellhead pressure of 25 psia

Tables 4.8 to 4.10 presents the critical gas rate for the onset of liquid loading predicted using the different methods for the three models. Additionally, the table present the average gas rate ( $q_{avg}$ ), standard deviation (std) and a spread band ( $s$ ) for the predicted gas flow rate. The spread band (Equation 4.15) was calculated using the difference between the maximum and minimum predicted critical gas rate divided by the average gas flow rate.

$$s = \frac{Max - Min}{Average} \quad (4.15)$$

Table 4.8. Liquid loading onset gas flow rate predicted using Gray model for the different methods

| WGR<br>stb/MMscf | Liquid loading onset rate |              |           |      |      |
|------------------|---------------------------|--------------|-----------|------|------|
|                  | Turner                    | $p_{wf,min}$ | $q_{avg}$ | std  | $s$  |
| 1                | 0.19                      | 0.19         | 0.19      | 0.02 | 0.03 |
| 16.67            | 0.19                      | 0.18         | 0.18      | 0.04 | 0.08 |
| 100              | 0.22                      | 0.14         | 0.18      | 0.20 | 0.39 |
| 300              | 0.27                      | 0.11         | 0.19      | 0.43 | 0.87 |
| Total,avg        | -                         | -            | -         | -    | 0.34 |

Table 4.9. Liquid loading onset gas flow rate predicted using OLGA model for the different methods

| WGR<br>stb/MMscf | Liquid loading onset rate |              |      |           |      |      |
|------------------|---------------------------|--------------|------|-----------|------|------|
|                  | Turner                    | $p_{wf,min}$ | FR   | $q_{avg}$ | std  | $s$  |
| 1                | 0.15                      | 0.10         | 0.10 | 0.11      | 0.2  | 0.6  |
| 16.67            | 0.18                      | 0.17         | 0.14 | 0.16      | 0.10 | 0.2  |
| 100              | 0.25                      | 0.25         | 0.23 | 0.24      | 0.05 | 0.1  |
| 300              | 0.40                      | 0.12         | 0.50 | 0.34      | 0.47 | 1.1  |
| Total,avg        | -                         | -            | -    | -         | -    | 0.47 |

Table 4.10. Liquid loading onset gas flow rate predicted using PROSPER model for the different methods

| WGR<br>stb/MMscf | Liquid loading onset rate |              |      |           |      |      |
|------------------|---------------------------|--------------|------|-----------|------|------|
|                  | Turner                    | $p_{wf,min}$ | FR   | $q_{avg}$ | std  | $s$  |
| 1                | 0.21                      | 0.12         | 0.50 | 0.28      | 0.6  | 1.38 |
| 16.67            | 0.22                      | 0.10         | 0.52 | 0.28      | 0.63 | 1.51 |
| 100              | 0.29                      | 0.10         | 0.64 | 0.34      | 0.66 | 1.58 |
| 300              | 0.36                      | 0.09         | 0.78 | 0.41      | 0.70 | 1.70 |
| Total,avg        | -                         | -            | -    | -         | -    | 1.54 |

General a consistently observation was noticed, for all the Gray and OLGA models the prediction of critical gas flow rate by Turner et al. (1969) gave the most conservative, the minimum pressure is the most optimistic (with the lowest bound) and the flow regime is always in between. While for PROSPER the flow regime transition have shown to be the most conservative having the highest critical gas flow rate.

From Tables 4.8 to 4.10 prediction given by Gray and PROSPER models, the critical gas rate increased with increase of WGR when Turner et al. (1969) criteria was used and reversed scenario was seen for the nodal analysis method (minimum pressure in the curve). On the other hand, OLGA predictions did not show a consistent trend when using the minimum pressure criteria as the other models. This could be due to errors when the simulator extrapolated the original PVT table used in the simulations. The average critical gas flow rate estimated from the simulator prediction have shown to increase with increase of WGR and PROSPER model presented standard deviation values above 50% for all the cases. The higher standard deviation is due to the critical gas flow rate values predicted by the flow regime transition criteria. Considering the spread error a similar behaviour as the standard deviation was observed, where the spread increased when WGR increased and PROSPER had the highest spread error.

Overall the models presented quite different standard deviation for a given WGR and constant wellhead pressure. This could mean that, the liquid loading onset rate is dependent not only on the onset criteria employed but also on the pressure drop model.

A study was performed to evaluate how does the wellbore transitions from unloaded to full loaded and to quantify the fraction of the wellbore that is filled with liquid. To identify the status of a well at certain location, the actual superficial gas velocity calculated by the models was compared with the critical gas velocity predicted by Turner criteria and the

critical gas velocity at which the annular-slug flow transition was identified. If the critical gas velocity was higher than the actual superficial gas velocity then at that location the well was considered to be loaded. Figure 4.49 present progression of liquid accumulation in the wellbore as the gas flow rate decreases.

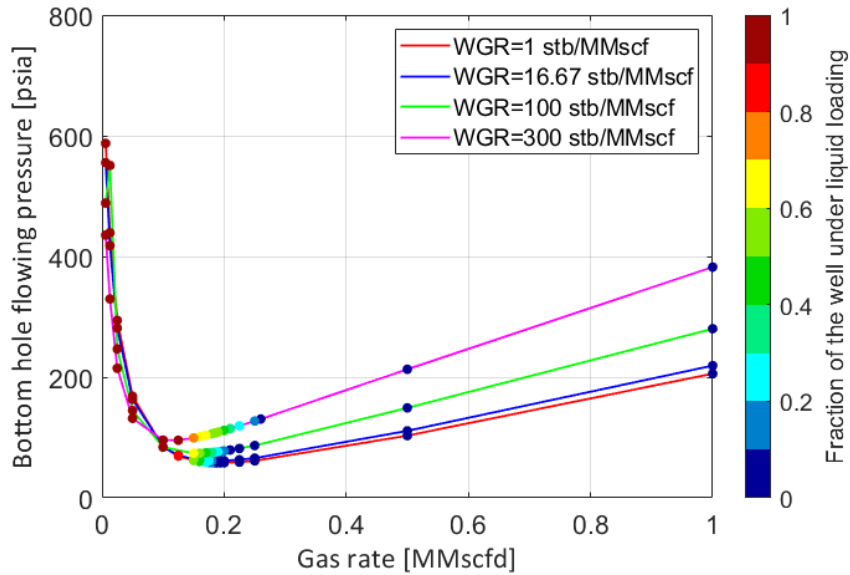


Figure 4.49. Wellbore transition from unloaded to fully loaded for several gas flow rates and WGR estimated by Gray correlation model using Turner equation criteria

It can be observed that once the onset of liquid loading is reached, if the gas rate further decrease the well loads up rapidly. As the water-gas ratio increases the critical gas flow rate also increases.

During the simulation in OLGAs it was noticed that the onset of liquid loading along the wellbore could be identified by using the pressure profile chart and flow regime (Figure 4.50).

WGR=16.7 stb/MMscf  
 $q_g=0.125$  MMscfd

| Well Depth [ft] | Pressure [psia] | Flow Regime [-] |
|-----------------|-----------------|-----------------|
| 0               | 25              | AN              |
| 69              | 25.4            | AN              |
| 139             | 26.2            | AN              |
| 208             | 27              | AN              |
| 277             | 27.8            | AN              |
| 347             | 28.6            | AN              |
| 416             | 29.4            | AN              |
| 485             | 30.2            | AN              |
| 555             | 30.9            | AN              |
| 624             | 31.7            | AN              |
| 694             | 32.4            | AN              |
| 763             | 33.2            | AN              |
| 832             | 33.9            | AN              |
| 902             | 34.6            | AN              |
| 971             | 35.4            | AN              |
| 1040            | 36.1            | AN              |
| 1110            | 36.8            | AN              |
| 1179            | 37.5            | AN              |
| 1248            | 38.2            | AN              |
| 1318            | 39              | AN              |
| 1387            | 39.7            | AN              |
| 1456            | 40.4            | AN              |
| 1526            | 41.2            | AN              |
| 1595            | 41.9            | AN              |
| 1665            | 42.7            | AN              |
| 1734            | 43.4            | AN              |
| 1803            | 44.2            | AN              |
| 1873            | 45              | AN              |
| 1942            | 45.8            | AN              |
| 2011            | 46.7            | AN              |
| 2081            | 47.6            | AN              |
| 2150            | 48.7            | AN              |
| 2219            | 49.9            | AN              |
| 2289            | 51.5            | AN              |
| 2358            | 53.9            | SL              |
| 2427            | 56.9            | SL              |
| 2497            | 59.9            | SL              |
| 2566            | 63              | SL              |
| 2636            | 66.1            | SL              |
| 2705            | 69.2            | SL              |
| 2774            | 72.4            | SL              |
| 2844            | 75.6            | SL              |
| 2913            | 78.8            | SL              |
| 2982            | 82.0            | SL              |
| 3052            | 85.3            | SL              |
| 3121            | 88.6            | SL              |
| 3190            | 92.0            | SL              |
| 3260            | 95.4            | SL              |
| 3329            | 98.8            | SL              |
| 3398            | 102.2           | SL              |
| 3468            | 105.7           | SL              |

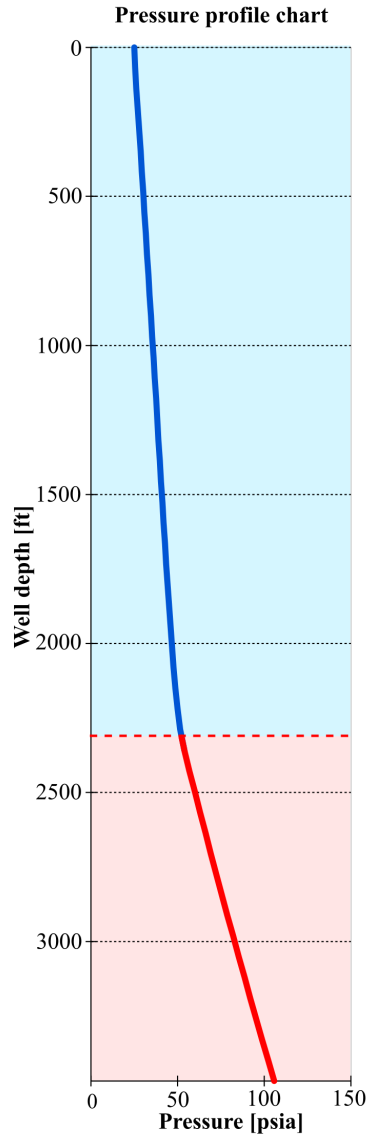


Figure 4.50. Wellbore transition from unloaded to full loaded for several gas flow rates, WGR=300 stb/MMscf estimated by all models using Turner and Flow regime criteria

The pressure profile chart in Figure 4.50 shows the pressure drop per meter across the well bore for the case with 0.125 MMscf gas flow rate and 16.7 stb/MMscf of water-gas ratio, where liquid loading was identified. The pressure profile shows a significant increase in the slug region (0.047 psia/ft) compared to the annular region (0.012 psia/ft). This can be considered as an anticipation of the slug behaviour, where an increase of both the gravity and frictional pressure drop was observed.

Gas rate versus fraction of well filled with liquid were plotted in order to have a better understanding of how the liquid accumulates in the wellbore as the gas flow rate reduces, using the different model and onset prediction criteria. Results are shown in Figure 4.51 to Figure 4.54.

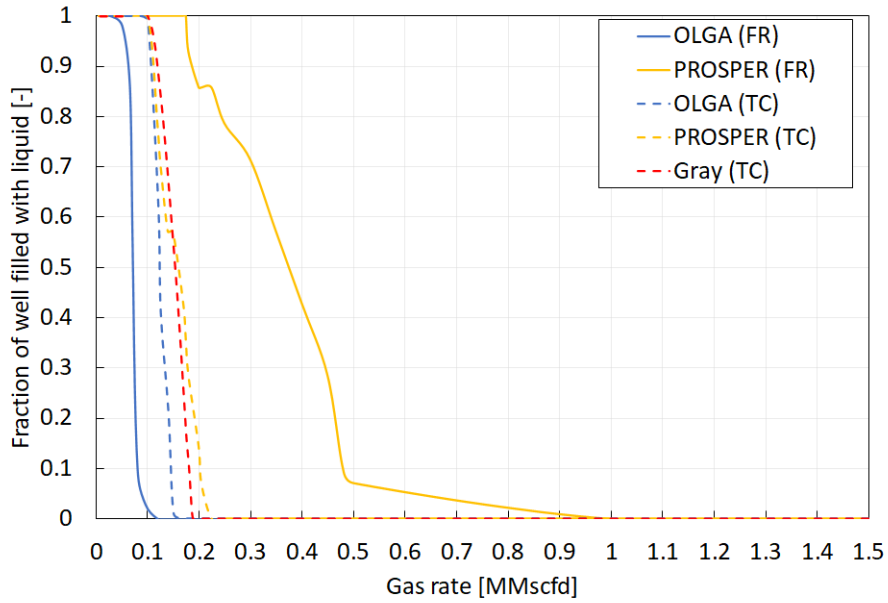


Figure 4.51. Wellbore transition from unloaded to full loaded for several gas flow rates, WGR=1stb/MMscf estimated by all models using Turner and Flow regime criteria

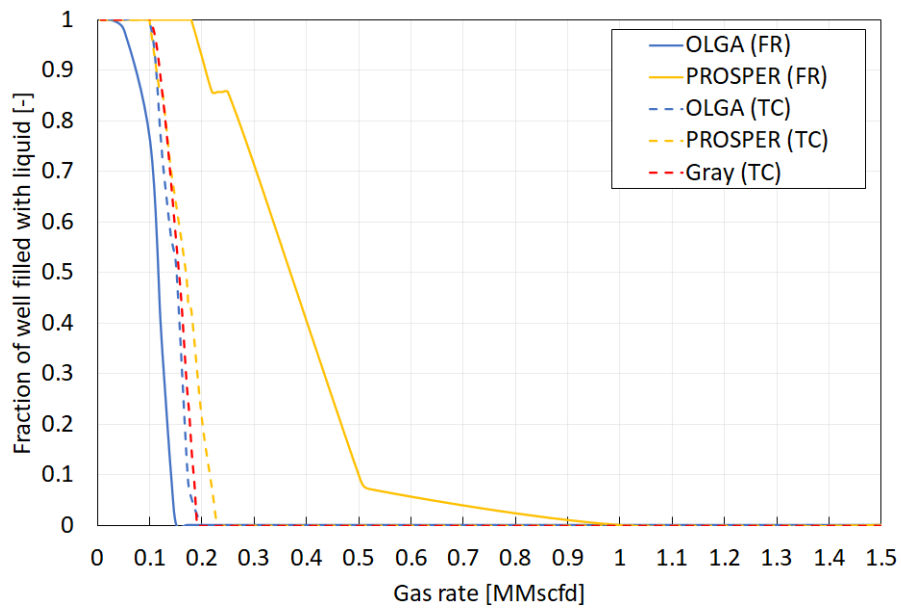


Figure 4.52. Wellbore transition from unloaded to full loaded for several gas flow rates, WGR=16.7stb/MMscf estimated by all models using Turner (TC) and Flow regime (FR) criteria

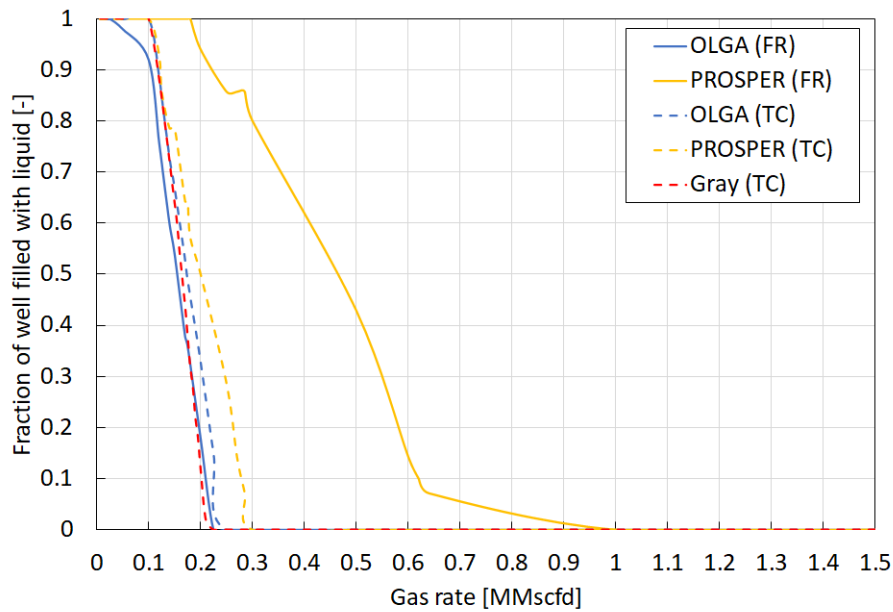


Figure 4.53. Wellbore transition from unloaded to full loaded for several gas flow rates, WGR=100stb/MMscf estimated by all models using (TC) and Flow regime (FR) criteria

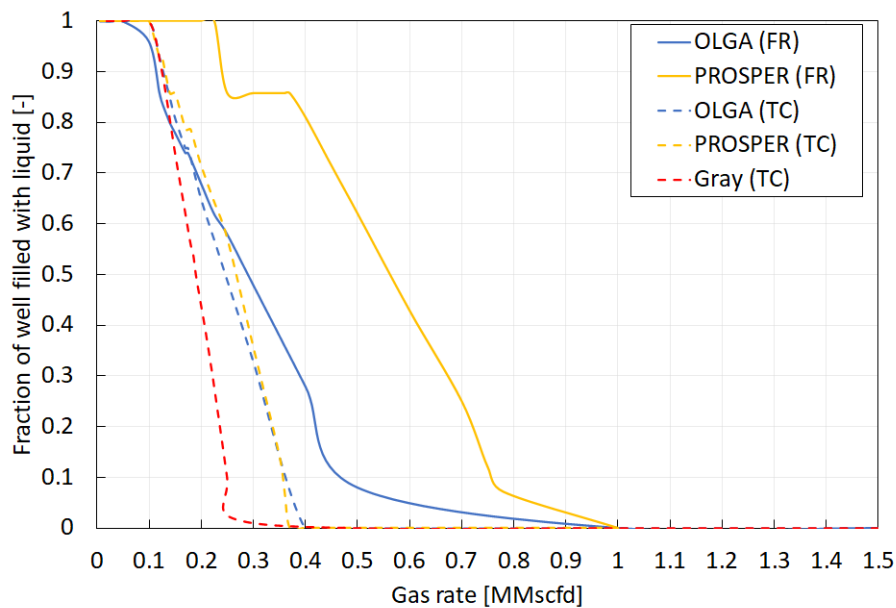


Figure 4.54. Wellbore transition from unloaded to full loaded for several gas flow rates, WGR=300stb/MMscf estimated by all models using (TC) and Flow regime (FR) criteria

For all the simulated scenarios PROSPER results have shown to be more conservative when flow regime transition criteria is used. On the other hand the Turner criteria have shown to have a similar shape for all the models, except for WGR=300 stb/MMscf, where the predicted results were more optimistic, i.e, gave later predictions. To mention that Gray model was not tested for water ratios above 5 bbl/MMcf, which could underestimate pressure predictions for WGR=300 stb/MMscf. Overall, it could be observed that as the onset of liquid loading is identified, an exponential increase of liquid on the wellbore is expected as the gas flow rate keeps reducing.



# Chapter 5

## Conclusion

### 5.1 Conclusions

The following conclusions can be drawn from the results obtained in this research:

#### i. Effect of fluid viscosity on two-phase flow in inclined pipe

An experimental study on the effect of fluid viscosity on flow pattern mapping for two-phase flow in an inclined pipe has been conducted. Observed flow patterns were compared with flow pattern transition modeled by Barnea (1986) and a commercial transient simulator (OLGA 7.3). From the work presented, the following conclusions were derived:

- Most of the flow pattern regions observed by Barnea et al. (1980*a*), Barnea et al. (1980*b*), Barnea et al. (1985) and Barnea (1987) were observed experimentally also in present study.
- The unified model for flow pattern transition proposed by Barnea (1987) predicted satisfactorily the experimentally measured flow pattern map of the two-phase system with viscous fluid as liquid phase at all tested pipe inclinations.
- In general, flow pattern maps predicted with OLGA 7.3 were not in good agreement with measured data. OLGA 7.3 patterns were similar for the slug flow at 70°–78°, but failed on the prediction of slug-annular transition flow for inclinations below 60°.
- Total pressure gradient agreed quite well with the predicted total pressure gradients from OLGA 7.3 for all tested inclination angles.

#### ii. Applicability of existing models for liquid loading prediction

An experimental study on the applicability of available models to predict important parameters during gas production in inclined wells has been conducted. From the work presented, the following conclusions were derived:

- Models based on droplet model underestimate the annular-slug flow pattern transition for all inclination angles.

- OLGA 7.3 does not predict the transition of intermittent (slug) to annular flow for inclinations lower than  $60^\circ$ . Instead the software predicts a transition slug to stratified-wavy flow.
- Overall, the Luo et al. (2014) model overestimated the transition of intermittent to annular flow, thus giving a worse performance for the liquid film model group of approximately 60% relative error.
- On air-water and air-Exxsol D80 the model presented by Shekhar et al. (2017) performed well at inclinations lower than  $60^\circ$ , where the effect of film thickness was more relevant.
- For high liquid velocities the Barnea (1986) model gave a better prediction than the Shekhar et al. (2017) model for two-phase flow with viscous liquid for all the inclinations.
- The observed critical gas velocity for viscous oil was lower compared to other fluids.
- OLGA 7.3 transition gas velocities, presented a good agreement with the experimental data for pipe inclination lower than  $45^\circ$  despite the fact that slug-stratified wavy flow was predicted instead of slug-annular transition.
- The relative error in OLGA 7.3 tended to increase with increasing pipe inclination.

### iii. Effect of entrainment on the annular-slug flow regime transition for liquid loading prediction

In this study, field and experimental data on the onset of liquid loading and flow pattern transition were compared with the liquid film model, and was used for predicting critical gas velocity in gas well. The standard liquid film models assume negligible entrainment. Therefore, the present work was performed considering entrainment on the liquid film model on the prediction of critical gas velocity. From the work performed and presented the following conclusions were derived:

- The predictability of the Shekhar et al. model (2017) of the laboratory data air-water and air-Exxsol D80 system improved when liquid droplet entrainment is included.
- Luo et al. model (2014) overestimated the annular-slug transition boundary flow for all cases studied, consequently also the critical gas velocity for liquid loading predictions.
- Adding an empirical correlation to account for the liquid droplet fraction in the liquid film model by Barnea (1986) and Shekhar et al. (2017) improved the prediction of liquid loading onset for all the analysed data, giving results close to the actual velocity present in the well and observed experimentally.
- In the case of vertical gas wells, droplet entrainment did not have any effect on the critical gas velocity prediction. This was most probably due to the fact that the film thickness is constant at such geometries and the variation of the deposition or entrainment rate in the gas core is negligible.

- Luo et al. (2014) and Shekhar et al. (2017) did not predicted the critical gas velocity satisfactorily in vertical pipes.

#### iv. **Effect of film distribution on the determination of onset of liquid loading**

A new model for estimating the onset velocity of liquid loading in inclined pipes is presented based on the flow pattern transition from annular to intermittent flow. Model correlations were developed using published by Paz (1994). The new method was developed using the same guidelines as the models proposed by Barnea (1986) and Shekhar et al. (2017). The distinctive features of the new model are:

- (a) The method is suitable for inclined pipes, the effect of pipe inclination on the liquid film thickness varies as the inclination changes and liquid loading initiates at position in the pipe with maximum film thickness, similarly to the approach proposed by Shekhar et al. (2017). However, the critical superficial gas velocity is predicted by employing liquid hold-up variation caused by non-uniform film distribution in the pipe circumference.
- (b) A new interfacial friction factor equation was developed, which account for the liquid hold-up variation due to pipe inclination.
  - Stated modifications were achieved with an accurate predictions of critical gas velocities as function of pipe inclination, showing a better agreement when compared to those of other methods proposed in the literature.
  - The proposed method was tested against experimental data for which it proved to have a good agreement. An experimental data published by Guner (2012) was used for validation of the model. It was shown that the new model was conservative but predicted the values within the range of transition determined on his experiment.
  - Evaluating the new model against field data from Belfroid et al. (2008), Veeken et al. (2010) and Turner et al. (1969), it was observed that for a better prediction it was necessary with an upwards adjustment of the proposed interface friction factor.

#### v. **Study on liquid accumulation development along the wellbore**

A numerical study of three models evaluated the wellbore transitions from unloaded to fully loaded, and quantified the increase in pressure drop and the fraction of wellbore that was filled with liquid, by using several onset liquid loading criteria. From the work presented the following conclusions were derived:

- The criteria of estimating the onset of liquid loading using the nodal analysis (minimum pressure in the curve) concept, liquid-droplet reversal and flow regime transition did not match.
- In all cases the rate at which the critical velocity was reached increased when the water-gas ratio increased.

- For all the scenarios calculated through Gray and OLGA models, the result of critical gas flow rate by Turner et al. (1969) gave the most conservative, the minimum pressure was the most optimistic (with the lowest bound) and the flow regime was always in between. While for PROSPER the flow regime transition proved to be the most conservative having the highest critical gas flow rate.
- The models presented quite different standard deviation for a give WGR and constant wellhead pressure. This could mean that the uncertainty in the liquid loading onset depends on the transition criteria and the pressure droplet model employed.
- After the identification of onset of liquid loading, the wellbore transition from unloaded to fully loaded happened rapidly when the Turner et al. criteria (1969) was used for all the models.
- Flow regime criteria is more conservative than Turner et al. (1969) for both OLGA and PROSPER.
- As the onset of liquid loading is identified, an exponential increase of liquid on the wellbore is expected as the gas flow rate keeps reducing.

## 5.2 Recommendations for future research

The following recommendations can be made for further work on the topic of onset of liquid loading in gas well for inclined pipe:

- Focus on evaluating Barnea (1987), Shekhar et al. (2017) and the new model on two-phase flow system with viscous liquid for a wide range of pipe geometries.
- Further improvement of the closure relationships is needed for the new model to give better predictions of gas-liquid flow behaviour for lower pipe inclinations.
- Consistent test data from experiments on multiphase flow over large ranges of relevant parameters are needed in order to derive better rules and/or methods to improve the predictive ability of the models on liquid loading onset for gas wells.
- Evaluate experimentally the behaviour of the liquid loading onset at three-phase flow conditions.
- Model the on role of the formation interaction with the near-wellbore in the onset of liquid loading.

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**URL:** <https://doi.org/10.1002/aic.690320513>
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**URL:** <https://doi.org/10.2118/120580-MS>

# Appendix A

## Experimental procedure

The experimental procedure prior and after any experiment do be performed at the multiphase laboratory at NTNU are presented in this appendix.

### Start-up

1. Visual inspection of the flow loop, to ensure that all the valves are correctly connected.
2. Use the check list available in the lab to verify the position of each valve and to certify that the valves are connected according to the experiment to perform. The valves should be verified both both close to the meters and close to the pumps.
3. Set the desired inclination in the test section using the lift handle connected to the lift mechanism. Measure the inclination angle with the angle meter.
4. Mount the high-speed camera on the visualisation section and connect to the power source.
5. Start the air by slowly open the valve besides the large buffer tank (7 bar), allowing air to flow to the small buffer tank (4 bar). The desired water and/or oil pump must be selected. In case of using centrifugal pumps, the recommended operation frequency should be 30Hz and the maximum should be 45Hz.
6. Once everything is checked, open the air safety valve located close to the air control valves.
7. In the main computer launch the LABview Program to turn on the acquisition system for the instruments.
8. Connect the high-speed camera to the designated computer and launch the camera viewer program.

## Daily Calibration

The daily calibrations were conducted as follows:

1. Clean the pressure taps and the impulse tubes to remove any purged liquid.
2. Check and if necessary, adjust the capacitance or conductance probes minimum and maximum values.
3. Start the water/oil pump and fill completely the test section. The choice of liquid used on the calibration depends on the experiments to be performed on the same day. Example if water will be the liquid phase on the scheduled experiments then calibration must be done with water.
4. Circulate the liquid in the test section for at least 15 minutes, or more if necessary, until steady-state conditions are reached.
5. Fill the impulsive tube with the liquid circulating in the test section. Make sure no bubbles are present.
6. Shut down the flow, by slowly decreasing the pump frequency is fully switched off. Simultaneously, close the control valves to avoid back-flow of the liquid.
7. Check and if necessary, adjust the probes maximum value.
8. Start logging the data for 2 minutes.
9. Use the logged pressure to check if the absolute pressures are reading according to the expected pressure calculated in Figure 3.7. Sometimes a trapped bubble in the pressure taps where the sensor is connected can lead to a wrong reading.
10. Empty the test section and sample the data again for 2 minutes.
11. Check if the differential pressure transmitter readings goes with the expected pressure calculated in Figure 3.8. Adjust the calibration range if necessary.

## Shut-down

Similarly, the laboratory has a shut-down routine

1. Slowly stop the water/oil flow by reduce the frequency of the pump until the pumps are fully switched off.
2. Keep running the air flow to clean the test section and the flexible pipe.
3. Stop the air flow.
4. Close valve at the large buffer tank and the air safety valve, as well as all the valves in the mixing sections.
5. Write down activities and changes done during the day in the laboratory dossier.

# Appendix B

## Models derivations

In this appendix, computational details related to models used for flow pattern and pressure prediction in inclined section are presented. The model is otherwise presented and tested in Chapter 3 and 4.

The issues dealt with in this appendix are:

- Barnea (1986) model for determination annular to intermittent flow transition.
- Gray (1978) for pressure calculation.
- Development of a new model used on determination of annular to intermittent flow transition for the liquid loading onset predictions.

### **B.1 Barnea (1986) model for annular-intermittent flow transition**

Barnea (1987) unified model is a mechanistic model developed with the propose of predicting flow pattern transition for the whole range of pipe inclination through operative equations and dimensionless maps, that incorporate the effect of flow rates, fluid properties, pipe size and pipe inclination. For each individual boundary a transition mechanism is presented, and a logical path is used for a systematic determination of the flow pattern, i.e., solving through a decision tree (Figure B.1).

As mentioned in Section 2.1 the thesis will focus on describing the transition mechanism behind the determination of annular-intermittent flow boundary and for a better understanding the published model described in Barnea (1986) were used.

Diverse mechanisms were suggested for annular to intermittent flow transition. Taitel et al. (1980) suggested that in order to maintain annular flow, the gas velocity must be large enough to lift the largest stable drop present in the gas core. Barnea et al. (1982*a*) adopted a different idea and suggested that the transition from annular to intermittent flow occurs when the liquid holdup is large enough to block the gas core, creating a stable slug. Later, Barnea (1986) define annular flow as gas flowing along the center of the pipe

and the liquid flowing as a film around the pipe walls, and that annular to intermittent transition would occur when this characteristic structure no longer exists.

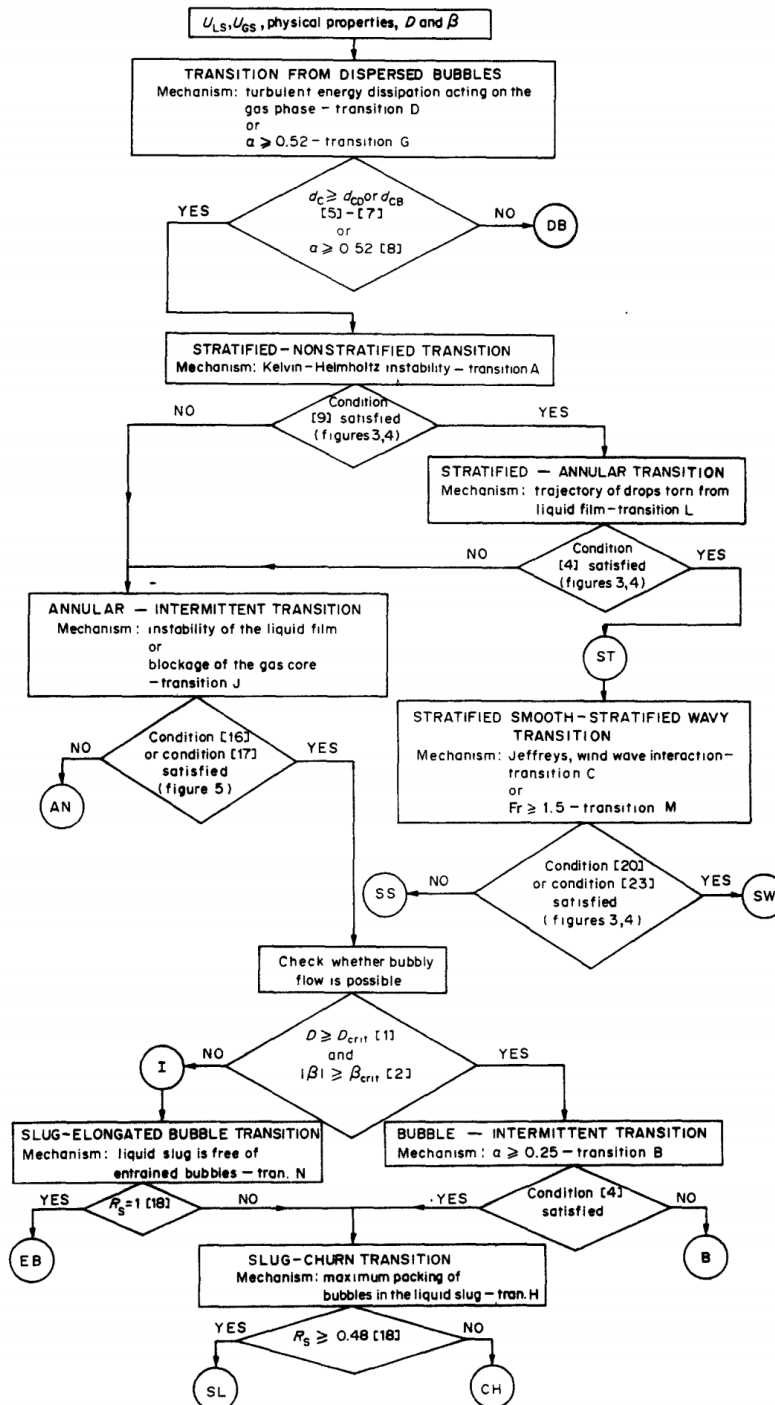


Figure B.1. Logic steps for flow pattern determination Barnea (1987)

Geometry of annular flow is presented in Figure B.2. The gas phase flow in the centre of the pipe while liquid phase as a film with a uniform thickness around the pipe wall. No liquid droplet in the gas core is assumed.

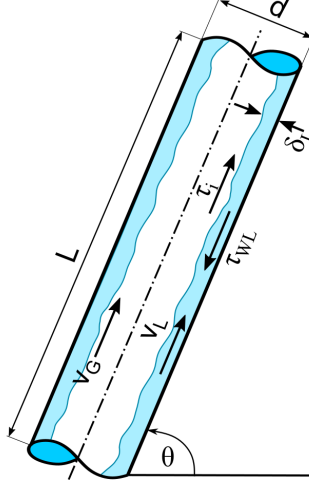


Figure B.2. Physical model for annular flow in an upward flow. Adapted from Shoham (2006)

Using the momentum balance for steady annular flow gives equation for:

*Liquid film*

$$- A_l \frac{dp}{dL} - \tau_{wl} S_l + \tau_i S_i - \rho_l A_l g \sin \theta = 0 \quad (\text{B.1})$$

and

*Gas core*

$$- A_g \frac{dp}{dL} - \tau_{wl} S_l - \rho_g A_g g \sin \theta = 0 \quad (\text{B.2})$$

where  $\tau_i$  and  $\tau_{wl}$  are the interfacial and wall shear stress, respectively,  $A_l$  and  $A_g$  are the cross-sectional area occupied by the liquid and gas phase, respectively,  $S_l$  and  $S_i$  are the perimeter over which  $\tau_i$  and  $\tau_{wl}$  act, respectively,  $\rho_l$  and  $\rho_g$  are liquid and gas densities, respectively.  $\theta$  is the angle of inclination from the horizontal,  $g$  the gravitational acceleration,  $p$  is the static pressure and  $L$  the axial coordinate.

Simplifying the pressure gradient from both liquid and gas momentum equations yields the combined momentum (force) balance equation for liquid-gas two-phase for steady-state annular flow, as follows:

$$\tau_i S_i \left( \frac{1}{A_l} + \frac{1}{A_g} \right) - g(\rho_l - \rho_g) \sin \theta - \tau_{wl} \frac{S_l}{A_l} = 0 \quad (\text{B.3})$$

The wall shear stress of the liquid  $\tau_{wl}$  is related to the liquid average axial velocity ( $v_l$ ) by

$$\tau_{wl} = f_l \frac{\rho_l v_l^2}{2} \quad (\text{B.4})$$

with the liquid/wall friction factor  $f_l$  evaluated from

$$f_l = C_l \left( \frac{\rho_l D_l v_l}{\mu_l} \right)^{-n} \quad (\text{B.5})$$



where  $D_l = 4A_l/S_l$  is the hydraulic diameter,  $\nu_l$  is the liquid viscosity and  $C_l$  and  $n$  are constants in the friction factor correlation, where  $C_l = 0.046$ ,  $n = 0.2$  for turbulent liquid film and  $C_l = 16$ ,  $n = 1$  for laminar liquid film.

and the respective liquid velocity

$$v_l = \frac{v_{sl}A}{A_l} \quad (\text{B.6})$$

Deriving the geometrical parameters based on uniform film thickness ( $\delta$ ) shown in Figure B.3, yield to Equation B.7:

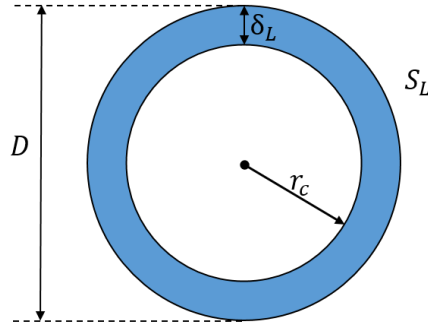


Figure B.3. Annular flow geometry for uniform film thickness

$$S_l = \pi D \quad S_i = \pi(D - 2\delta) \quad A_l = \pi(D\delta - \delta^2) \quad A_g = \pi\left(\frac{D}{2} - \delta\right)^2 \quad (\text{B.7})$$

Substituting the geometrical relationships and the liquid shear stress expression into Equation B.3 and rearranging for the interfacial shear stress yields:

$$\tau_i = g(\rho_l - \rho_g)D \sin \beta (\tilde{\delta}_l - \tilde{\delta}_l^2)(1 - 2\tilde{\delta}_l) + \frac{1}{32}C_l\rho_l \left(\frac{D\rho_l}{\mu_l}\right)^{-n} (v_{sl})^{2-n} \left[\frac{(1 - 2\tilde{\delta}_l)}{(\tilde{\delta}_l - \tilde{\delta}_l^2)^2}\right] \quad (\text{B.8})$$

Equation B.8 relates the required interfacial shear stress provided by the liquid phase to maintain the annular flow structure to the dimensionless film thickness ( $\tilde{\delta} = \delta/D$ ), for a given superficial liquid velocity  $v_{sl}$ . This relation for upward flow is shown in Figure B.4 for different values of liquid velocities. Note that  $\tilde{\tau}_i$  is the dimensionless interfacial shear stress given by

$$\tilde{\tau}_i = \frac{\tau_i}{g(\rho_l - \rho_g)D} \quad (\text{B.9})$$

The supplied interfacial shear stress provided by the gas phase for vertical upward flow as follow:

$$\tau_i = \frac{1}{2}f_i \frac{\rho_g v_{sg}^2}{(1 - 2\tilde{\delta}_l)^4} \quad (\text{B.10})$$

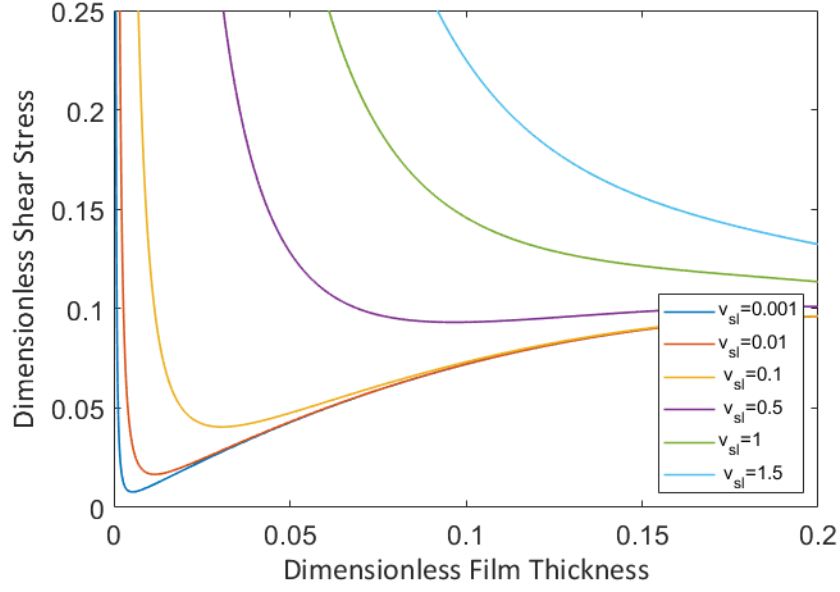


Figure B.4. Dimensionless interfacial shear stress at different liquid velocities

where the gas velocity in the core is given by

$$v_g = \frac{v_{sg}}{(1 - 2\tilde{\delta}_l)^2} \quad (\text{B.11})$$

Barnea (1986) mentioned that the basic mechanism which determine the interfacial shear are not fully understood and the available relationships are largely empirical. Barnea then used an equation developed by Wallis (1969) to estimate the interfacial friction factor ( $f_i$ ):

$$f_i = f_{sg}(1 + 300\tilde{\delta}_l) \quad (\text{B.12})$$

where  $f_{sg}$  is the friction factor in the absence of the film, determined by:

$$f_{sg} = C_g \left( \frac{v_{sg} D \rho_g}{\mu_g} \right)^{-m} \quad (\text{B.13})$$

where  $v_{sg}$  is gas superficial velocity,  $\nu_g$  is the gas kinematic viscosity,  $C_g = 0.046$ ,  $m = 0.2$  for turbulent liquid film and  $C_g = 16$ ,  $m = 1$  for laminar liquid film.

Equation B.10 relates the provided interfacial shear stress to dimensionless film thickness for a given superficial gas velocity,  $v_{sg}$ . This relationship is given by the dashed line in Figure B.5.

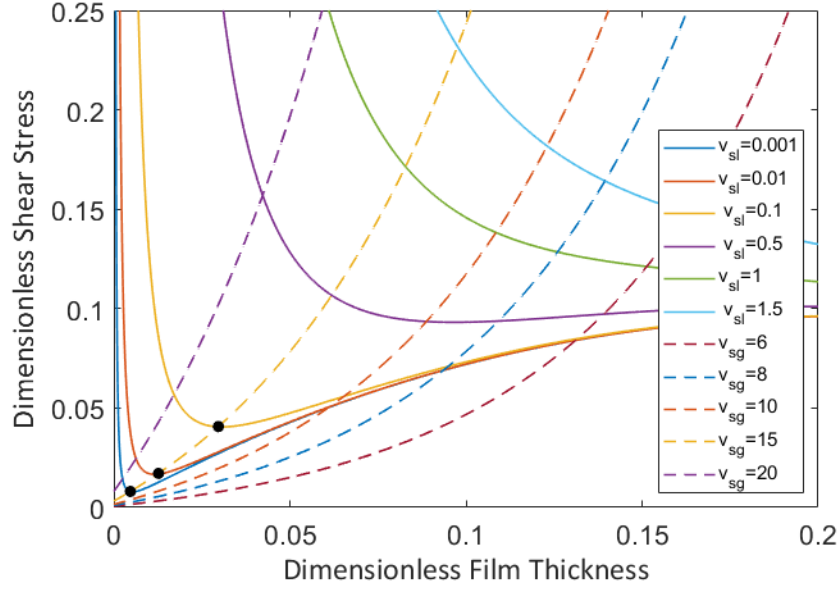


Figure B.5. Steady state solutions for vertical annular flow

For a given set of operational conditions, any intersection between the solid lines and the dashed line is a possible steady-state solution for annular flow.

Barnea (1986) mentioned that the transition from annular to intermittent flow occur if the gas core is blocked by the liquid promoting a change to slug flow. This blockage occurs due to two different mechanisms:

### 1. The instability of annular flow configuration

In Figure B.4 the minimum velocity profile represents a sudden change in the superficial liquid velocity, indicating reversal of film. (Shekhar et al., 2017)

The condition at the minimum points is obtained by differentiating Equation B.8 with respect to  $\tilde{\delta}_l$  and equating it to zero  $\left(\frac{\partial \tau_i}{\partial \tilde{\delta}_l} = 0\right)$ , yielding

$$g(\rho_l - \rho_g)D \sin \beta [(1 - 2\tilde{\delta}_l)^2 - 2(\tilde{\delta}_l - \tilde{\delta}_l^2)] - \frac{1}{16} C_l \rho_l \left(\frac{D \rho_l}{\mu_l}\right)^{-n} (v_{sl})^{2-n} \left[\frac{(\tilde{\delta}_l - \tilde{\delta}_l^2) + (1 - 2\tilde{\delta}_l)^2}{(\tilde{\delta}_l - \tilde{\delta}_l^2)^3}\right] = 0 \quad (\text{B.14})$$

Equation B.14 gives film thickness at the minimum of the curve,  $\tilde{\delta}_l$  for a given  $v_{sl}$ . Solving simultaneously Equations B.8 and B.10 with  $\tilde{\delta}_l$ , that satisfies Equation B.14 yield the value of  $v_{sg}$  at the transition boundary. The black points in Figure B.5 represents the solutions at annular to slug low transition.

### 2. Spontaneous blockage of the core due to wave growth on liquid film

Blockage of the gas core in annular flow may also occur when the supply of liquid in the film is large enough to provide a liquid bridge and create a stable slug, this may

happen at relatively higher liquid flow rates. The criteria for this transition is based on the minimum liquid holdup in a slug,  $H_{LLS,MIN} = 0.48$ . Taitel and Dukler (1976) presented a similar slug flow transition in pipelines, caused by blockage occurring when,

$$\frac{A_L}{AH_{LLS,MIN}} = \frac{H_L}{H_{LLS,MIN}} \geq 0.5 \quad (\text{B.15})$$

$H_{LLS,MIN}$  corresponds to the liquid holdup in the slug only on the transition boundary to annular flow, and is not valid fully developed slug flow, away from the transition boundary. The Green point in Figure B.6 represents the final transition boundary given by

$$H_L \geq 0.24 \quad \text{or} \quad \tilde{\delta}_l \geq 0.65 \quad (\text{B.16})$$

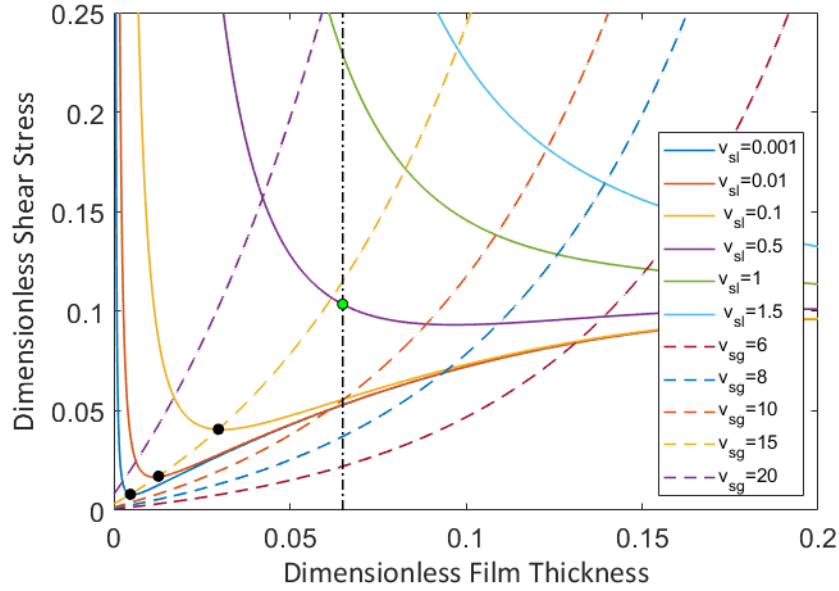


Figure B.6. Solution for liquid blockage of the core due to wave growth

In Figure B.6, combined criterion is shown, the minimum points (black) corresponding to the instability criteria and the criteria of wave growth and pipe blockage (green point) representing the existence of annular flow.

## B.2 Gray correlation

The correlation is normally used to determine the pressure in a well at different depths when producing gas and liquids. Pressure gradient is determined as the sum of the pressure gradient originating from gravity, friction and acceleration Equation B.17 to Equation B.17 respectively,

$$\left(\frac{dp}{dx}\right)_G = \frac{g}{144g_c}(\alpha\rho_g + (1 - \alpha)\rho_l) = \frac{g}{144g_c}\bar{\rho} \quad (\text{B.17})$$

$$\left(\frac{dp}{dx}\right)_F = \frac{2f\rho_{NS}v_m^2}{144g_cD} \quad (\text{B.18})$$

$$\left(\frac{dp}{dx}\right)_A = \rho_{NS}v_m \frac{dv_m}{dx} \quad (\text{B.19})$$

Where  $\alpha$  is the empirical in-situ volume fraction of gas,  $\bar{\rho}$  is average density,  $\rho_{NS}$  is the no-slip density.

The acceleration term is usually neglected during the calculation. In Gray correlation liquid densities were taken to be independent of pressure and temperature. Another important assumption is that there is no solution condensate in the gas, meaning that all the condensate rate measured at the surface is constant. The in-situ volume fraction of gas ( $\alpha$ ) is calculated using the following equation

$$\alpha = \frac{1 - \exp \left\{ -2.314 \left[ N_V \left( 1 + \frac{205}{N_B} \right) \right]^B \right\}}{R + 1} \quad (\text{B.20})$$

Where:  $N_V$ ,  $N_B$ , B and R are dimensionless parameters found from dimensionless analysis and laboratory tests.

The correlation is untested by the author for:

1. Flow velocities > 50 ft/sec;
2. Tubing size > 3.5 inches nominal, tested only for tubing ID 1.049 - 2.992 in
3. Condensate ratios > 50 bbl/MMcf;
4. Water ratios > 5 bbl/MMcf;

### Gravity force

To determine the gravity force, the in-situ volume fraction of gas  $\alpha$  should be calculated. For this, four parameters were presented as mainly influence on the holdup in condensate wells:

$$N_V = \frac{\rho_{NS}^2 V_m^4}{g\sigma(\rho_l - \rho_g)} \quad (\text{B.21})$$

$$N_B = \frac{gD^2(\rho_l - \rho_g)}{\sigma} \quad (\text{B.22})$$

$$R = \frac{v_{sl}}{v_{sg}} \quad (\text{B.23})$$

$$B = 0.0814 \left[ 1 - 0.0554 \ln \left\{ 1 + \frac{730R}{R + 1} \right\} \right] \quad (\text{B.24})$$

In determining the above parameters the surface tension is required, approximation where then developed. Turner et al. (1969)

$$\sigma_c = 0.044 - 1.3 \times 10^{-4}(T - 460) \left( \frac{p_d - p}{p_d - 2120} \right)^{2.5} \quad (\text{B.25})$$

$$\sigma_w = (2.115 - 0.119 \ln p) [0.174 - 2.09 \times 10^{-4}(t - 460)] \quad (\text{B.26})$$

$$\sigma_m = \frac{q_c \sigma_c + 0.617 q_w \sigma_w}{q_c + 0.617 q_w} \quad (\text{B.27})$$

### Frictional force

The Gray correlation assumes that the effective roughness of the pipe ( $r$ ) is dependent on the value of  $R$ . The conditions are as follow:

$$r = \begin{cases} r' = 28.5 \frac{\tau}{\rho_m V_m^2} & R \geq 0.007 \\ r_g + R \frac{r' - r_g}{0.007} & R < 0.007 \end{cases}$$

The effective roughness must be larger than or equal to  $2.77 \times 10^{-5}$ , where  $r_g$  is the dry hydraulic tubing roughness and Reynold's number is assumed to be  $10^7$ . (Oudemans, 2007; Turner et al., 1969)

Note: The original publication contains a misprint (0.0007 instead of 0.007). Also, the surface tension is given in units of  $lb_f/s^2$ .

The friction factor can be determined using standing correlation. The no-slip density is then determined:

$$\rho_{NS} = \rho_l C_l + (1 - C_l) \rho_g \quad (\text{B.28})$$

$$C_l = \frac{v_{sl}}{v_{sl} + v_{sg}} \quad (\text{B.29})$$

### B.3 New model proposed

In Section 2.2.2 was mentioned that Paz (1994) performed experimental investigation on two-phase annular flow on the effect of inclination angle on the liquid film thickness distribution the circumferential of the pipe. Figures B.7 to Figure B.11 show the fitting of the Paz (1994) measured data on the estimation of liquid area.

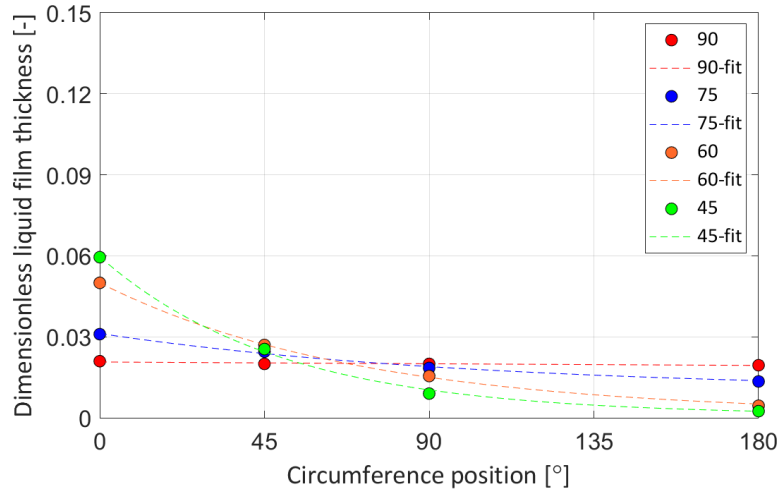


Figure B.7. Fitting Paz (1994) data ( $v_{sl}=0.012$  m/s and  $v_{sg}=18.29$  m/s)

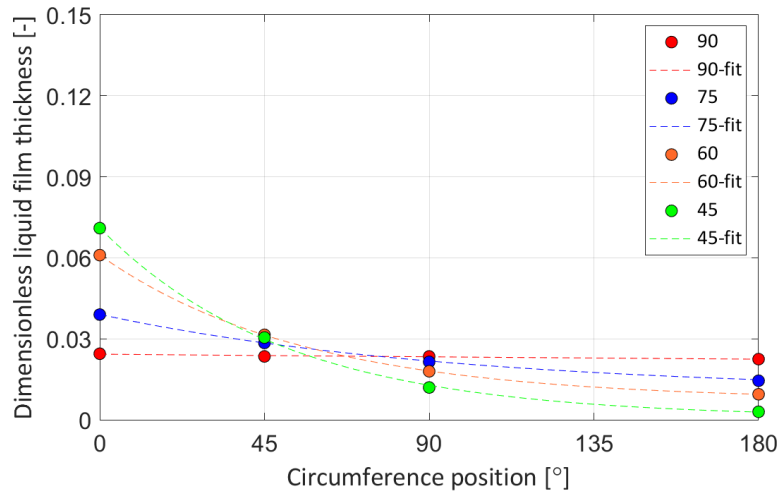


Figure B.8. Fitting Paz (1994) data ( $v_{sl}=0.024$  m/s and  $v_{sg}=18.29$  m/s)

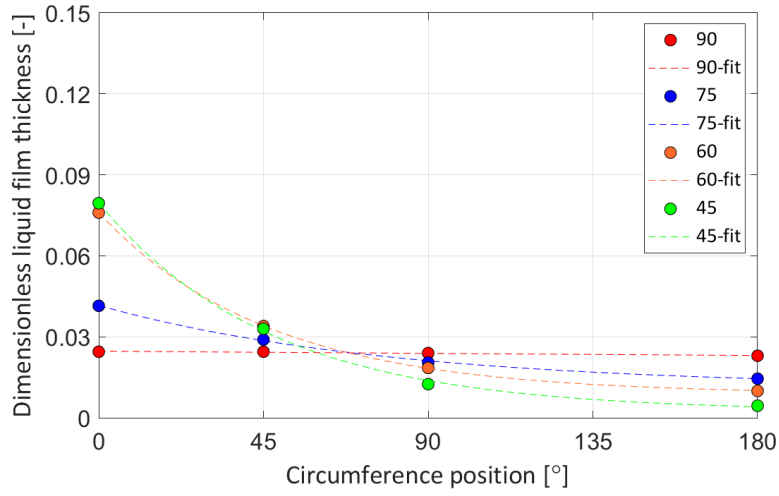


Figure B.9. Fitting Paz (1994) data ( $v_{sl}=0.031$  m/s and  $v_{sg}=18.29$  m/s)

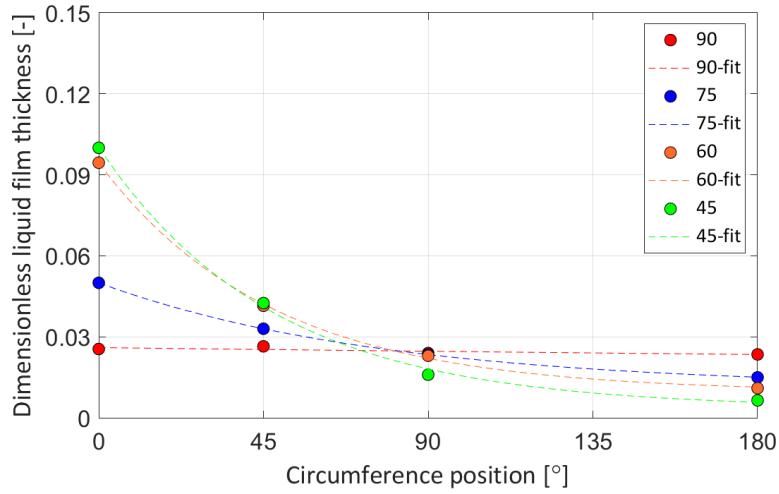


Figure B.10. Fitting Paz (1994) data ( $v_{sl}=0.046$  m/s and  $v_{sg}=18.29$  m/s)

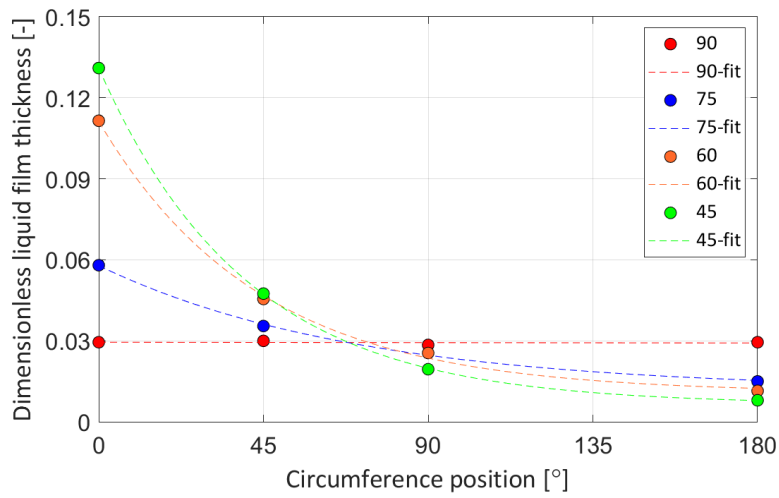


Figure B.11. Fitting Paz (1994) data ( $v_{sl}=0.061$  m/s and  $v_{sg}=18.29$  m/s)



## B.4 Results

The models described on Section 2.2 were implemented using Matlab R2018a and run for the acquired data sets given in the measured results (Section 3.6). For each test case, the models were run to compute the annular-intermittent flow transition and critical gas velocity on the liquid loading onset.

Computations were further treated statistically. Experimental and calculated data were compared point by point. For each data point, an absolute error was determined according to:

$$err_{abs,X} = \left| \frac{X_{calc} - X_{meas}}{X_{meas}} \right| \quad (\text{B.30})$$

where X stands for a physical variable critical gas velocity,  $X_{calc}$  is the model prediction value and  $X_{meas}$  is the experimental (measured) value.

Then a relative percent error was determined by

$$err_{rel,X} = \frac{100}{n} \sum_1^n err_{abs,i} \quad (\text{B.31})$$

$n$  is the number of data points in the data set considered.

### B.4.1 Summary of the relative error presented in Section 4.2 and 4.3

Table B.1. Relative error summary for air-water system presented in Figure 4.5

| Model                  | Pipe inclination |       |       |       |       |        |
|------------------------|------------------|-------|-------|-------|-------|--------|
|                        | 20°              | 30°   | 45°   | 60°   | 70°   | 78°    |
| Barnea (1986)          | 11.66            | 22.49 | 10.25 | 10.43 | 17.69 | 23.79  |
| Luo et al. (2014)      | 75.32            | 38.98 | 62.10 | 75.86 | 63.66 | 50.30  |
| Shekhar et al. (2017)  | 42.54            | 11.11 | 20.88 | 23.13 | 21.40 | 15.42  |
| Turner et al. (1969)   | 16.08            | 27.02 | 26.86 | 26.47 | 22.26 | 20.97  |
| Belfroid et al. (2008) | 11.28            | 25.32 | 18.51 | 17.89 | 16.80 | 20.88  |
| OLGA                   | 22.81            | 16.48 | 22.80 | 36.02 | 84.51 | 113.87 |

Table B.2. Relative error summary for air-Exxsol D80 system presented in Figure 4.8

| Model                  | Pipe inclination |       |       |
|------------------------|------------------|-------|-------|
|                        | 30°              | 45°   | 60°   |
| Barnea (1986)          | 24.98            | 16.00 | 19.86 |
| Luo et al. (2014)      | 37.90            | 45.93 | 87.54 |
| Shekhar et al. (2017)  | 8.09             | 8.77  | 31.24 |
| Turner et al. (1969)   | 38.70            | 45.53 | 34.23 |
| Belfroid et al. (2008) | 37.28            | 39.31 | 26.56 |
| OLGA                   | 16.88            | 35.51 | 42.44 |

Table B.3. Relative error summary for air-water system presented in Figure 4.13

| Model                 | Pipe inclination |       |       |       |       |       |
|-----------------------|------------------|-------|-------|-------|-------|-------|
|                       | 20°              | 30°   | 45°   | 60°   | 70°   | 78°   |
| Barnea (1986)         | 10.26            | 21.21 | 8.26  | 6.88  | 15.04 | 20.71 |
| Luo et al. (2014)     | 72.00            | 35.57 | 55.28 | 66.31 | 57.95 | 47.04 |
| Shekhar et al. (2017) | 39.69            | 7.64  | 17.79 | 19.67 | 18.92 | 10.56 |

Table B.4. Relative error summary for air-Exxsol D80 system presented in Figure 4.14

| Model                 | Pipe inclination |       |       |
|-----------------------|------------------|-------|-------|
|                       | 30°              | 45°   | 60°   |
| Barnea (1986)         | 22.91            | 18.77 | 18.25 |
| Luo et al. (2014)     | 34.28            | 34.46 | 71.60 |
| Shekhar et al. (2017) | 5.67             | 3.47  | 23.72 |

# Appendix C

## Measured experimental data

In this appendix the acquired experimental data is presented, as well as the differential pressure transmitter signal showing their behaviour when different flow pattern was present in the test section.

### C.1 Differential pressure transmitter and capacitance probes signal

In this section, differential pressure transmitter and capacitance probes signal for a given gas and liquid velocity and pipe inclination will be presented aiming to show how the pressure gradient behaviour changes according to the flow pattern.

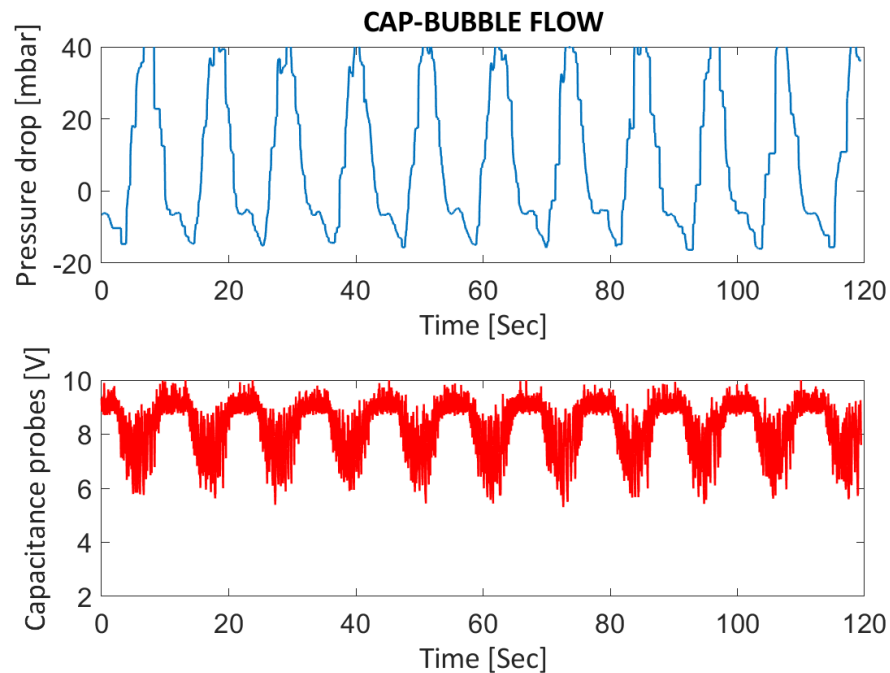


Figure C.1. Differential pressure transmitter and capacitance probes signal for  $v_{sl}=1$  m/s,  $v_{sg}=0.57$  m/s,  $\theta = 60^\circ$ , showing Cap-bubble flow

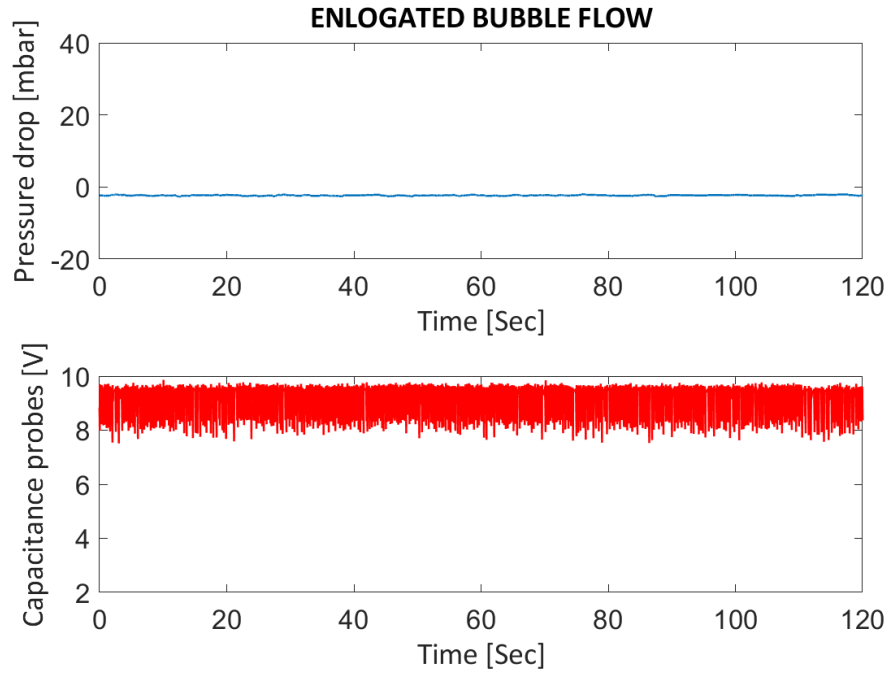


Figure C.2. Differential pressure transmitter and capacitance probes signal for  $v_{sl}=0.6$  m/s,  $v_{sg}=0.58$  m/s,  $\theta = 20^\circ$ , showing Elongated-bubble flow

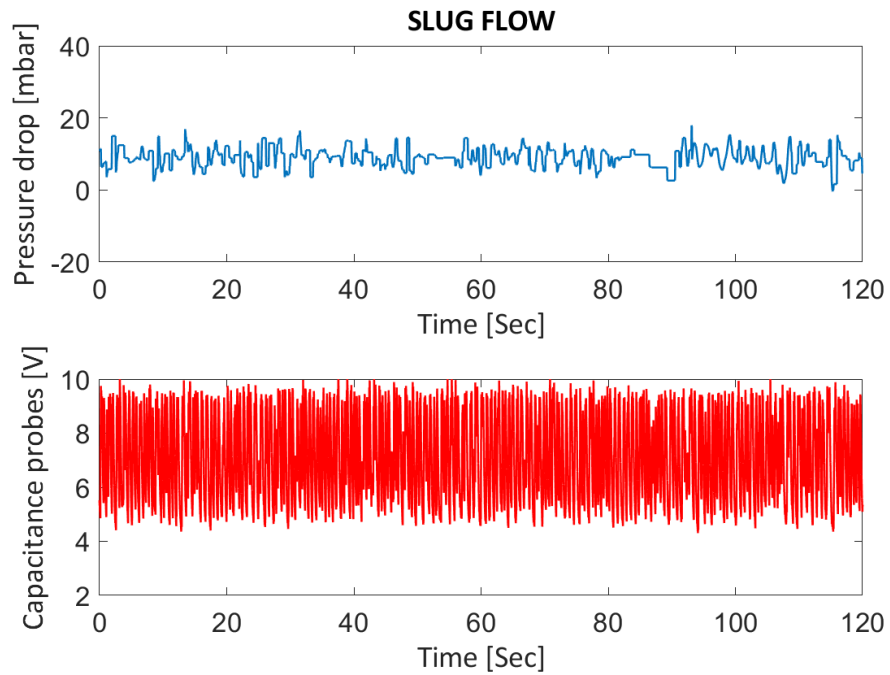


Figure C.3. Differential pressure transmitter and capacitance probes signal for  $v_{sl}=0.6$  m/s,  $v_{sg}=1.07$  m/s,  $\theta = 20^\circ$ , showing Slug flow

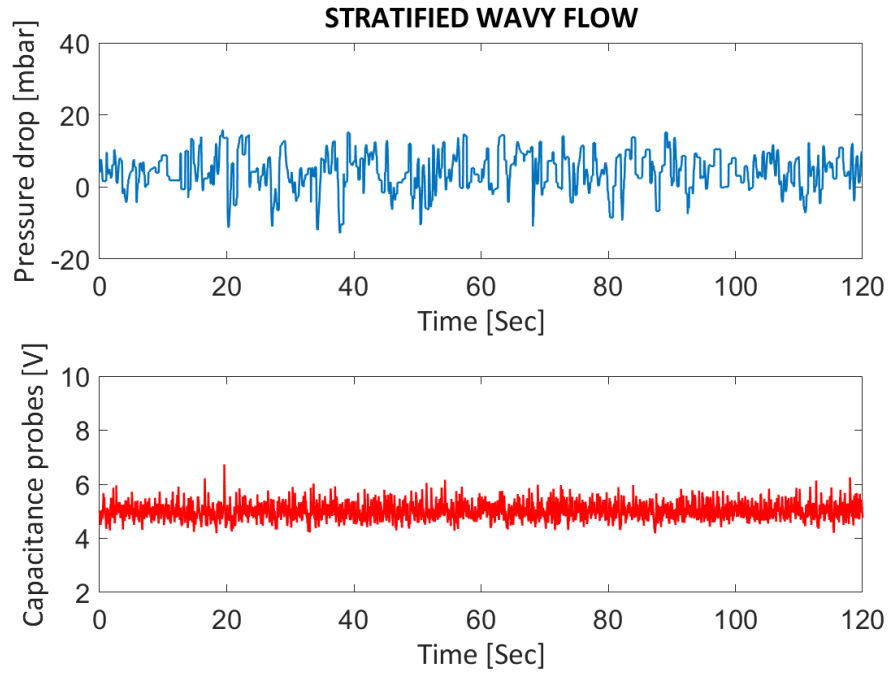


Figure C.4. Differential pressure transmitter and capacitance probes signal for  $v_{sl}=0.6$  m/s,  $v_{sg}=17.72$  m/s,  $\theta = 20^\circ$ , showing Stratified-Wavy flow

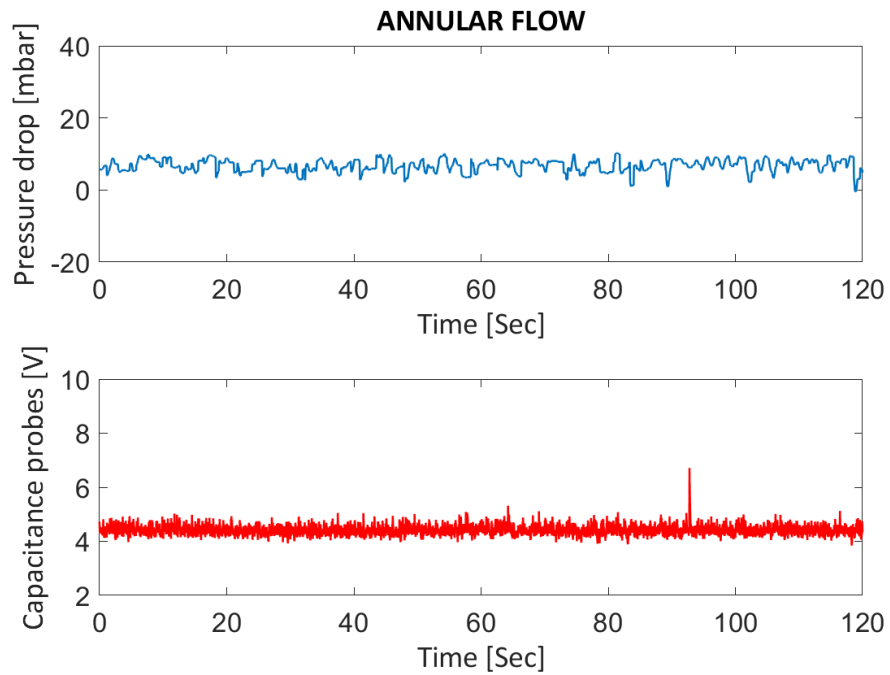


Figure C.5. Differential pressure transmitter and capacitance probes signal for  $v_{sl}=0.6$  m/s,  $v_{sg}=31.68$  m/s,  $\theta = 20^\circ$ , showing Annular flow

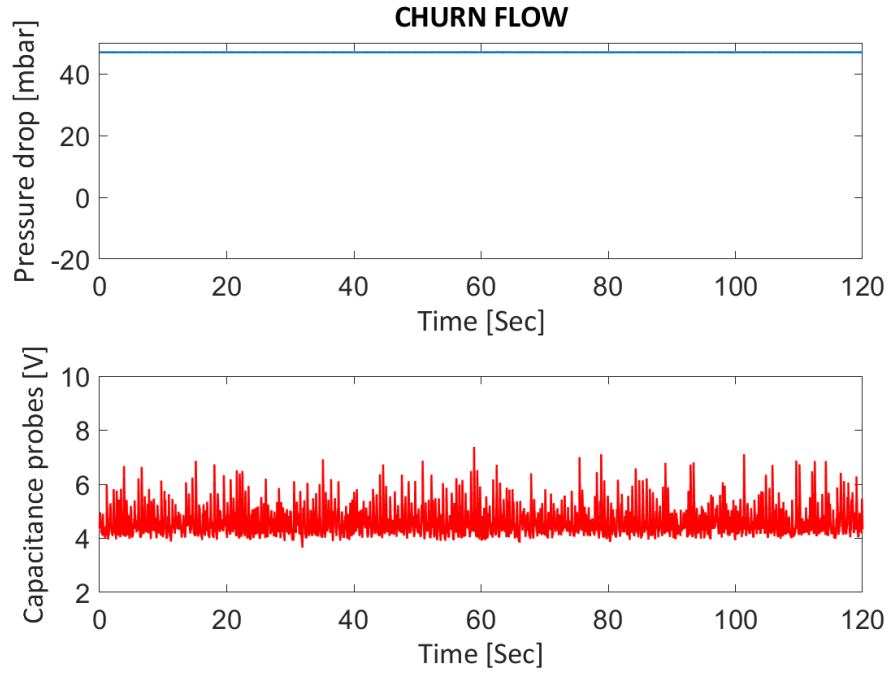


Figure C.6. Differential pressure transmitter and capacitance probes signal for  $v_{sl}=0.6$  m/s,  $v_{sg}=12.22$  m/s,  $\theta = 70^\circ$ , showing Churn flow

## C.2 Tabulated measured data

This appendix contains the following tabulated data:

- Inclination angle measured from horizontal;
- Superficial velocity of gas and liquid
- Temperature under which the experiment were performed;
- Measured pressure measure during experiment;
- Estimated liquid holdup;
- Identified flow regime.

The data were measured for air-water, air-Exxsol D80 and air-Mixed oil two-phase flow system.

In addition the appendix show the behaviour of the pressure gradient changes with inclinations and flow regime present in the test section.

## C.2.1 Air-water system

Table C.1. Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|
| 1     | 20               | 41.93           | 0.02            | 21.91   | 1010          | 0.012        | AN  | 27    | 20               | 19.09           | 0.1             | 19.18   | 733           | 0.065        | OLL |
| 2     | 20               | 29.51           | 0.02            | 21.91   | 555           | 0.015        | AN  | 28    | 20               | 14.01           | 0.1             | 22.54   | 747           | 0.094        | SL  |
| 3     | 20               | 20.73           | 0.02            | 21.90   | 331           | 0.019        | AN  | 29    | 20               | 10.93           | 0.1             | 19.20   | 784           | 0.105        | SL  |
| 4     | 20               | 13.94           | 0.02            | 21.87   | 381           | 0.055        | OLL | 30    | 20               | 7.48            | 0.1             | 22.52   | 847           | 0.127        | SL  |
| 5     | 20               | 7.50            | 0.02            | 21.84   | 548           | 0.080        | SL  | 31    | 20               | 5.68            | 0.1             | 22.58   | 893           | 0.177        | SL  |
| 6     | 20               | 5.66            | 0.02            | 21.78   | 555           | 0.080        | SL  | 32    | 20               | 4.20            | 0.1             | 22.61   | 967           | 0.216        | SL  |
| 7     | 20               | 4.13            | 0.02            | 21.77   | 577           | 0.094        | SL  | 33    | 30               | 57.76           | 0.01            | 19.04   | 1464          | 0.011        | AN  |
| 8     | 20               | 61.53           | 0.06            | 18.67   | 2470          | 0.011        | AN  | 34    | 30               | 50.82           | 0.01            | 19.03   | 1172          | 0.011        | AN  |
| 9     | 20               | 53.37           | 0.06            | 18.65   | 1998          | 0.012        | AN  | 35    | 30               | 44.00           | 0.01            | 19.04   | 900           | 0.011        | AN  |
| 10    | 20               | 47.96           | 0.06            | 18.61   | 1725          | 0.012        | AN  | 36    | 30               | 36.26           | 0.01            | 19.05   | 645           | 0.012        | AN  |
| 11    | 20               | 42.84           | 0.06            | 22.59   | 1399          | 0.017        | AN  | 37    | 30               | 33.10           | 0.01            | 19.06   | 523           | 0.012        | AN  |
| 12    | 20               | 36.09           | 0.06            | 18.64   | 1129          | 0.018        | AN  | 38    | 30               | 29.92           | 0.01            | 19.09   | 439           | 0.012        | AN  |
| 13    | 20               | 30.35           | 0.06            | 18.63   | 793           | 0.024        | AN  | 39    | 30               | 27.06           | 0.01            | 19.08   | 361           | 0.012        | AN  |
| 14    | 20               | 28.39           | 0.06            | 22.57   | 699           | 0.024        | AN  | 40    | 30               | 23.69           | 0.01            | 19.13   | 291           | 0.013        | AN  |
| 15    | 20               | 21.07           | 0.06            | 22.53   | 501           | 0.035        | AN  | 41    | 30               | 21.57           | 0.01            | 19.12   | 254           | 0.013        | AN  |
| 16    | 20               | 14.54           | 0.06            | 22.54   | 527           | 0.071        | OLL | 42    | 30               | 19.47           | 0.01            | 19.11   | 224           | 0.014        | OLL |
| 17    | 20               | 7.63            | 0.05            | 22.48   | 656           | 0.106        | SL  | 43    | 30               | 16.99           | 0.01            | 19.07   | 294           | 0.022        | SL  |
| 18    | 20               | 5.63            | 0.05            | 22.49   | 692           | 0.123        | SL  | 44    | 30               | 13.88           | 0.01            | 19.12   | 528           | 0.047        | SL  |
| 19    | 20               | 4.13            | 0.05            | 22.51   | 735           | 0.131        | SL  | 45    | 30               | 10.77           | 0.01            | 19.09   | 571           | 0.057        | SL  |
| 20    | 20               | 57.12           | 0.1             | 18.99   | 2710          | 0.012        | AN  | 46    | 30               | 55.60           | 0.02            | 19.15   | 1616          | 0.011        | AN  |
| 21    | 20               | 48.98           | 0.1             | 19.01   | 2230          | 0.014        | AN  | 47    | 30               | 48.96           | 0.02            | 19.16   | 1348          | 0.011        | AN  |
| 22    | 20               | 43.98           | 0.1             | 19.07   | 1883          | 0.016        | AN  | 48    | 30               | 41.38           | 0.02            | 19.14   | 1043          | 0.012        | AN  |
| 23    | 20               | 37.22           | 0.1             | 19.10   | 1443          | 0.022        | AN  | 49    | 30               | 33.74           | 0.02            | 19.14   | 726           | 0.013        | AN  |
| 24    | 20               | 28.35           | 0.1             | 19.14   | 975           | 0.036        | AN  | 50    | 30               | 29.16           | 0.02            | 19.17   | 569           | 0.015        | AN  |
| 25    | 20               | 23.95           | 0.1             | 19.17   | 872           | 0.048        | AN  | 51    | 30               | 25.34           | 0.02            | 19.18   | 463           | 0.017        | AN  |
| 26    | 20               | 21.44           | 0.1             | 22.56   | 782           | 0.060        | AN  | 52    | 30               | 22.40           | 0.02            | 19.17   | 414           | 0.020        | OLL |

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Table C.1. (*cont.*) Experimental data for air-water system in 60 mm inner diameter acrylic pipe

| <b>Exp</b><br># | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | <b>T</b><br>°C | <b>dp/dx</b><br>Pa/m | <b>H<sub>L</sub></b><br>[-] | <b>FR</b><br>[-] | <b>Exp</b><br># | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | <b>T</b><br>°C | <b>dp/dx</b><br>Pa/m | <b>H<sub>L</sub></b><br>[-] | <b>FR</b><br>[-] |
|-----------------|------------------|-----------------|-----------------|----------------|----------------------|-----------------------------|------------------|-----------------|------------------|-----------------|-----------------|----------------|----------------------|-----------------------------|------------------|
| 53              | 30               | 18.85           | 0.02            | 19.18          | 452                  | 0.032                       | SL               | 80              | 30               | 29.65           | 0.2             | 19.17          | 1151                 | 0.041                       | AN               |
| 54              | 30               | 14.87           | 0.02            | 19.21          | 643                  | 0.052                       | SL               | 81              | 30               | 25.63           | 0.2             | 19.14          | 1088                 | 0.058                       | OLL              |
| 55              | 30               | 7.31            | 0.02            | 19.21          | 642                  | 0.086                       | SL               | 82              | 30               | 23.40           | 0.2             | 19.16          | 1132                 | 0.069                       | SL               |
| 56              | 30               | 44.08           | 0.05            | 24.09          | 1522                 | 0.013                       | AN               | 83              | 30               | 21.56           | 0.2             | 19.11          | 1125                 | 0.074                       | SL               |
| 57              | 30               | 38.98           | 0.05            | 24.08          | 1253                 | 0.014                       | AN               | 84              | 30               | 20.80           | 0.2             | 19.12          | 1173                 | 0.079                       | SL               |
| 58              | 30               | 33.64           | 0.05            | 24.05          | 977                  | 0.017                       | AN               | 85              | 30               | 20.07           | 0.2             | 19.12          | 1249                 | 0.078                       | SL               |
| 59              | 30               | 28.97           | 0.05            | 24.05          | 751                  | 0.020                       | AN               | 86              | 30               | 18.60           | 0.2             | 19.16          | 1199                 | 0.088                       | SL               |
| 60              | 30               | 25.24           | 0.05            | 24.03          | 617                  | 0.025                       | AN               | 87              | 30               | 16.67           | 0.2             | 19.16          | 1201                 | 0.093                       | SL               |
| 61              | 30               | 23.32           | 0.05            | 24.05          | 582                  | 0.028                       | OLL              | 88              | 30               | 13.81           | 0.2             | 19.14          | 1188                 | 0.105                       | SL               |
| 62              | 30               | 21.68           | 0.05            | 24.15          | 583                  | 0.032                       | SL               | 89              | 30               | 7.93            | 0.2             | 19.16          | 1202                 | 0.128                       | SL               |
| 63              | 30               | 19.24           | 0.05            | 24.14          | 618                  | 0.040                       | SL               | 90              | 45               | 57.71           | 0.01            | 19.58          | 1731                 | 0.011                       | AN               |
| 64              | 30               | 17.20           | 0.05            | 24.10          | 691                  | 0.054                       | SL               | 91              | 45               | 50.52           | 0.01            | 19.58          | 1440                 | 0.011                       | AN               |
| 65              | 30               | 14.02           | 0.05            | 24.12          | 768                  | 0.064                       | SL               | 92              | 45               | 43.93           | 0.01            | 19.64          | 1220                 | 0.012                       | AN               |
| 66              | 30               | 58.77           | 0.1             | 19.23          | 2700                 | 0.023                       | AN               | 93              | 45               | 37.43           | 0.01            | 19.63          | 1019                 | 0.012                       | AN               |
| 67              | 30               | 51.70           | 0.1             | 19.23          | 2500                 | 0.025                       | AN               | 94              | 45               | 31.71           | 0.01            | 19.68          | 814                  | 0.013                       | AN               |
| 68              | 30               | 43.93           | 0.1             | 19.22          | 1920                 | 0.027                       | AN               | 95              | 45               | 27.83           | 0.01            | 19.69          | 701                  | 0.013                       | AN               |
| 69              | 30               | 37.24           | 0.1             | 19.21          | 1547                 | 0.033                       | AN               | 96              | 45               | 25.69           | 0.01            | 19.68          | 643                  | 0.013                       | AN               |
| 70              | 30               | 30.08           | 0.1             | 19.24          | 1034                 | 0.040                       | AN               | 97              | 45               | 24.37           | 0.01            | 19.66          | 615                  | 0.014                       | AN               |
| 71              | 30               | 25.32           | 0.1             | 19.24          | 854                  | 0.051                       | OLL              | 98              | 45               | 23.43           | 0.01            | 19.68          | 588                  | 0.014                       | AN               |
| 72              | 30               | 21.78           | 0.1             | 19.21          | 900                  | 0.071                       | SL               | 99              | 45               | 20.97           | 0.01            | 19.69          | 561                  | 0.015                       | AN               |
| 73              | 30               | 19.80           | 0.1             | 19.22          | 973                  | 0.075                       | SL               | 100             | 45               | 19.80           | 0.01            | 19.70          | 557                  | 0.017                       | OLL              |
| 74              | 30               | 16.16           | 0.1             | 19.20          | 985                  | 0.089                       | SL               | 101             | 45               | 16.73           | 0.01            | 19.71          | 811                  | 0.029                       | SL               |
| 75              | 30               | 8.50            | 0.1             | 19.21          | 1079                 | 0.115                       | SL               | 102             | 45               | 15.22           | 0.01            | 19.73          | 922                  | 0.041                       | SL               |
| 76              | 30               | 50.69           | 0.2             | 19.17          | 2787                 | 0.017                       | AN               | 103             | 45               | 51.22           | 0.02            | 20.06          | 1654                 | 0.011                       | AN               |
| 77              | 30               | 43.30           | 0.2             | 19.14          | 2094                 | 0.022                       | AN               | 104             | 45               | 41.81           | 0.02            | 20.07          | 1318                 | 0.012                       | AN               |
| 78              | 30               | 37.46           | 0.2             | 19.04          | 1699                 | 0.028                       | AN               | 105             | 45               | 37.21           | 0.02            | 20.06          | 1165                 | 0.013                       | AN               |
| 79              | 30               | 33.05           | 0.2             | 19.10          | 1374                 | 0.036                       | AN               | 106             | 45               | 32.24           | 0.02            | 20.09          | 970                  | 0.014                       | AN               |

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Table C.1. (*cont.*) Experimental data for air-water system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|
| 107   | 45               | 28.07           | 0.02            | 20.10   | 841           | 0.016        | AN  | 134   | 45               | 10.70           | 0.05            | 19.81   | 1260          | 0.077        | SL  |
| 108   | 45               | 26.06           | 0.02            | 20.17   | 775           | 0.016        | AN  | 135   | 45               | 50.02           | 0.1             | 20.21   | 2469          | 0.013        | AN  |
| 109   | 45               | 24.63           | 0.02            | 20.19   | 729           | 0.017        | AN  | 136   | 45               | 44.32           | 0.1             | 20.17   | 2294          | 0.016        | AN  |
| 110   | 45               | 23.73           | 0.02            | 20.19   | 721           | 0.018        | AN  | 137   | 45               | 40.96           | 0.10            | 20.19   | 2172          | 0.017        | AN  |
| 111   | 45               | 21.46           | 0.02            | 20.25   | 713           | 0.022        | OLL | 138   | 45               | 37.74           | 0.10            | 20.18   | 1937          | 0.021        | AN  |
| 112   | 45               | 20.36           | 0.02            | 20.25   | 747           | 0.026        | SL  | 139   | 45               | 35.18           | 0.10            | 20.19   | 1735          | 0.023        | AN  |
| 113   | 45               | 18.66           | 0.02            | 20.27   | 888           | 0.036        | SL  | 140   | 45               | 33.18           | 0.10            | 20.20   | 1585          | 0.025        | AN  |
| 114   | 45               | 17.31           | 0.02            | 20.27   | 964           | 0.042        | SL  | 141   | 45               | 31.39           | 0.10            | 20.20   | 1445          | 0.027        | AN  |
| 115   | 45               | 16.65           | 0.02            | 20.27   | 983           | 0.041        | SL  | 142   | 45               | 29.39           | 0.10            | 20.21   | 1335          | 0.030        | AN  |
| 116   | 45               | 12.02           | 0.02            | 20.29   | 1109          | 0.052        | AN  | 143   | 45               | 28.17           | 0.10            | 20.23   | 1243          | 0.033        | AN  |
| 117   | 45               | 6.75            | 0.02            | 20.28   | 1143          | 0.063        | AN  | 144   | 45               | 26.95           | 0.10            | 20.24   | 1235          | 0.038        | AN  |
| 118   | 45               | 49.69           | 0.05            | 19.88   | 2105          | 0.014        | AN  | 145   | 45               | 24.76           | 0.10            | 20.26   | 1188          | 0.045        | OLL |
| 119   | 45               | 44.83           | 0.05            | 19.91   | 1970          | 0.016        | AN  | 146   | 45               | 23.66           | 0.10            | 20.28   | 1278          | 0.051        | SL  |
| 120   | 45               | 41.69           | 0.05            | 19.86   | 1832          | 0.016        | AN  | 147   | 45               | 22.25           | 0.10            | 20.16   | 1375          | 0.057        | SL  |
| 121   | 45               | 37.63           | 0.05            | 19.86   | 1619          | 0.019        | AN  | 148   | 45               | 21.26           | 0.10            | 20.11   | 1404          | 0.062        | SL  |
| 122   | 45               | 34.76           | 0.05            | 19.84   | 1420          | 0.021        | AN  | 149   | 45               | 19.94           | 0.10            | 20.14   | 1370          | 0.062        | SL  |
| 123   | 45               | 32.82           | 0.05            | 19.88   | 1331          | 0.022        | AN  | 150   | 45               | 16.54           | 0.10            | 20.13   | 1432          | 0.070        | SL  |
| 124   | 45               | 29.49           | 0.05            | 19.90   | 1173          | 0.025        | AN  | 151   | 45               | 12.92           | 0.10            | 20.15   | 1549          | 0.077        | SL  |
| 125   | 45               | 26.88           | 0.05            | 19.89   | 1025          | 0.030        | AN  | 152   | 45               | 6.74            | 0.10            | 20.09   | 1610          | 0.097        | SL  |
| 126   | 45               | 25.19           | 0.05            | 23.06   | 965           | 0.026        | OLL | 153   | 45               | 50.49           | 0.20            | 20.06   | 3048          | 0.009        | AN  |
| 127   | 45               | 24.27           | 0.05            | 19.91   | 1029          | 0.039        | SL  | 154   | 45               | 42.97           | 0.20            | 20.09   | 2560          | 0.015        | AN  |
| 128   | 45               | 23.11           | 0.05            | 19.90   | 1118          | 0.043        | SL  | 155   | 45               | 37.52           | 0.20            | 20.13   | 2312          | 0.024        | AN  |
| 129   | 45               | 22.08           | 0.05            | 19.96   | 1172          | 0.047        | SL  | 156   | 45               | 32.69           | 0.20            | 20.09   | 1803          | 0.031        | AN  |
| 130   | 45               | 20.89           | 0.05            | 19.93   | 1229          | 0.055        | SL  | 157   | 45               | 29.33           | 0.20            | 20.05   | 1597          | 0.039        | SL  |
| 131   | 45               | 18.35           | 0.05            | 19.90   | 1230          | 0.059        | SL  | 158   | 45               | 27.10           | 0.20            | 20.10   | 1599          | 0.049        | SL  |
| 132   | 45               | 17.00           | 0.05            | 19.87   | 1251          | 0.064        | SL  | 159   | 45               | 26.07           | 0.20            | 20.12   | 1519          | 0.052        | SL  |
| 133   | 45               | 14.88           | 0.05            | 19.84   | 1246          | 0.069        | SL  | 160   | 45               | 24.69           | 0.20            | 20.13   | 1477          | 0.053        | OLL |

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Table C.1. (*cont.*) Experimental data for air-water system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|
| 161   | 45               | 23.40           | 0.20            | 20.14   | 1568          | 0.064        | SL  | 188   | 60               | 24.48           | 0.02            | 19.88   | 535           | 0.018        | AN  |
| 162   | 45               | 21.87           | 0.20            | 20.11   | 1650          | 0.069        | SL  | 189   | 60               | 22.58           | 0.02            | 19.83   | 507           | 0.020        | AN  |
| 163   | 45               | 20.71           | 0.20            | 20.09   | 1673          | 0.074        | SL  | 190   | 60               | 21.72           | 0.02            | 19.84   | 496           | 0.021        | OLL |
| 164   | 45               | 19.46           | 0.20            | 20.07   | 1653          | 0.076        | SL  | 191   | 60               | 20.72           | 0.02            | 19.82   | 503           | 0.023        | SL  |
| 165   | 45               | 16.82           | 0.2             | 20.11   | 1724          | 0.082        | SL  | 192   | 60               | 19.26           | 0.02            | 19.86   | 632           | 0.031        | SL  |
| 166   | 45               | 14.69           | 0.2             | 20.12   | 1683          | 0.087        | SL  | 193   | 60               | 17.87           | 0.02            | 19.86   | 740           | 0.033        | SL  |
| 167   | 45               | 10.72           | 0.2             | 20.12   | 1934          | 0.100        | SL  | 194   | 60               | 15.73           | 0.02            | 19.84   | 871           | 0.040        | SL  |
| 168   | 60               | 49.59           | 0.01            | 19.83   | 1176          | 0.011        | AN  | 195   | 60               | 12.65           | 0.02            | 19.82   | 1006          | 0.041        | SL  |
| 169   | 60               | 41.55           | 0.01            | 19.85   | 930           | 0.012        | AN  | 196   | 60               | 6.63            | 0.02            | 19.82   | 1297          | 0.058        | SL  |
| 170   | 60               | 37.13           | 0.01            | 19.85   | 793           | 0.012        | AN  | 197   | 60               | 55.41           | 0.05            | 20.19   | 2057          | 0.011        | AN  |
| 171   | 60               | 30.87           | 0.01            | 19.87   | 594           | 0.013        | AN  | 198   | 60               | 48.99           | 0.05            | 20.20   | 1766          | 0.012        | AN  |
| 172   | 60               | 27.80           | 0.01            | 19.88   | 509           | 0.014        | AN  | 199   | 60               | 42.69           | 0.05            | 20.19   | 1558          | 0.013        | AN  |
| 173   | 60               | 25.00           | 0.01            | 19.88   | 432           | 0.014        | AN  | 200   | 60               | 36.73           | 0.05            | 20.16   | 1288          | 0.015        | AN  |
| 174   | 60               | 23.41           | 0.01            | 19.91   | 396           | 0.014        | AN  | 201   | 60               | 30.50           | 0.05            | 20.16   | 993           | 0.019        | AN  |
| 175   | 60               | 21.40           | 0.01            | 19.97   | 365           | 0.015        | AN  | 202   | 60               | 27.09           | 0.05            | 20.16   | 841           | 0.022        | AN  |
| 176   | 60               | 20.20           | 0.01            | 20.02   | 356           | 0.016        | AN  | 203   | 60               | 23.70           | 0.05            | 20.20   | 763           | 0.032        | OLL |
| 177   | 60               | 19.48           | 0.01            | 20.02   | 356           | 0.017        | OLL | 204   | 60               | 22.54           | 0.05            | 20.23   | 886           | 0.040        | SL  |
| 178   | 60               | 18.72           | 0.01            | 20.02   | 372           | 0.019        | SL  | 205   | 60               | 21.68           | 0.05            | 20.21   | 971           | 0.046        | SL  |
| 179   | 60               | 16.39           | 0.01            | 20.02   | 614           | 0.017        | SL  | 206   | 60               | 18.93           | 0.05            | 20.25   | 1057          | 0.052        | SL  |
| 180   | 60               | 12.03           | 0.01            | 20.04   | 953           | 0.034        | SL  | 207   | 60               | 17.41           | 0.05            | 20.26   | 1100          | 0.056        | SL  |
| 181   | 60               | 7.70            | 0.01            | 20.00   | 1111          | 0.039        | SL  | 208   | 60               | 15.83           | 0.05            | 20.24   | 1142          | 0.061        | SL  |
| 182   | 60               | 56.05           | 0.02            | 19.91   | 1592          | 0.011        | AN  | 209   | 60               | 14.77           | 0.05            | 20.25   | 1161          | 0.060        | SL  |
| 183   | 60               | 45.71           | 0.02            | 19.92   | 1204          | 0.012        | AN  | 210   | 60               | 10.01           | 0.05            | 20.24   | 1330          | 0.069        | SL  |
| 184   | 60               | 41.05           | 0.02            | 19.87   | 1056          | 0.012        | AN  | 211   | 60               | 50.81           | 0.1             | 19.94   | 2620          | 0.013        | AN  |
| 185   | 60               | 35.73           | 0.02            | 19.86   | 889           | 0.013        | AN  | 212   | 60               | 44.19           | 0.1             | 19.98   | 2309          | 0.016        | AN  |
| 186   | 60               | 30.50           | 0.02            | 19.89   | 721           | 0.015        | AN  | 213   | 60               | 37.64           | 0.1             | 19.98   | 2066          | 0.022        | AN  |
| 187   | 60               | 28.25           | 0.02            | 19.89   | 642           | 0.016        | AN  | 214   | 60               | 35.22           | 0.1             | 20.00   | 1873          | 0.025        | AN  |

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Table C.1. (*cont.*) Experimental data for air-water system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|
| 215   | 60               | 32.89           | 0.1             | 19.96   | 1616          | 0.028        | AN  | 242   | 70               | 33.04           | 0.01            | 20.94   | 830           | 0.013        | AN  |
| 216   | 60               | 30.07           | 0.1             | 19.96   | 1409          | 0.030        | AN  | 243   | 70               | 27.10           | 0.01            | 20.95   | 662           | 0.014        | AN  |
| 217   | 60               | 28.90           | 0.1             | 19.96   | 1336          | 0.033        | AN  | 244   | 70               | 23.76           | 0.01            | 20.97   | 553           | 0.014        | AN  |
| 218   | 60               | 25.57           | 0.1             | 19.93   | 1214          | 0.047        | OLL | 245   | 70               | 21.12           | 0.01            | 20.94   | 536           | 0.016        | AN  |
| 219   | 60               | 23.99           | 0.1             | 19.90   | 1275          | 0.055        | SL  | 246   | 70               | 19.77           | 0.01            | 20.98   | 526           | 0.017        | AN  |
| 220   | 60               | 23.15           | 0.1             | 19.87   | 1389          | 0.057        | SL  | 247   | 70               | 18.11           | 0.01            | 20.97   | 528           | 0.020        | OLL |
| 221   | 60               | 20.86           | 0.1             | 19.89   | 1503          | 0.064        | SL  | 248   | 70               | 16.88           | 0.01            | 20.99   | 621           | 0.025        | SL  |
| 222   | 60               | 18.57           | 0.1             | 19.88   | 1573          | 0.075        | SL  | 249   | 70               | 15.30           | 0.01            | 21.00   | 823           | 0.022        | SL  |
| 223   | 60               | 15.81           | 0.1             | 19.90   | 1591          | 0.078        | SL  | 250   | 70               | 10.87           | 0.01            | 20.99   | 1157          | 0.033        | SL  |
| 224   | 60               | 9.11            | 0.1             | 19.94   | 1744          | 0.095        | SL  | 251   | 70               | 5.51            | 0.01            | 20.99   | 1701          | 0.060        | SL  |
| 225   | 60               | 51.42           | 0.2             | 20.22   | 3150          | 0.014        | AN  | 252   | 70               | 56.60           | 0.02            | 20.60   | 1756          | 0.011        | AN  |
| 226   | 60               | 42.56           | 0.2             | 20.19   | 2665          | 0.021        | AN  | 253   | 70               | 49.37           | 0.02            | 20.60   | 1471          | 0.012        | AN  |
| 227   | 60               | 36.32           | 0.2             | 20.18   | 2160          | 0.030        | AN  | 254   | 70               | 43.60           | 0.02            | 20.63   | 1297          | 0.012        | AN  |
| 228   | 60               | 29.64           | 0.2             | 20.18   | 1627          | 0.041        | AN  | 255   | 70               | 37.41           | 0.02            | 20.58   | 1110          | 0.013        | AN  |
| 229   | 60               | 25.77           | 0.2             | 20.17   | 1502          | 0.057        | AN  | 256   | 70               | 34.11           | 0.02            | 20.60   | 1002          | 0.014        | AN  |
| 230   | 60               | 24.86           | 0.2             | 20.19   | 1494          | 0.061        | OLL | 257   | 70               | 26.39           | 0.02            | 20.58   | 739           | 0.017        | AN  |
| 231   | 60               | 23.27           | 0.2             | 20.19   | 1691          | 0.067        | SL  | 258   | 70               | 23.60           | 0.02            | 20.57   | 677           | 0.019        | AN  |
| 232   | 60               | 21.92           | 0.2             | 20.20   | 1737          | 0.072        | SL  | 259   | 70               | 22.33           | 0.02            | 20.61   | 661           | 0.021        | AN  |
| 233   | 60               | 21.27           | 0.2             | 20.25   | 1737          | 0.074        | SL  | 260   | 70               | 21.32           | 0.02            | 20.60   | 643           | 0.022        | AN  |
| 234   | 60               | 18.76           | 0.2             | 20.25   | 1805          | 0.086        | SL  | 261   | 70               | 20.03           | 0.02            | 20.64   | 641           | 0.025        | OLL |
| 235   | 60               | 15.69           | 0.2             | 20.25   | 1806          | 0.091        | SL  | 262   | 70               | 18.32           | 0.02            | 20.65   | 765           | 0.036        | SL  |
| 236   | 60               | 12.15           | 0.2             | 20.26   | 1879          | 0.094        | SL  | 263   | 70               | 16.22           | 0.02            | 20.69   | 938           | 0.036        | SL  |
| 237   | 60               | 7.35            | 0.2             | 20.28   | 2051          | 0.115        | SL  | 264   | 70               | 13.20           | 0.02            | 20.68   | 1089          | 0.044        | SL  |
| 238   | 70               | 57.13           | 0.01            | 20.94   | 1651          | 0.011        | AN  | 265   | 70               | 8.73            | 0.02            | 20.68   | 1477          | 0.066        | SL  |
| 239   | 70               | 49.26           | 0.01            | 20.94   | 1338          | 0.011        | AN  | 266   | 70               | 56.78           | 0.05            | 20.06   | 2343          | 0.011        | AN  |
| 240   | 70               | 41.17           | 0.01            | 20.92   | 1076          | 0.012        | AN  | 267   | 70               | 47.33           | 0.05            | 22.84   | 1964          | 0.012        | AN  |
| 241   | 70               | 35.74           | 0.01            | 20.96   | 918           | 0.012        | AN  | 268   | 70               | 41.03           | 0.05            | 22.82   | 1766          | 0.013        | AN  |

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Table C.1. (*cont.*) Experimental data for air-water system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR  |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----|
| 269   | 70               | 36.41           | 0.05            | 22.79   | 1553          | 0.015        | AN  | 296   | 70               | 37.08           | 0.2             | 20.64   | 2433          | 0.025        | AN  |
| 270   | 70               | 29.42           | 0.05            | 22.82   | 1205          | 0.018        | AN  | 297   | 70               | 32.88           | 0.2             | 20.70   | 1969          | 0.030        | AN  |
| 271   | 70               | 28.34           | 0.05            | 22.04   | 1077          | 0.022        | AN  | 298   | 70               | 28.74           | 0.2             | 20.69   | 1730          | 0.038        | AN  |
| 272   | 70               | 24.18           | 0.05            | 22.40   | 920           | 0.025        | OLL | 299   | 70               | 23.72           | 0.2             | 20.72   | 1650          | 0.063        | OLL |
| 273   | 70               | 23.17           | 0.05            | 22.85   | 963           | 0.027        | SL  | 300   | 70               | 22.08           | 0.2             | 20.66   | 1770          | 0.069        | SL  |
| 274   | 70               | 22.60           | 0.05            | 22.32   | 1005          | 0.033        | SL  | 301   | 70               | 19.71           | 0.2             | 20.69   | 1879          | 0.078        | SL  |
| 275   | 70               | 20.89           | 0.05            | 22.81   | 1173          | 0.041        | SL  | 302   | 70               | 17.83           | 0.20            | 20.64   | 1936          | 0.086        | SL  |
| 276   | 70               | 19.76           | 0.05            | 22.81   | 1216          | 0.044        | SL  | 303   | 70               | 16.05           | 0.20            | 20.62   | 2015          | 0.096        | SL  |
| 277   | 70               | 17.97           | 0.05            | 22.79   | 1296          | 0.045        | SL  | 304   | 70               | 12.33           | 0.20            | 20.58   | 2044          | 0.105        | SL  |
| 278   | 70               | 16.16           | 0.05            | 22.81   | 1355          | 0.052        | SL  | 305   | 70               | 4.43            | 0.20            | 20.64   | 2457          | 0.158        | SL  |
| 279   | 70               | 13.17           | 0.05            | 22.77   | 1451          | 0.060        | SL  | 306   | 78               | 45.47           | 0.01            | 22.60   | 1085          | 0.012        | AN  |
| 280   | 70               | 10.86           | 0.05            | 22.75   | 1583          | 0.065        | SL  | 307   | 78               | 39.17           | 0.01            | 22.58   | 886           | 0.012        | AN  |
| 281   | 70               | 7.60            | 0.05            | 22.73   | 1801          | 0.081        | SL  | 308   | 78               | 32.80           | 0.01            | 22.59   | 697           | 0.012        | AN  |
| 282   | 70               | 57.12           | 0.1             | 20.33   | 2952          | 0.012        | AN  | 309   | 78               | 29.45           | 0.01            | 22.66   | 591           | 0.013        | AN  |
| 283   | 70               | 50.58           | 0.1             | 20.34   | 2607          | 0.013        | AN  | 310   | 78               | 25.14           | 0.01            | 22.67   | 480           | 0.014        | AN  |
| 284   | 70               | 43.42           | 0.1             | 20.32   | 2353          | 0.016        | AN  | 311   | 78               | 22.80           | 0.01            | 22.58   | 438           | 0.014        | AN  |
| 285   | 70               | 36.34           | 0.1             | 20.36   | 1978          | 0.021        | AN  | 312   | 78               | 21.05           | 0.01            | 22.56   | 416           | 0.015        | AN  |
| 286   | 70               | 28.11           | 0.1             | 20.36   | 1369          | 0.030        | AN  | 313   | 78               | 18.78           | 0.01            | 22.59   | 376           | 0.017        | AN  |
| 287   | 70               | 23.47           | 0.1             | 20.32   | 1283          | 0.051        | OLL | 314   | 78               | 16.45           | 0.01            | 22.58   | 363           | 0.019        | OLL |
| 288   | 70               | 21.60           | 0.1             | 20.28   | 1539          | 0.062        | SL  | 315   | 78               | 15.47           | 0.01            | 22.64   | 372           | 0.021        | SL  |
| 289   | 70               | 19.12           | 0.1             | 20.32   | 1615          | 0.069        | SL  | 316   | 78               | 14.71           | 0.01            | 22.68   | 405           | 0.024        | SL  |
| 290   | 70               | 15.65           | 0.1             | 20.34   | 1707          | 0.085        | SL  | 317   | 78               | 11.92           | 0.01            | 22.72   | 687           | 0.022        | SL  |
| 291   | 70               | 9.09            | 0.1             | 20.35   | 1868          | 0.105        | SL  | 318   | 78               | 9.37            | 0.01            | 22.71   | 1003          | 0.023        | SL  |
| 292   | 70               | 59.28           | 0.2             | 20.72   | 3634          | 0.012        | AN  | 319   | 78               | 4.67            | 0.01            | 22.70   | 1866          | 0.068        | SL  |
| 293   | 70               | 53.93           | 0.2             | 20.73   | 3343          | 0.013        | AN  | 320   | 78               | 51.18           | 0.02            | 20.97   | 1356          | 0.010        | AN  |
| 294   | 70               | 50.11           | 0.2             | 20.76   | 3094          | 0.014        | AN  | 321   | 78               | 45.20           | 0.02            | 20.99   | 1142          | 0.010        | AN  |
| 295   | 70               | 43.59           | 0.2             | 20.70   | 2688          | 0.018        | AN  | 322   | 78               | 38.52           | 0.02            | 20.99   | 944           | 0.011        | AN  |

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Table C.1. (*cont.*) Experimental data for air-water system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | $H_L$ | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | $H_L$ | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|-------|-----------|------------|----------|----------|----------|----------|--------------|-------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]   | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]   | [-]       |
| 323        | 78       | 32.81    | 0.02     | 21.02    | 776          | 0.012 | AN        | 350        | 78       | 41.68    | 0.1      | 21.68    | 2142         | 0.014 | AN        |
| 324        | 78       | 26.70    | 0.02     | 21.02    | 592          | 0.014 | AN        | 351        | 78       | 37.75    | 0.1      | 21.70    | 1924         | 0.017 | AN        |
| 325        | 78       | 24.55    | 0.02     | 21.04    | 534          | 0.015 | AN        | 352        | 78       | 32.21    | 0.1      | 21.72    | 1515         | 0.020 | AN        |
| 326        | 78       | 23.02    | 0.02     | 21.06    | 518          | 0.016 | AN        | 353        | 78       | 26.13    | 0.1      | 21.70    | 1088         | 0.025 | AN        |
| 327        | 78       | 21.70    | 0.02     | 21.05    | 506          | 0.017 | AN        | 354        | 78       | 24.40    | 0.1      | 21.72    | 1008         | 0.028 | OLL       |
| 328        | 78       | 20.32    | 0.02     | 20.98    | 459          | 0.018 | AN        | 355        | 78       | 21.63    | 0.1      | 21.73    | 1076         | 0.043 | SL        |
| 329        | 78       | 18.97    | 0.02     | 20.94    | 468          | 0.019 | OLL       | 356        | 78       | 20.07    | 0.1      | 21.76    | 1089         | 0.054 | SL        |
| 330        | 78       | 17.84    | 0.02     | 20.96    | 475          | 0.022 | SL        | 357        | 78       | 19.15    | 0.1      | 22.17    | 1206         | 0.061 | SL        |
| 331        | 78       | 16.52    | 0.02     | 20.97    | 473          | 0.026 | SL        | 358        | 78       | 17.65    | 0.1      | 22.22    | 1303         | 0.067 | SL        |
| 332        | 78       | 13.20    | 0.02     | 20.98    | 728          | 0.029 | SL        | 359        | 78       | 16.22    | 0.1      | 22.32    | 1377         | 0.075 | SL        |
| 333        | 78       | 7.03     | 0.02     | 21.00    | 1465         | 0.070 | SL        | 360        | 78       | 12.06    | 0.1      | 22.41    | 1559         | 0.104 | SL        |
| 334        | 78       | 2.58     | 0.02     | 21.03    | 2026         | 0.097 | SL        | 361        | 78       | 10.12    | 0.1      | 22.44    | 1653         | 0.122 | SL        |
| 335        | 78       | 50.41    | 0.05     | 20.92    | 1897         | 0.010 | AN        | 362        | 78       | 6.55     | 0.1      | 22.48    | 1932         | 0.157 | SL        |
| 336        | 78       | 42.70    | 0.05     | 21.07    | 1630         | 0.012 | AN        | 363        | 78       | 51.33    | 0.2      | 22.45    | 3319         | 0.012 | AN        |
| 337        | 78       | 37.63    | 0.05     | 21.19    | 1419         | 0.013 | AN        | 364        | 78       | 41.10    | 0.2      | 22.40    | 2780         | 0.019 | AN        |
| 338        | 78       | 33.24    | 0.05     | 21.24    | 1192         | 0.015 | AN        | 365        | 78       | 37.88    | 0.2      | 22.40    | 2487         | 0.022 | AN        |
| 339        | 78       | 27.21    | 0.05     | 21.24    | 911          | 0.019 | AN        | 366        | 78       | 31.89    | 0.2      | 22.33    | 1996         | 0.028 | AN        |
| 340        | 78       | 24.50    | 0.05     | 21.25    | 776          | 0.021 | AN        | 367        | 78       | 27.15    | 0.2      | 22.33    | 1694         | 0.036 | AN        |
| 341        | 78       | 21.94    | 0.05     | 21.25    | 767          | 0.027 | OLL       | 368        | 78       | 24.49    | 0.2      | 22.40    | 1508         | 0.044 | OLL       |
| 342        | 78       | 20.61    | 0.05     | 21.66    | 769          | 0.030 | SL        | 369        | 78       | 21.63    | 0.2      | 22.40    | 1611         | 0.067 | SL        |
| 343        | 78       | 19.23    | 0.05     | 21.49    | 818          | 0.039 | SL        | 370        | 78       | 20.22    | 0.2      | 22.50    | 1711         | 0.079 | SL        |
| 344        | 78       | 17.97    | 0.05     | 21.35    | 901          | 0.045 | SL        | 371        | 78       | 18.59    | 0.2      | 22.50    | 1807         | 0.090 | SL        |
| 345        | 78       | 16.50    | 0.05     | 21.31    | 978          | 0.050 | SL        | 372        | 78       | 17.41    | 0.2      | 22.50    | 1882         | 0.099 | SL        |
| 346        | 78       | 14.74    | 0.05     | 21.32    | 1045         | 0.058 | SL        | 373        | 78       | 13.57    | 0.2      | 22.50    | 1974         | 0.127 | SL        |
| 347        | 78       | 10.17    | 0.05     | 21.29    | 1349         | 0.087 | SL        | 374        | 78       | 10.83    | 0.2      | 22.50    | 2004         | 0.143 | SL        |
| 348        | 78       | 7.31     | 0.05     | 21.28    | 1661         | 0.117 | SL        | 375        | 78       | 6.97     | 0.2      | 22.50    | 2256         | 0.168 | SL        |
| 349        | 78       | 4.86     | 0.05     | 21.29    | 2004         | 0.118 | SL        | -          | -        | -        | -        | -        | -            | -     | -         |

## C.2.2 Air-Exxsol D80 system

Table C.2. Experimental data for air-Exxsol D80 system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | FR<br>[-] | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | FR<br>[-] |
|-------|------------------|-----------------|-----------------|---------|---------------|-----------|-------|------------------|-----------------|-----------------|---------|---------------|-----------|
| 1     | 30               | 50.48           | 0.02            | 23.91   | 1445          | AN        | 24    | 30               | 20.57           | 0.05            | 21.02   | 447           | SL        |
| 2     | 30               | 43.50           | 0.02            | 23.91   | 1167          | AN        | 25    | 30               | 19.13           | 0.05            | 21.02   | 491           | SL        |
| 3     | 30               | 41.22           | 0.02            | 23.90   | 1064          | AN        | 26    | 30               | 17.79           | 0.05            | 21.05   | 505           | SL        |
| 4     | 30               | 38.04           | 0.02            | 23.88   | 941           | AN        | 27    | 30               | 16.06           | 0.05            | 21.06   | 504           | SL        |
| 5     | 30               | 34.78           | 0.02            | 23.93   | 813           | AN        | 28    | 30               | 9.80            | 0.05            | 21.06   | 532           | SL        |
| 6     | 30               | 32.65           | 0.02            | 23.93   | 740           | AN        | 29    | 30               | 46.81           | 0.1             | 24.64   | 1509          | AN        |
| 7     | 30               | 29.21           | 0.02            | 23.91   | 610           | AN        | 30    | 30               | 44.75           | 0.1             | 24.66   | 1478          | AN        |
| 8     | 30               | 26.90           | 0.02            | 23.92   | 521           | AN        | 31    | 30               | 41.72           | 0.1             | 24.61   | 1390          | AN        |
| 9     | 30               | 25.04           | 0.02            | 23.94   | 446           | AN        | 32    | 30               | 38.68           | 0.1             | 24.56   | 1247          | AN        |
| 10    | 30               | 23.24           | 0.02            | 23.94   | 403           | AN        | 34    | 30               | 31.72           | 0.1             | 24.61   | 910           | AN        |
| 11    | 30               | 21.70           | 0.02            | 23.97   | 374           | AN        | 35    | 30               | 28.80           | 0.1             | 24.59   | 760           | AN        |
| 12    | 30               | 20.77           | 0.02            | 23.96   | 362           | AN        | 36    | 30               | 26.83           | 0.1             | 24.53   | 665           | AN        |
| 13    | 30               | 19.69           | 0.02            | 23.96   | 357           | AN        | 37    | 30               | 24.06           | 0.1             | 24.56   | 530           | AN        |
| 14    | 30               | 18.49           | 0.02            | 23.96   | 370           | OLL       | 38    | 30               | 22.43           | 0.1             | 24.61   | 466           | OLL       |
| 15    | 30               | 16.89           | 0.02            | 23.97   | 416           | SL        | 39    | 30               | 21.23           | 0.1             | 24.61   | 481           | SL        |
| 16    | 30               | 15.66           | 0.02            | 23.94   | 425           | SL        | 40    | 30               | 20.00           | 0.1             | 24.59   | 519           | SL        |
| 17    | 30               | 13.75           | 0.02            | 23.64   | 425           | SL        | 41    | 30               | 18.62           | 0.1             | 24.53   | 562           | SL        |
| 18    | 30               | 9.64            | 0.02            | 23.97   | 459           | SL        | 42    | 30               | 17.47           | 0.1             | 24.60   | 624           | SL        |
| 19    | 30               | 40.37           | 0.05            | 20.99   | 1159          | AN        | 43    | 30               | 15.94           | 0.1             | 24.58   | 710           | SL        |
| 20    | 30               | 33.37           | 0.05            | 21.01   | 851           | AN        | 44    | 30               | 14.27           | 0.1             | 24.55   | 691           | SL        |
| 21    | 30               | 27.77           | 0.05            | 21.01   | 628           | AN        | 45    | 30               | 10.94           | 0.1             | 24.62   | 704           | SL        |
| 22    | 30               | 24.08           | 0.05            | 21.01   | 485           | AN        | 46    | 30               | 38.45           | 0.2             | 18.75   | 1461          | AN        |
| 23    | 30               | 21.93           | 0.05            | 21.00   | 418           | OLL       | 47    | 30               | 31.27           | 0.2             | 18.80   | 1028          | AN        |

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Table C.2. (*cont.*) Experimental data for air-Exxsol D80 system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|-----------|------------|----------|----------|----------|----------|--------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]       |
| 48         | 30       | 24.27    | 0.2      | 18.81    | 685          | AN        | 75         | 45       | 22.45    | 0.04     | 18.47    | 2017         | SL        |
| 49         | 30       | 21.35    | 0.2      | 18.81    | 620          | OLL       | 76         | 45       | 21.09    | 0.04     | 18.47    | 2047         | SL        |
| 50         | 30       | 19.27    | 0.2      | 18.82    | 690          | SL        | 77         | 45       | 19.65    | 0.04     | 18.46    | 2114         | SL        |
| 51         | 30       | 17.21    | 0.2      | 18.84    | 848          | SL        | 78         | 45       | 18.26    | 0.04     | 18.45    | 2127         | SL        |
| 52         | 30       | 15.24    | 0.2      | 18.87    | 888          | SL        | 79         | 45       | 16.63    | 0.04     | 18.46    | 2120         | SL        |
| 53         | 30       | 13.49    | 0.2      | 18.94    | 890          | SL        | 80         | 45       | 15.16    | 0.04     | 18.47    | 2112         | SL        |
| 54         | 30       | 10.21    | 0.2      | 18.97    | 888          | SL        | 81         | 45       | 11.01    | 0.04     | 18.41    | 2165         | SL        |
| 55         | 30       | 8.15     | 0.2      | 19.06    | 941          | SL        | 82         | 45       | 7.21     | 0.04     | 18.43    | 2247         | SL        |
| 56         | 45       | 47.19    | 0.02     | 18.22    | 2807         | AN        | 83         | 45       | 45.82    | 0.1      | 18.85    | 3041         | AN        |
| 57         | 45       | 38.32    | 0.02     | 18.21    | 2453         | AN        | 84         | 45       | 38.75    | 0.1      | 18.84    | 2750         | AN        |
| 58         | 45       | 33.31    | 0.02     | 18.26    | 2228         | AN        | 85         | 45       | 33.69    | 0.1      | 18.86    | 2511         | AN        |
| 59         | 45       | 29.39    | 0.02     | 18.27    | 2091         | AN        | 86         | 45       | 28.37    | 0.1      | 18.84    | 2287         | AN        |
| 60         | 45       | 25.00    | 0.02     | 18.52    | 1973         | AN        | 87         | 45       | 24.30    | 0.1      | 18.85    | 2127         | OLL       |
| 61         | 45       | 21.96    | 0.02     | 18.48    | 1926         | OLL       | 88         | 45       | 21.87    | 0.1      | 18.82    | 2162         | SL        |
| 62         | 45       | 19.68    | 0.02     | 18.42    | 1958         | SL        | 89         | 45       | 20.26    | 0.1      | 18.84    | 2208         | SL        |
| 63         | 45       | 18.35    | 0.02     | 18.36    | 1980         | SL        | 90         | 45       | 18.21    | 0.1      | 18.85    | 2256         | SL        |
| 64         | 45       | 17.21    | 0.02     | 18.37    | 1972         | SL        | 91         | 45       | 16.77    | 0.1      | 18.88    | 2230         | SL        |
| 65         | 45       | 15.71    | 0.02     | 18.31    | 1978         | SL        | 92         | 45       | 14.52    | 0.1      | 18.84    | 2226         | SL        |
| 66         | 45       | 12.58    | 0.02     | 18.34    | 2071         | SL        | 93         | 45       | 11.53    | 0.1      | 18.84    | 2286         | SL        |
| 67         | 45       | 9.39     | 0.02     | 18.35    | 2103         | SL        | 94         | 45       | 7.72     | 0.1      | 18.77    | 2332         | SL        |
| 68         | 45       | 5.73     | 0.02     | 18.33    | 2252         | SL        | 95         | 60       | 39.38    | 0.01     | 19.76    | 2606         | AN        |
| 69         | 45       | 46.36    | 0.04     | 18.37    | 2881         | AN        | 96         | 60       | 35.13    | 0.01     | 19.76    | 2441         | AN        |
| 70         | 45       | 39.99    | 0.04     | 18.42    | 2601         | AN        | 97         | 60       | 30.09    | 0.01     | 19.74    | 2259         | AN        |
| 71         | 45       | 35.60    | 0.04     | 18.41    | 2425         | AN        | 98         | 60       | 27.67    | 0.01     | 19.71    | 2193         | AN        |
| 72         | 45       | 29.34    | 0.04     | 18.46    | 2162         | AN        | 99         | 60       | 24.54    | 0.01     | 19.73    | 2103         | AN        |
| 73         | 45       | 25.84    | 0.04     | 18.44    | 2091         | AN        | 100        | 60       | 22.53    | 0.01     | 19.74    | 2050         | AN        |
| 74         | 45       | 24.01    | 0.04     | 18.44    | 2007         | OLL       | 101        | 60       | 19.96    | 0.01     | 19.75    | 1990         | AN        |

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Table C.2. (*cont.*) Experimental data for air-Exxsol D80 system in 60 mm inner diameter acrylic pipe

| <b>Exp</b><br># | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | <b>T</b><br>°C | <b>dp/dx</b><br>Pa/m | <b>FR</b><br>[-] | <b>Exp</b><br># | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | <b>T</b><br>°C | <b>dp/dx</b><br>Pa/m | <b>FR</b><br>[-] |
|-----------------|------------------|-----------------|-----------------|----------------|----------------------|------------------|-----------------|------------------|-----------------|-----------------|----------------|----------------------|------------------|
| 102             | 60               | 18.68           | 0.01            | 19.76          | 1959                 | AN               | 118             | 60               | 8.49            | 0.04            | 19.81          | 2430                 | SL               |
| 103             | 60               | 16.50           | 0.01            | 19.71          | 1912                 | AN               | 119             | 60               | 47.74           | 0.1             | 19.86          | 3484                 | AN               |
| 104             | 60               | 14.77           | 0.01            | 19.71          | 1865                 | OLL              | 120             | 60               | 41.64           | 0.1             | 19.85          | 3335                 | AN               |
| 105             | 60               | 12.06           | 0.01            | 19.71          | 1872                 | SL               | 121             | 60               | 37.96           | 0.1             | 19.87          | 3147                 | AN               |
| 106             | 60               | 8.49            | 0.01            | 19.69          | 1960                 | SL               | 122             | 60               | 33.30           | 0.1             | 19.88          | 2829                 | AN               |
| 107             | 60               | 47.33           | 0.04            | 19.72          | 3074                 | AN               | 123             | 60               | 28.05           | 0.1             | 19.87          | 2526                 | AN               |
| 108             | 60               | 38.58           | 0.04            | 19.73          | 2785                 | AN               | 124             | 60               | 25.97           | 0.1             | 19.88          | 2501                 | AN               |
| 109             | 60               | 31.27           | 0.04            | 19.73          | 2480                 | AN               | 125             | 60               | 24.29           | 0.1             | 19.87          | 2447                 | OLL              |
| 110             | 60               | 25.14           | 0.04            | 19.74          | 2251                 | AN               | 126             | 60               | 22.82           | 0.1             | 19.89          | 2530                 | SL               |
| 111             | 60               | 23.11           | 0.04            | 19.74          | 2222                 | AN               | 127             | 60               | 21.77           | 0.1             | 19.89          | 2563                 | SL               |
| 112             | 60               | 21.86           | 0.04            | 19.75          | 2216                 | OLL              | 128             | 60               | 19.57           | 0.1             | 19.89          | 2605                 | SL               |
| 113             | 60               | 20.19           | 0.04            | 19.76          | 2263                 | SL               | 129             | 60               | 17.53           | 0.1             | 19.90          | 2625                 | SL               |
| 114             | 60               | 18.72           | 0.04            | 19.76          | 2316                 | SL               | 130             | 60               | 16.46           | 0.1             | 19.92          | 2661                 | SL               |
| 115             | 60               | 16.89           | 0.04            | 19.77          | 2277                 | SL               | 131             | 60               | 14.59           | 0.1             | 19.93          | 2620                 | SL               |
| 116             | 60               | 15.40           | 0.04            | 19.78          | 2331                 | SL               | 132             | 60               | 9.70            | 0.1             | 19.92          | 2653                 | SL               |
| 117             | 60               | 12.48           | 0.04            | 19.80          | 2381                 | SL               |                 |                  |                 |                 |                |                      |                  |



### C.2.3 Air-mixed oil system

Table C.3. Experimental data for air-mixed oil flow in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR<br>[-] | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR<br>[-] |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----------|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----------|
| 1     | 10               | 0.26            | 0.03            | -       | 847           | 0.726        | EB        | 27    | 10               | 32.08           | 0.52            | -       | 2003          | 0.050        | AN        |
| 2     | 10               | 0.58            | 0.03            | -       | 639           | 0.562        | EB        | 28    | 10               | 0.26            | 0.85            | -       | 1762          | 0.965        | EB        |
| 3     | 10               | 1.08            | 0.03            | -       | 543           | 0.439        | EB        | 29    | 10               | 0.58            | 0.85            | -       | 1646          | 0.858        | EB        |
| 4     | 10               | 2.29            | 0.03            | -       | 476           | 0.358        | SL        | 30    | 10               | 1.09            | 0.85            | -       | 1574          | 0.745        | SL        |
| 5     | 10               | 5.04            | 0.03            | -       | 390           | 0.257        | SL        | 31    | 10               | 2.32            | 0.85            | -       | 1537          | 0.592        | SL        |
| 6     | 10               | 18.44           | 0.03            | -       | 424           | 0.098        | SW        | 32    | 10               | 5.05            | 0.84            | -       | 1848          | 0.446        | SL        |
| 7     | 10               | 26.73           | 0.02            | -       | 747           | 0.042        | AN        | 33    | 10               | 5.06            | 0.77            | -       | 1782          | 0.431        | SL        |
| 8     | 10               | 36.39           | 0.04            | -       | 967           | 0.054        | AN        | 34    | 10               | 15.13           | 0.83            | -       | 2427          | 0.200        | SW        |
| 9     | 10               | 0.13            | 0.37            | -       | 1454          | 0.965        | EB        | 35    | 10               | 19.42           | 0.78            | -       | 2357          | 0.166        | SW        |
| 10    | 10               | 0.26            | 0.36            | -       | 1317          | 0.891        | EB        | 36    | 10               | 24.90           | 0.82            | -       | 2650          | 0.119        | SW        |
| 11    | 10               | 0.58            | 0.37            | -       | 1135          | 0.745        | EB        | 37    | 10               | 29.77           | 0.78            | -       | 2688          | 0.095        | AN        |
| 12    | 10               | 1.09            | 0.37            | -       | 1026          | 0.634        | EB        | 38    | 10               | 0.13            | 0.98            | -       | 1868          | 1.007        | EB        |
| 13    | 10               | 2.32            | 0.37            | -       | 970           | 0.495        | SL        | 39    | 10               | 0.25            | 0.98            | -       | 1857          | 0.984        | EB        |
| 14    | 10               | 5.42            | 0.37            | 19.80   | 1006          | 0.369        | SL        | 40    | 10               | 0.57            | 0.98            | -       | 1761          | 0.903        | EB        |
| 15    | 10               | 10.89           | 0.35            | 20.53   | 991           | 0.173        | SL        | 41    | 10               | 1.05            | 0.98            | -       | 1713          | 0.793        | SL        |
| 16    | 10               | 15.26           | 0.34            | -       | 1194          | 0.150        | SW        | 42    | 10               | 2.27            | 0.98            | -       | 1715          | 0.635        | SL        |
| 17    | 10               | 19.71           | 0.39            | -       | 1446          | 0.119        | SW        | 43    | 10               | 5.02            | 0.96            | -       | 2125          | 0.492        | SL        |
| 18    | 10               | 25.71           | 0.37            | -       | 1373          | 0.060        | AN        | 44    | 10               | 10.96           | 1.03            | -       | 2596          | 0.252        | SL        |
| 19    | 10               | 30.59           | 0.35            | -       | 1327          | 0.038        | AN        | 45    | 10               | 15.20           | 1.00            | -       | 2676          | 0.210        | SW        |
| 20    | 10               | 0.26            | 0.63            | -       | 1570          | 0.944        | EB        | 46    | 10               | 19.40           | 0.95            | -       | 2676          | 0.171        | SW        |
| 21    | 10               | 0.58            | 0.63            | -       | 1429          | 0.815        | EB        | 47    | 10               | 24.90           | 0.90            | -       | 2710          | 0.131        | SW        |
| 22    | 10               | 1.09            | 0.64            | -       | 1333          | 0.696        | EB        | 48    | 10               | 28.93           | 0.94            | -       | 2714          | 0.112        | SW        |
| 23    | 10               | 2.31            | 0.64            | -       | 1266          | 0.557        | SL        | 49    | 10               | 34.71           | 0.89            | -       | 2714          | 0.092        | SW        |
| 24    | 10               | 5.05            | 0.62            | -       | 1364          | 0.418        | SL        | 50    | 10               | 40.63           | 0.87            | -       | 2714          | 0.061        | AN        |
| 25    | 10               | 19.25           | 0.59            | -       | 1932          | 0.161        | SW        | 51    | 10               | 0.24            | 1.33            | -       | 2122          | 0.997        | EB        |
| 26    | 10               | 24.72           | 0.56            | -       | 1939          | 0.105        | SW        | 52    | 10               | 0.57            | 1.33            | -       | 2108          | 0.943        | EB        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 53         | 10       | 1.08     | 1.33     | -        | 2102         | 0.849                | EB        | 80         | 15       | 0.13     | 0.43     | -        | 2158         | 0.979                | EB        |
| 54         | 10       | 2.29     | 1.32     | -        | 2231         | 0.705                | SL        | 81         | 15       | 0.26     | 0.43     | -        | 1955         | 0.908                | EB        |
| 55         | 10       | 5.05     | 1.30     | -        | 2799         | 0.544                | SL        | 82         | 15       | 0.58     | 0.44     | -        | 1676         | 0.772                | EB        |
| 56         | 10       | 11.67    | 1.26     | -        | 2712         | 0.256                | SL        | 83         | 15       | 1.08     | 0.45     | -        | 1475         | 0.657                | SL        |
| 57         | 10       | 15.08    | 1.19     | -        | 2714         | 0.225                | SL        | 84         | 15       | 2.31     | 0.45     | -        | 1300         | 0.508                | SL        |
| 58         | 10       | 19.22    | 1.17     | -        | 2714         | 0.194                | SW        | 85         | 15       | 5.01     | 0.44     | -        | 1280         | 0.368                | SL        |
| 59         | 10       | 24.60    | 1.13     | -        | 2714         | 0.161                | SW        | 86         | 15       | 7.03     | 0.42     | -        | 1554         | 0.271                | SL        |
| 60         | 10       | 28.61    | 1.10     | -        | 2714         | 0.153                | SW        | 87         | 15       | 12.14    | 0.42     | -        | 1421         | 0.191                | SL        |
| 61         | 10       | 34.10    | 1.06     | -        | 2714         | 0.147                | AN        | 88         | 15       | 17.97    | 0.41     | -        | 1816         | 0.164                | SW        |
| 62         | 10       | 40.99    | 1.03     | -        | 2714         | 0.061                | AN        | 89         | 15       | 24.59    | 0.39     | -        | 1664         | 0.108                | SW        |
| 63         | 15       | 0.12     | 0.05     | -        | 1730         | 0.892                | EB        | 90         | 15       | 32.05    | 0.37     | -        | 1761         | 0.061                | SW        |
| 64         | 15       | 0.25     | 0.05     | -        | 1333         | 0.736                | EB        | 91         | 15       | 35.85    | 0.36     | -        | 2093         | 0.046                | AN        |
| 65         | 15       | 0.57     | 0.05     | -        | 952          | 0.577                | EB        | 92         | 15       | 0.13     | 0.59     | -        | 2291         | 0.992                | EB        |
| 66         | 15       | 1.06     | 0.05     | -        | 796          | 0.467                | SL        | 93         | 15       | 0.25     | 0.59     | -        | 2141         | 0.946                | EB        |
| 67         | 15       | 2.27     | 0.05     | -        | 608          | 0.353                | SL        | 94         | 15       | 0.58     | 0.60     | -        | 1897         | 0.819                | EB        |
| 68         | 15       | 5.02     | 0.05     | -        | 491          | 0.239                | SL        | 95         | 15       | 1.08     | 0.60     | -        | 1708         | 0.695                | SL        |
| 69         | 15       | 0.13     | 0.15     | -        | 1850         | 0.928                | EB        | 96         | 15       | 2.30     | 0.60     | -        | 1505         | 0.548                | SL        |
| 70         | 15       | 0.26     | 0.16     | -        | 1557         | 0.823                | EB        | 97         | 15       | 5.01     | 0.60     | -        | 1654         | 0.394                | SL        |
| 71         | 15       | 0.58     | 0.15     | -        | 1174         | 0.650                | SL        | 98         | 15       | 8.03     | 0.59     | -        | 1908         | 0.276                | SL        |
| 72         | 15       | 1.08     | 0.15     | -        | 1020         | 0.546                | SL        | 99         | 15       | 12.16    | 0.58     | -        | 1947         | 0.223                | SL        |
| 73         | 15       | 2.30     | 0.15     | -        | 847          | 0.422                | SL        | 100        | 15       | 17.75    | 0.56     | -        | 2316         | 0.200                | SL        |
| 74         | 15       | 5.02     | 0.15     | -        | 762          | 0.299                | SL        | 101        | 15       | 24.78    | 0.54     | -        | 2074         | 0.139                | SW        |
| 75         | 15       | 8.39     | 0.16     | -        | 880          | 0.184                | SL        | 102        | 15       | 32.14    | 0.50     | -        | 2089         | 0.084                | SW        |
| 76         | 15       | 12.38    | 0.16     | -        | 860          | 0.162                | SL        | 103        | 15       | 0.13     | 0.84     | -        | 2468         | 0.995                | EB        |
| 77         | 15       | 17.91    | 0.15     | -        | 853          | 0.110                | SW        | 104        | 15       | 0.25     | 0.85     | -        | 2384         | 0.968                | EB        |
| 78         | 15       | 24.77    | 0.14     | -        | 1016         | 0.075                | SW        | 105        | 15       | 0.58     | 0.85     | -        | 2180         | 0.873                | EB        |
| 79         | 15       | 32.13    | 0.12     | -        | 1332         | 0.044                | AN        | 106        | 15       | 1.08     | 0.85     | -        | 2031         | 0.752                | SL        |

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Table C.3. (cont.) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|----|-------|------------------|-----------------|-----------------|---------|---------------|--------------|----|
| 107   | 15               | 2.30            | 0.85            | -       | 1855          | 0.600        | SL | 134   | 15               | 24.38           | 1.13            | -       | 3447          | 0.146        | AN |
| 108   | 15               | 5.01            | 0.85            | -       | 2079          | 0.440        | SL | 135   | 20               | 0.14            | 0.07            | 18.68   | 2290          | 0.903        | EB |
| 109   | 15               | 9.07            | 0.83            | -       | 2444          | 0.283        | SL | 136   | 20               | 0.27            | 0.08            | 18.70   | 1896          | 0.773        | EB |
| 110   | 15               | 12.44           | 0.86            | -       | 2666          | 0.251        | SL | 137   | 20               | 0.62            | 0.10            | 18.72   | 1599          | 0.618        | SL |
| 111   | 15               | 17.75           | 0.83            | -       | 2846          | 0.221        | SL | 138   | 20               | 1.15            | 0.11            | 18.76   | 1565          | 0.509        | SL |
| 112   | 15               | 24.67           | 0.77            | -       | 2746          | 0.133        | AN | 139   | 20               | 2.45            | 0.11            | 18.89   | 1535          | 0.391        | SL |
| 113   | 15               | 32.14           | 0.77            | -       | 3029          | 0.117        | AN | 140   | 20               | 5.38            | 0.11            | 18.95   | 1523          | 0.257        | SL |
| 114   | 15               | 0.13            | 1.05            | -       | 2595          | 0.998        | EB | 141   | 20               | 0.13            | 0.17            | -       | 2461          | 0.946        | EB |
| 115   | 15               | 0.26            | 1.05            | -       | 2559          | 0.976        | EB | 142   | 20               | 0.25            | 0.18            | -       | 2114          | 0.853        | EB |
| 116   | 15               | 0.58            | 1.06            | -       | 2400          | 0.904        | EB | 143   | 20               | 0.58            | 0.19            | -       | 1720          | 0.690        | EB |
| 117   | 15               | 1.08            | 1.06            | -       | 2286          | 0.783        | SL | 144   | 20               | 1.07            | 0.19            | -       | 1629          | 0.588        | SL |
| 118   | 15               | 2.30            | 1.06            | -       | 2190          | 0.627        | SL | 145   | 20               | 2.30            | 0.20            | -       | 1547          | 0.455        | SL |
| 119   | 15               | 5.01            | 1.05            | -       | 2476          | 0.462        | SL | 146   | 20               | 5.02            | 0.20            | -       | 1523          | 0.319        | SL |
| 120   | 15               | 6.91            | 1.05            | -       | 2840          | 0.342        | SL | 147   | 20               | 8.85            | 0.18            | 22.75   | 1210          | 0.204        | SL |
| 121   | 15               | 12.40           | 1.02            | -       | 3019          | 0.248        | SL | 148   | 20               | 12.44           | 0.18            | -       | 1101          | 0.181        | SL |
| 122   | 15               | 17.73           | 0.95            | -       | 3046          | 0.208        | SL | 149   | 20               | 17.76           | 0.17            | -       | 1005          | 0.130        | SW |
| 123   | 15               | 24.45           | 0.91            | -       | 3156          | 0.140        | AN | 150   | 20               | 24.60           | 0.16            | -       | 1175          | 0.091        | SW |
| 124   | 15               | 31.84           | 0.84            | -       | 3311          | 0.118        | AN | 151   | 20               | 32.14           | 0.15            | -       | 1503          | 0.056        | AN |
| 125   | 15               | 0.13            | 1.31            | -       | 2757          | 0.999        | EB | 152   | 20               | 0.13            | 0.41            | -       | 2647          | 0.985        | EB |
| 126   | 15               | 0.26            | 1.32            | -       | 2764          | 0.976        | EB | 153   | 20               | 0.25            | 0.41            | -       | 2438          | 0.918        | EB |
| 127   | 15               | 0.58            | 1.32            | -       | 2677          | 0.921        | EB | 154   | 20               | 0.58            | 0.42            | -       | 2188          | 0.783        | EB |
| 128   | 15               | 1.07            | 1.32            | -       | 2589          | 0.828        | SL | 155   | 20               | 1.06            | 0.43            | -       | 1996          | 0.667        | EB |
| 129   | 15               | 2.28            | 1.31            | -       | 2624          | 0.666        | SL | 156   | 20               | 2.27            | 0.43            | -       | 1734          | 0.526        | SL |
| 130   | 15               | 5.01            | 1.30            | -       | 2983          | 0.503        | SL | 157   | 20               | 5.02            | 0.43            | -       | 1682          | 0.380        | SL |
| 131   | 15               | 7.11            | 1.28            | -       | 3274          | 0.381        | SL | 158   | 20               | 8.87            | 0.44            | -       | 1711          | 0.247        | SL |
| 132   | 15               | 12.10           | 1.21            | -       | 3331          | 0.276        | AN | 159   | 20               | 12.47           | 0.43            | -       | 1585          | 0.198        | SL |
| 133   | 15               | 17.80           | 1.18            | -       | 3423          | 0.216        | AN | 160   | 20               | 17.76           | 0.42            | -       | 1822          | 0.163        | SW |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 161        | 20       | 24.60    | 0.40     | -        | 1844         | 0.117                | SW        | 188        | 20       | 1.08     | 1.04     | -        | 2824         | 0.790                | SL        |
| 162        | 20       | 32.23    | 0.37     | -        | 1830         | 0.070                | AN        | 189        | 20       | 2.29     | 1.04     | -        | 2652         | 0.631                | SL        |
| 163        | 20       | 0.13     | 0.59     | -        | 2961         | 0.996                | EB        | 190        | 20       | 5.01     | 1.03     | -        | 2802         | 0.459                | SL        |
| 164        | 20       | 0.26     | 0.59     | -        | 2778         | 0.957                | EB        | 191        | 20       | 6.91     | 1.03     | -        | 3093         | 0.298                | SL        |
| 165        | 20       | 0.58     | 0.60     | -        | 2473         | 0.842                | EB        | 192        | 20       | 11.86    | 1.01     | -        | 3226         | 0.218                | SL        |
| 166        | 20       | 1.07     | 0.61     | -        | 2260         | 0.723                | SL        | 193        | 20       | 17.68    | 0.95     | -        | 3388         | 0.177                | SW        |
| 167        | 20       | 2.29     | 0.61     | -        | 2030         | 0.574                | SL        | 194        | 20       | 24.40    | 0.89     | -        | 3228         | 0.133                | AN        |
| 168        | 20       | 5.09     | 0.61     | -        | 2043         | 0.417                | SL        | 195        | 20       | 31.74    | 0.84     | -        | 3354         | 0.097                | AN        |
| 169        | 20       | 6.91     | 0.61     | -        | 2060         | 0.299                | SL        | 196        | 20       | 0.13     | 1.30     | -        | 3418         | 1.000                | EB        |
| 170        | 20       | 12.41    | 0.60     | -        | 2109         | 0.225                | SL        | 197        | 20       | 0.25     | 1.30     | -        | 3412         | 0.983                | EB        |
| 171        | 20       | 17.72    | 0.58     | -        | 2547         | 0.200                | SW        | 198        | 20       | 0.58     | 1.30     | -        | 3284         | 0.931                | EB        |
| 172        | 20       | 24.76    | 0.55     | -        | 2306         | 0.150                | SW        | 199        | 20       | 1.07     | 1.30     | -        | 3147         | 0.837                | EB        |
| 173        | 20       | 31.68    | 0.56     | -        | 2395         | 0.108                | AN        | 200        | 20       | 2.27     | 1.30     | -        | 3087         | 0.675                | SL        |
| 174        | 20       | 0.13     | 0.83     | -        | 3134         | 0.996                | EB        | 201        | 20       | 5.01     | 1.29     | -        | 3391         | 0.508                | SL        |
| 175        | 20       | 0.26     | 0.83     | -        | 3026         | 0.969                | EB        | 202        | 20       | 7.12     | 1.28     | -        | 3692         | 0.321                | SL        |
| 176        | 20       | 0.58     | 0.84     | -        | 2768         | 0.876                | EB        | 203        | 20       | 11.92    | 1.22     | -        | 3799         | 0.231                | SL        |
| 177        | 20       | 1.07     | 0.84     | -        | 2559         | 0.758                | SL        | 204        | 20       | 17.55    | 1.16     | -        | 3829         | 0.178                | AN        |
| 178        | 20       | 2.30     | 0.85     | -        | 2342         | 0.603                | SL        | 205        | 20       | 24.80    | 1.12     | -        | 3963         | 0.142                | AN        |
| 179        | 20       | 5.01     | 0.84     | -        | 2440         | 0.435                | SL        | 206        | 20       | 31.36    | 1.06     | -        | 4119         | 0.110                | AN        |
| 180        | 20       | 6.92     | 0.85     | -        | 2662         | 0.286                | SL        | 207        | 25       | 0.13     | 0.14     | -        | 2954         | 0.91                 | EB        |
| 181        | 20       | 12.36    | 0.83     | -        | 2837         | 0.207                | SL        | 208        | 25       | 0.26     | 0.14     | -        | 2523         | 0.81                 | EB        |
| 182        | 20       | 17.64    | 0.79     | -        | 3045         | 0.176                | SW        | 209        | 25       | 0.58     | 0.15     | -        | 2006         | 0.65                 | EB        |
| 183        | 20       | 24.56    | 0.73     | -        | 2773         | 0.126                | AN        | 210        | 25       | 1.07     | 0.15     | -        | 1736         | 0.53                 | EB        |
| 184        | 20       | 31.51    | 0.69     | -        | 2797         | 0.081                | AN        | 211        | 25       | 2.28     | 0.16     | -        | 1416         | 0.38                 | SL        |
| 185        | 20       | 0.13     | 1.03     | -        | 3258         | 0.999                | EB        | 212        | 25       | 5.03     | 0.16     | -        | 1095         | 0.24                 | SL        |
| 186        | 20       | 0.25     | 1.03     | -        | 3199         | 0.976                | EB        | 213        | 25       | 6.92     | 0.16     | -        | 1237         | 0.20                 | SL        |
| 187        | 20       | 0.58     | 1.04     | -        | 2991         | 0.901                | EB        | 214        | 25       | 12.03    | 0.16     | -        | 1099         | 0.16                 | SL        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR<br>[-] | Exp # | $\theta$<br>° FH | $v_{sg}$<br>m/s | $v_{sl}$<br>m/s | T<br>°C | dp/dx<br>Pa/m | $H_L$<br>[-] | FR<br>[-] |
|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----------|-------|------------------|-----------------|-----------------|---------|---------------|--------------|-----------|
| 215   | 25               | 17.70           | 0.15            | -       | 1069          | 0.114        | SL        | 242   | 25               | 0.57            | 0.84            | -       | 3242          | 0.886        | EB        |
| 216   | 25               | 24.60           | 0.15            | -       | 1182          | 0.079        | AN        | 243   | 25               | 1.07            | 0.84            | -       | 2954          | 0.770        | EB        |
| 217   | 25               | 32.42           | 0.13            | -       | 1456          | 0.049        | AN        | 244   | 25               | 2.29            | 0.85            | -       | 2654          | 0.593        | SL        |
| 218   | 25               | 0.13            | 0.36            | -       | 3253          | 0.950        | EB        | 245   | 25               | 5.04            | 0.84            | -       | 2593          | 0.422        | SL        |
| 219   | 25               | 0.25            | 0.36            | -       | 2953          | 0.895        | EB        | 246   | 25               | 6.93            | 0.83            | -       | 2798          | 0.322        | SL        |
| 220   | 25               | 0.57            | 0.37            | -       | 2512          | 0.763        | EB        | 247   | 25               | 12.00           | 0.82            | -       | 2909          | 0.250        | SL        |
| 221   | 25               | 1.07            | 0.38            | -       | 2208          | 0.635        | EB        | 248   | 25               | 17.59           | 0.79            | -       | 3202          | 0.216        | SL        |
| 222   | 25               | 2.29            | 0.39            | -       | 1802          | 0.455        | SL        | 249   | 25               | 24.27           | 0.74            | -       | 2973          | 0.170        | AN        |
| 223   | 25               | 5.03            | 0.39            | -       | 1658          | 0.324        | SL        | 250   | 25               | 31.85           | 0.72            | -       | 3061          | 0.119        | AN        |
| 224   | 25               | 6.90            | 0.40            | -       | 1762          | 0.261        | SL        | 251   | 25               | 0.13            | 1.03            | -       | 3884          | 0.998        | EB        |
| 225   | 25               | 12.09           | 0.39            | -       | 1700          | 0.197        | SL        | 252   | 25               | 0.25            | 1.03            | -       | 3779          | 0.981        | EB        |
| 226   | 25               | 17.51           | 0.38            | -       | 1575          | 0.139        | SL        | 253   | 25               | 0.57            | 1.04            | -       | 3527          | 0.922        | EB        |
| 227   | 25               | 24.70           | 0.36            | -       | 1676          | 0.096        | AN        | 254   | 25               | 1.07            | 1.04            | -       | 3282          | 0.823        | EB        |
| 228   | 25               | 31.94           | 0.34            | -       | 1794          | 0.059        | AN        | 255   | 25               | 2.29            | 1.05            | -       | 3018          | 0.647        | SL        |
| 229   | 25               | 0.13            | 0.60            | -       | 3519          | 0.990        | EB        | 256   | 25               | 5.04            | 1.04            | -       | 3066          | 0.467        | SL        |
| 230   | 25               | 0.25            | 0.61            | -       | 3307          | 0.953        | EB        | 257   | 25               | 8.48            | 1.01            | -       | 3289          | 0.323        | SL        |
| 231   | 25               | 0.57            | 0.62            | -       | 2937          | 0.847        | EB        | 258   | 25               | 12.74           | 0.98            | -       | 3403          | 0.259        | SL        |
| 232   | 25               | 1.08            | 0.63            | -       | 2641          | 0.718        | EB        | 259   | 25               | 17.85           | 0.93            | -       | 3591          | 0.223        | SL        |
| 233   | 25               | 2.29            | 0.64            | -       | 2280          | 0.530        | SL        | 260   | 25               | 24.44           | 0.88            | -       | 3446          | 0.180        | AN        |
| 234   | 25               | 5.04            | 0.64            | -       | 2204          | 0.381        | SL        | 261   | 25               | 31.94           | 0.84            | -       | 3564          | 0.140        | AN        |
| 235   | 25               | 7.13            | 0.63            | -       | 2356          | 0.291        | SL        | 262   | 25               | 0.13            | 1.15            | -       | 3902          | 0.997        | EB        |
| 236   | 25               | 12.31           | 0.62            | -       | 2248          | 0.209        | SL        | 263   | 25               | 0.25            | 1.21            | -       | 3916          | 0.984        | EB        |
| 237   | 25               | 17.66           | 0.60            | -       | 2638          | 0.186        | SL        | 264   | 25               | 0.58            | 1.20            | -       | 3716          | 0.935        | EB        |
| 238   | 25               | 24.28           | 0.58            | -       | 2536          | 0.148        | AN        | 265   | 25               | 1.07            | 1.27            | -       | 3582          | 0.861        | EB        |
| 239   | 25               | 31.63           | 0.54            | -       | 2459          | 0.093        | AN        | 266   | 25               | 2.29            | 1.27            | -       | 3386          | 0.698        | EB        |
| 240   | 25               | 0.13            | 0.82            | -       | 3707          | 0.993        | EB        | 267   | 25               | 5.03            | 1.25            | -       | 3514          | 0.509        | SL        |
| 241   | 25               | 0.26            | 0.83            | -       | 3544          | 0.968        | EB        | 268   | 30               | 0.14            | 0.11            | 22.91   | 3525          | 0.919        | EB        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 269        | 30       | 0.27     | 0.12     | 22.88    | 2922         | 0.807                | EB        | 296        | 30       | 6.97     | 0.45     | 22.81    | 2173         | 0.246                | SL        |
| 270        | 30       | 0.63     | 0.13     | 22.89    | 2331         | 0.646                | EB        | 297        | 30       | 12.30    | 0.45     | 22.80    | 2058         | 0.186                | SL        |
| 271        | 30       | 1.16     | 0.13     | 22.90    | 2028         | 0.527                | EB        | 298        | 30       | 17.67    | 0.44     | 22.79    | 1939         | 0.131                | SL        |
| 272        | 30       | 2.47     | 0.14     | 22.91    | 1601         | 0.359                | SL        | 299        | 30       | 24.41    | 0.42     | 22.79    | 2119         | 0.097                | AN        |
| 273        | 30       | 5.45     | 0.14     | 22.90    | 1391         | 0.232                | SL        | 300        | 30       | 31.91    | 0.39     | 22.78    | 2039         | 0.057                | AN        |
| 274        | 30       | 9.64     | 0.14     | 22.71    | 1421         | 0.153                | SL        | 301        | 30       | 0.14     | 0.59     | 22.76    | 4065         | 0.984                | EB        |
| 275        | 30       | 14.55    | 0.14     | 22.80    | 1299         | 0.126                | SL        | 302        | 30       | 0.28     | 0.60     | 22.76    | 3852         | 0.950                | EB        |
| 276        | 30       | 20.55    | 0.14     | 22.84    | 1252         | 0.090                | SL        | 303        | 30       | 0.63     | 0.62     | 22.76    | 3395         | 0.850                | EB        |
| 277        | 30       | 26.69    | 0.13     | 22.87    | 1355         | 0.066                | AN        | 304        | 30       | 1.17     | 0.63     | 22.75    | 3062         | 0.725                | EB        |
| 278        | 30       | 31.64    | 0.12     | 22.90    | 1475         | 0.044                | AN        | 305        | 30       | 2.50     | 0.64     | 22.75    | 2651         | 0.537                | SL        |
| 279        | 30       | 0.14     | 0.17     | 22.68    | 3611         | 0.930                | EB        | 306        | 30       | 5.45     | 0.64     | 22.75    | 2507         | 0.384                | SL        |
| 280        | 30       | 0.28     | 0.18     | 22.69    | 3084         | 0.839                | EB        | 307        | 30       | 7.14     | 0.63     | 22.75    | 2515         | 0.282                | SL        |
| 281        | 30       | 0.63     | 0.18     | 22.70    | 2476         | 0.673                | EB        | 308        | 30       | 11.95    | 0.63     | 22.74    | 2455         | 0.204                | SL        |
| 282        | 30       | 1.17     | 0.19     | 22.73    | 2113         | 0.549                | EB        | 309        | 30       | 17.66    | 0.60     | 22.74    | 2757         | 0.170                | SL        |
| 283        | 30       | 2.50     | 0.19     | 22.74    | 1752         | 0.388                | SL        | 310        | 30       | 24.34    | 0.57     | 22.73    | 2804         | 0.139                | AN        |
| 284        | 30       | 5.46     | 0.20     | 22.76    | 1467         | 0.248                | SL        | 311        | 30       | 31.59    | 0.54     | 22.72    | 2605         | 0.088                | AN        |
| 285        | 30       | 7.01     | 0.20     | 22.77    | 1541         | 0.197                | SL        | 312        | 30       | 0.13     | 0.90     | 22.69    | 4360         | 0.996                | EB        |
| 286        | 30       | 12.07    | 0.19     | 22.77    | 1462         | 0.151                | SL        | 313        | 30       | 0.26     | 0.90     | 22.68    | 4199         | 0.971                | EB        |
| 287        | 30       | 17.72    | 0.19     | 22.76    | 1315         | 0.103                | SL        | 314        | 30       | 0.59     | 0.91     | 22.68    | 3847         | 0.898                | EB        |
| 288        | 30       | 24.49    | 0.19     | 22.78    | 1351         | 0.068                | AN        | 315        | 30       | 1.11     | 0.92     | 22.68    | 3514         | 0.785                | EB        |
| 289        | 30       | 31.90    | 0.18     | 22.78    | 1719         | 0.045                | AN        | 316        | 30       | 2.37     | 0.92     | 22.67    | 3156         | 0.605                | SL        |
| 290        | 30       | 0.14     | 0.42     | 22.83    | 3853         | 0.963                | EB        | 317        | 30       | 5.23     | 0.92     | 22.67    | 3029         | 0.424                | SL        |
| 291        | 30       | 0.27     | 0.43     | 22.82    | 3544         | 0.917                | EB        | 318        | 30       | 6.90     | 0.91     | 22.65    | 3215         | 0.321                | SL        |
| 292        | 30       | 0.63     | 0.44     | 22.82    | 3063         | 0.792                | EB        | 319        | 30       | 12.36    | 0.87     | 22.65    | 3291         | 0.212                | SL        |
| 293        | 30       | 1.17     | 0.45     | 22.80    | 2714         | 0.660                | EB        | 320        | 30       | 17.47    | 0.83     | 22.65    | 3584         | 0.193                | SL        |
| 294        | 30       | 2.49     | 0.46     | 22.09    | 2246         | 0.471                | SL        | 321        | 30       | 24.18    | 0.80     | 22.64    | 3393         | 0.152                | AN        |
| 295        | 30       | 5.44     | 0.46     | 22.81    | 2044         | 0.331                | SL        | 322        | 30       | 31.50    | 0.73     | 22.62    | 3294         | 0.107                | AN        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 323        | 30       | 0.10     | 1.05     | 22.79    | 4473         | 1.001                | EB        | 350        | 45       | 5.02     | 0.45     | -        | 3018         | 0.316                | SL        |
| 324        | 30       | 0.20     | 1.05     | 22.82    | 4341         | 0.984                | EB        | 351        | 45       | 6.90     | 0.45     | -        | 3019         | 0.246                | SL        |
| 325        | 30       | 0.46     | 1.06     | 22.84    | 4045         | 0.925                | EB        | 352        | 45       | 12.14    | 0.44     | -        | 3000         | 0.184                | SL        |
| 326        | 30       | 0.88     | 1.07     | 22.85    | 3729         | 0.826                | EB        | 353        | 45       | 17.64    | 0.43     | -        | 2929         | 0.138                | SL        |
| 327        | 30       | 1.90     | 1.07     | 22.87    | 3443         | 0.650                | SL        | 354        | 45       | 24.47    | 0.41     | -        | 2913         | 0.099                | AN        |
| 328        | 30       | 4.37     | 1.06     | 22.88    | 3429         | 0.455                | SL        | 355        | 45       | 31.91    | 0.38     | -        | 2905         | 0.067                | AN        |
| 329        | 30       | 6.92     | 1.27     | 23.07    | 4143         | 0.376                | SL        | 356        | 45       | 0.13     | 0.61     | -        | 5675         | 0.985                | CB        |
| 330        | 30       | 12.21    | 1.20     | 23.07    | 4237         | 0.272                | SL        | 357        | 45       | 0.25     | 0.61     | -        | 5406         | 0.957                | CB        |
| 331        | 30       | 17.65    | 1.15     | 23.07    | 4390         | 0.221                | SL        | 358        | 45       | 0.57     | 0.63     | -        | 5012         | 0.880                | CB        |
| 332        | 30       | 24.20    | 1.12     | 23.08    | 4464         | 0.179                | AN        | 359        | 45       | 1.07     | 0.65     | -        | 4281         | 0.758                | SL        |
| 333        | 30       | 32.03    | 1.07     | 23.10    | 4679         | 0.163                | AN        | 360        | 45       | 2.28     | 0.67     | -        | 3634         | 0.567                | SL        |
| 334        | 45       | 0.14     | 0.12     | -        | 5357         | 0.961                | CB        | 361        | 45       | 5.03     | 0.67     | -        | 3329         | 0.390                | SL        |
| 335        | 45       | 0.27     | 0.13     | -        | 4684         | 0.882                | CB        | 362        | 45       | 6.90     | 0.67     | -        | 3434         | 0.302                | SL        |
| 336        | 45       | 0.60     | 0.14     | -        | 3669         | 0.715                | CB        | 363        | 45       | 12.20    | 0.66     | -        | 3310         | 0.214                | SL        |
| 337        | 45       | 1.13     | 0.15     | -        | 3154         | 0.577                | SL        | 364        | 45       | 17.55    | 0.64     | -        | 3260         | 0.169                | SL        |
| 338        | 45       | 2.40     | 0.16     | -        | 2924         | 0.398                | SL        | 365        | 45       | 24.37    | 0.62     | -        | 3728         | 0.146                | AN        |
| 339        | 45       | 5.30     | 0.16     | -        | 2906         | 0.252                | SL        | 366        | 45       | 31.80    | 0.59     | -        | 3655         | 0.105                | AN        |
| 340        | 45       | 7.33     | 0.16     | -        | 2905         | 0.190                | SL        | 367        | 45       | 0.13     | 0.82     | -        | 5891         | 0.993                | CB        |
| 341        | 45       | 12.26    | 0.16     | -        | 2904         | 0.146                | SL        | 368        | 45       | 0.25     | 0.83     | -        | 5630         | 0.967                | CB        |
| 342        | 45       | 17.75    | 0.16     | -        | 2904         | 0.110                | SL        | 369        | 45       | 0.57     | 0.84     | -        | 5227         | 0.903                | CB        |
| 343        | 45       | 24.56    | 0.15     | -        | 2904         | 0.079                | AN        | 370        | 45       | 1.07     | 0.85     | -        | 4654         | 0.791                | CB        |
| 344        | 45       | 32.06    | 0.14     | -        | 2904         | 0.053                | AN        | 371        | 45       | 2.29     | 0.87     | -        | 4071         | 0.609                | SL        |
| 345        | 45       | 0.13     | 0.36     | -        | 5467         | 0.954                | CB        | 372        | 45       | 5.02     | 0.87     | -        | 3757         | 0.416                | SL        |
| 346        | 45       | 0.25     | 0.39     | -        | 5191         | 0.914                | CB        | 373        | 45       | 6.90     | 0.86     | -        | 3866         | 0.316                | SL        |
| 347        | 45       | 0.57     | 0.41     | -        | 4549         | 0.804                | CB        | 374        | 45       | 12.06    | 0.84     | -        | 3742         | 0.221                | SL        |
| 348        | 45       | 1.07     | 0.43     | -        | 3764         | 0.660                | SL        | 375        | 45       | 17.62    | 0.79     | -        | 4001         | 0.177                | SL        |
| 349        | 45       | 2.28     | 0.44     | -        | 3162         | 0.472                | SL        | 376        | 45       | 24.38    | 0.75     | -        | 4370         | 0.155                | AN        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 377        | 45       | 31.38    | 0.73     | -        | 4263         | 0.121                | AN        | 404        | 60       | 24.36    | 0.19     | -        | 4213         | 0.104                | AN        |
| 378        | 45       | 0.13     | 1.07     | -        | 6128         | 0.999                | CB        | 405        | 60       | 31.81    | 0.18     | -        | 4213         | 0.070                | AN        |
| 379        | 45       | 0.25     | 1.07     | -        | 5903         | 0.981                | CB        | 406        | 60       | 0.13     | 0.29     | -        | 6800         | 0.983                | CB        |
| 380        | 45       | 0.57     | 1.08     | -        | 5565         | 0.930                | CB        | 407        | 60       | 0.25     | 0.31     | -        | 6523         | 0.944                | CB        |
| 381        | 45       | 1.07     | 1.09     | -        | 5070         | 0.845                | CB        | 408        | 60       | 0.57     | 0.34     | -        | 5999         | 0.850                | CB        |
| 382        | 45       | 2.29     | 1.10     | -        | 4540         | 0.672                | SL        | 409        | 60       | 1.07     | 0.38     | -        | 4762         | 0.697                | CB        |
| 383        | 45       | 5.03     | 1.10     | -        | 4314         | 0.471                | SL        | 410        | 60       | 2.28     | 0.41     | -        | 4214         | 0.511                | SL        |
| 384        | 45       | 7.01     | 1.08     | -        | 4471         | 0.350                | SL        | 411        | 60       | 5.01     | 0.43     | -        | 4213         | 0.346                | SL        |
| 385        | 45       | 12.04    | 1.03     | -        | 4371         | 0.257                | SL        | 412        | 60       | 6.91     | 0.43     | -        | 4213         | 0.271                | SL        |
| 386        | 45       | 17.55    | 0.98     | -        | 4745         | 0.215                | SL        | 413        | 60       | 11.96    | 0.42     | -        | 4213         | 0.208                | SL        |
| 387        | 45       | 24.28    | 0.95     | -        | 5208         | 0.183                | AN        | 414        | 60       | 17.68    | 0.41     | -        | 4213         | 0.161                | SL        |
| 388        | 45       | 31.47    | 0.91     | -        | 5011         | 0.152                | AN        | 415        | 60       | 24.52    | 0.39     | -        | 4213         | 0.119                | AN        |
| 389        | 45       | 0.12     | 1.24     | -        | 6268         | 1.003                | CB        | 416        | 60       | 31.89    | 0.36     | -        | 4213         | 0.087                | AN        |
| 390        | 45       | 0.24     | 1.26     | -        | 6116         | 0.989                | CB        | 417        | 60       | 0.13     | 0.62     | -        | 7028         | 0.990                | CB        |
| 391        | 45       | 0.57     | 1.22     | -        | 5760         | 0.941                | CB        | 418        | 60       | 0.25     | 0.64     | -        | 6677         | 0.962                | CB        |
| 392        | 45       | 1.07     | 1.27     | -        | 5367         | 0.874                | SL        | 419        | 60       | 0.57     | 0.65     | -        | 6328         | 0.898                | CB        |
| 393        | 45       | 2.28     | 1.28     | -        | 4921         | 0.707                | SL        | 420        | 60       | 1.07     | 0.67     | -        | 5843         | 0.804                | CB        |
| 394        | 45       | 5.02     | 1.28     | -        | 4714         | 0.497                | SL        | 421        | 60       | 2.27     | 0.71     | -        | 4335         | 0.589                | SL        |
| 395        | 60       | 0.14     | 0.11     | -        | 6586         | 0.962                | CB        | 422        | 60       | 5.01     | 0.73     | -        | 4247         | 0.398                | SL        |
| 396        | 60       | 0.26     | 0.13     | -        | 6079         | 0.920                | CB        | 423        | 60       | 7.15     | 0.72     | -        | 4265         | 0.309                | SL        |
| 397        | 60       | 0.60     | 0.16     | -        | 4984         | 0.745                | CB        | 424        | 60       | 12.10    | 0.71     | -        | 4232         | 0.233                | SL        |
| 398        | 60       | 1.13     | 0.17     | -        | 4236         | 0.603                | SL        | 425        | 60       | 17.45    | 0.69     | -        | 4237         | 0.190                | SL        |
| 399        | 60       | 2.41     | 0.19     | -        | 4213         | 0.415                | SL        | 426        | 60       | 24.33    | 0.62     | -        | 4275         | 0.160                | SL        |
| 400        | 60       | 5.28     | 0.20     | -        | 4213         | 0.286                | SL        | 427        | 60       | 31.78    | 0.62     | -        | 4341         | 0.124                | AN        |
| 401        | 60       | 6.94     | 0.21     | -        | 4213         | 0.215                | SL        | 428        | 60       | 0.13     | 0.80     | -        | 7114         | 0.993                | CB        |
| 402        | 60       | 12.05    | 0.20     | -        | 4213         | 0.170                | SL        | 429        | 60       | 0.25     | 0.82     | -        | 6837         | 0.972                | CB        |
| 403        | 60       | 17.62    | 0.20     | -        | 4213         | 0.140                | SL        | 430        | 60       | 0.57     | 0.83     | -        | 6331         | 0.912                | CB        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 431        | 60       | 1.06     | 0.85     | -        | 6002         | 0.831                | CB        | 458        | 70       | 0.57     | 0.15     | -        | -            | 0.665                | CB        |
| 432        | 60       | 2.29     | 0.88     | -        | 4646         | 0.620                | SL        | 459        | 70       | 1.04     | 0.16     | -        | -            | 0.494                | SL        |
| 433        | 60       | 5.02     | 0.89     | -        | 4366         | 0.431                | SL        | 460        | 70       | 2.24     | 0.18     | -        | -            | 0.299                | SL        |
| 434        | 60       | 7.31     | 0.88     | -        | 4338         | 0.337                | SL        | 461        | 70       | 5.00     | 0.19     | -        | -            | 0.162                | SL        |
| 435        | 60       | 12.00    | 0.87     | -        | 4321         | 0.253                | SL        | 462        | 70       | 5.05     | 0.19     | -        | -            | 0.136                | SL        |
| 436        | 60       | 17.34    | 0.83     | -        | 4409         | 0.207                | SL        | 463        | 70       | 8.62     | 0.19     | -        | -            | 0.085                | CH        |
| 437        | 60       | 24.05    | 0.79     | -        | 4771         | 0.173                | SL        | 464        | 70       | 13.76    | 0.19     | -        | -            | 0.061                | CH        |
| 438        | 60       | 31.65    | 0.73     | -        | 5043         | 0.145                | AN        | 465        | 70       | 17.95    | 0.19     | -        | -            | 0.052                | AN        |
| 439        | 60       | 0.13     | 1.03     | -        | 7315         | 0.988                | CB        | 466        | 70       | 25.01    | 0.18     | -        | -            | 0.036                | AN        |
| 440        | 60       | 0.25     | 1.03     | -        | 7033         | 0.968                | CB        | 467        | 70       | 34.01    | 0.17     | -        | -            | 0.025                | AN        |
| 441        | 60       | 0.57     | 1.04     | -        | 6604         | 0.918                | CB        | 468        | 70       | 0.13     | 0.25     | -        | 7372         | 0.949                | CB        |
| 442        | 60       | 1.07     | 1.05     | -        | 6257         | 0.836                | CB        | 469        | 70       | 0.57     | 0.34     | -        | 6383         | 0.794                | CB        |
| 443        | 60       | 2.28     | 1.08     | -        | 5097         | 0.648                | SL        | 470        | 70       | 1.06     | 0.34     | -        | -            | 0.590                | SL        |
| 444        | 60       | 5.02     | 1.08     | -        | 4702         | 0.454                | SL        | 471        | 70       | 2.25     | 0.37     | -        | -            | 0.362                | SL        |
| 445        | 60       | 7.14     | 1.07     | -        | 4702         | 0.350                | SL        | 472        | 70       | 5.01     | 0.39     | -        | -            | 0.203                | SL        |
| 446        | 60       | 12.34    | 1.03     | -        | 4604         | 0.260                | SL        | 473        | 70       | 6.35     | 0.38     | -        | -            | 0.150                | SL        |
| 447        | 60       | 17.41    | 0.97     | -        | 4838         | 0.212                | SL        | 474        | 70       | 9.87     | 0.38     | -        | -            | 0.108                | CH        |
| 448        | 60       | 25.82    | 0.91     | -        | 5765         | 0.176                | SL        | 475        | 70       | 13.88    | 0.38     | -        | -            | 0.084                | CH        |
| 449        | 60       | 30.86    | 0.89     | -        | 6071         | 0.161                | AN        | 476        | 70       | 17.95    | 0.37     | -        | -            | 0.069                | CH        |
| 450        | 60       | 0.13     | 1.21     | -        | 7487         | 0.998                | CB        | 477        | 70       | 24.72    | 0.35     | -        | -            | 0.049                | AN        |
| 451        | 60       | 0.25     | 1.22     | -        | 7260         | 0.983                | CB        | 478        | 70       | 30.56    | 0.34     | -        | -            | 0.037                | AN        |
| 452        | 60       | 0.57     | 1.24     | -        | 6838         | 0.941                | CB        | 479        | 70       | 0.13     | 0.56     | -        | 7315         | 0.957                | CB        |
| 453        | 60       | 1.07     | 1.24     | -        | 6424         | 0.868                | CB        | 480        | 70       | 0.26     | 0.57     | -        | 7231         | 0.929                | CB        |
| 454        | 60       | 2.28     | 1.26     | -        | 5515         | 0.693                | SL        | 481        | 70       | 0.58     | 0.60     | -        | 6779         | 0.841                | CB        |
| 455        | 60       | 5.02     | 1.26     | -        | 5132         | 0.485                | SL        | 482        | 70       | 1.08     | 0.62     | -        | 6311         | 0.706                | CB        |
| 456        | 70       | 0.12     | 0.10     | -        | 7194         | 0.951                | CB        | 483        | 70       | 2.28     | 0.67     | -        | -            | 0.460                | SL        |
| 457        | 70       | 0.25     | 0.13     | -        | 6270         | 0.858                | CB        | 484        | 70       | 5.02     | 0.69     | -        | -            | 0.267                | SL        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 485        | 70       | 5.68     | 0.69     | -        | -            | 0.208                | SL        | 512        | 70       | 12.34    | 1.14     | -        | 4845         | 0.153                | SL        |
| 486        | 70       | 9.74     | 0.68     | -        | -            | 0.140                | CH        | 513        | 70       | 17.88    | 1.10     | -        | 5328         | 0.117                | CH        |
| 487        | 70       | 14.93    | 0.66     | -        | -            | 0.098                | CH        | 514        | 70       | 24.93    | 1.06     | -        | 7046         | 0.103                | CH        |
| 488        | 70       | 20.49    | 0.62     | -        | -            | 0.075                | CH        | 515        | 70       | 31.77    | 1.01     | -        | 7319         | 0.085                | AN        |
| 489        | 70       | 28.13    | 0.61     | -        | -            | 0.060                | AN        | 516        | 70       | 36.14    | 1.02     | -        | 7547         | 0.082                | AN        |
| 490        | 70       | 31.47    | 0.59     | -        | -            | 0.050                | AN        | 517        | 78       | 0.13     | 0.11     | -        | 7704         | 0.866                | CB        |
| 491        | 70       | 0.10     | 0.91     | -        | 7733         | 0.966                | CB        | 518        | 78       | 0.26     | 0.13     | -        | 6814         | 0.782                | CB        |
| 492        | 70       | 0.20     | 0.92     | -        | 7231         | 0.938                | CB        | 519        | 78       | 0.58     | 0.15     | -        | 5373         | 0.596                | CB        |
| 493        | 70       | 0.45     | 0.93     | -        | 6985         | 0.870                | CB        | 520        | 78       | 1.06     | 0.17     | -        | 5136         | 0.418                | SL        |
| 494        | 70       | 0.85     | 0.94     | -        | 6615         | 0.772                | CB        | 521        | 78       | 2.27     | 0.19     | -        | 5136         | 0.243                | SL        |
| 495        | 70       | 1.86     | 0.97     | -        | -            | 0.529                | SL        | 522        | 78       | 5.02     | 0.20     | -        | 5136         | 0.146                | SL        |
| 496        | 70       | 4.22     | 0.98     | -        | -            | 0.303                | SL        | 523        | 78       | 7.82     | 0.20     | -        | 5136         | 0.092                | SL        |
| 497        | 70       | 5.20     | 0.97     | -        | -            | 0.259                | SL        | 524        | 78       | 12.17    | 0.20     | -        | 5136         | 0.065                | CH        |
| 498        | 70       | 7.48     | 0.96     | -        | -            | 0.192                | SL        | 525        | 78       | 18.03    | 0.19     | -        | 5136         | 0.048                | CH        |
| 499        | 70       | 12.22    | 0.93     | -        | -            | 0.127                | CH        | 526        | 78       | 25.14    | 0.18     | -        | 5136         | 0.033                | AN        |
| 500        | 70       | 17.82    | 0.86     | -        | -            | 0.091                | CH        | 527        | 78       | 29.70    | 0.18     | -        | 5136         | 0.028                | AN        |
| 501        | 70       | 24.95    | 0.81     | -        | -            | 0.073                | CH        | 528        | 78       | 0.13     | 0.26     | -        | 7670         | 0.877                | CB        |
| 502        | 70       | 32.00    | 0.78     | -        | 5028         | 0.057                | AN        | 529        | 78       | 0.25     | 0.28     | -        | 7447         | 0.829                | CB        |
| 503        | 70       | 36.58    | 0.78     | -        | 5040         | 0.065                | AN        | 530        | 78       | 0.57     | 0.33     | -        | 6986         | 0.718                | CB        |
| 504        | 70       | 0.13     | 1.20     | -        | 7174         | 0.977                | CB        | 531        | 78       | 1.06     | 0.37     | -        | 5340         | 0.534                | CB        |
| 505        | 70       | 0.25     | 1.20     | -        | 7660         | 0.955                | CB        | 532        | 78       | 2.26     | 0.41     | -        | 5136         | 0.319                | SL        |
| 506        | 70       | 0.58     | 1.21     | -        | 7211         | 0.904                | CB        | 533        | 78       | 5.02     | 0.43     | -        | 5136         | 0.183                | SL        |
| 507        | 70       | 1.07     | 1.22     | -        | 6740         | 0.817                | CB        | 534        | 78       | 7.39     | 0.45     | -        | 5136         | 0.124                | SL        |
| 508        | 70       | 2.29     | 1.24     | -        | 4812         | 0.600                | SL        | 535        | 78       | 12.15    | 0.44     | -        | 5136         | 0.085                | CH        |
| 509        | 70       | 5.04     | 1.25     | -        | -            | 0.368                | SL        | 536        | 78       | 17.91    | 0.42     | -        | 5136         | 0.064                | CH        |
| 510        | 70       | 5.95     | 1.23     | -        | -            | 0.283                | SL        | 537        | 78       | 24.92    | 0.39     | -        | 5136         | 0.046                | AN        |
| 511        | 70       | 8.08     | 1.21     | -        | -            | 0.218                | SL        | 538        | 78       | 32.26    | 0.36     | -        | 5136         | 0.034                | AN        |

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Table C.3. (*cont.*) Experimental data for air-mixed system in 60 mm inner diameter acrylic pipe

| <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> | <b>Exp</b> | $\theta$ | $v_{sg}$ | $v_{sl}$ | <b>T</b> | <b>dp/dx</b> | <b>H<sub>L</sub></b> | <b>FR</b> |
|------------|----------|----------|----------|----------|--------------|----------------------|-----------|------------|----------|----------|----------|----------|--------------|----------------------|-----------|
| #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       | #          | ° FH     | m/s      | m/s      | °C       | Pa/m         | [-]                  | [-]       |
| 539        | 78       | 0.13     | 0.55     | -        | 8332         | 0.911                | CB        | 557        | 78       | 12.07    | 0.87     | -        | -            | 0.096                | CH        |
| 540        | 78       | 0.25     | 0.56     | -        | 7560         | 0.879                | CB        | 558        | 78       | 17.59    | 0.80     | -        | -            | 0.065                | CH        |
| 541        | 78       | 0.57     | 0.58     | -        | 7161         | 0.794                | CB        | 559        | 78       | 24.47    | 0.75     | -        | -            | 0.045                | AN        |
| 542        | 78       | 1.06     | 0.61     | -        | 6464         | 0.664                | CB        | 560        | 78       | 31.08    | 0.71     | -        | -            | 0.027                | AN        |
| 543        | 78       | 2.26     | 0.67     | -        | 5136         | 0.425                | SL        | 561        | 78       | 0.13     | 1.19     | -        | -            | -                    | CB        |
| 544        | 78       | 5.03     | 0.69     | -        | 5136         | 0.254                | SL        | 562        | 78       | 0.26     | 1.19     | -        | -            | -                    | CB        |
| 545        | 78       | 7.81     | 0.68     | -        | 5136         | 0.155                | SL        | 563        | 78       | 0.58     | 1.20     | -        | -            | -                    | CB        |
| 546        | 78       | 12.10    | 0.67     | -        | 5136         | 0.112                | SL        | 564        | 78       | 1.08     | 1.21     | -        | -            | -                    | CB        |
| 547        | 78       | 17.80    | 0.65     | -        | 5136         | 0.085                | CH        | 565        | 78       | 2.30     | 1.24     | -        | -            | -                    | SL        |
| 548        | 78       | 24.87    | 0.61     | -        | 5136         | 0.073                | AN        | 566        | 78       | 5.04     | 1.24     | -        | -            | -                    | SL        |
| 549        | 78       | 30.70    | 0.57     | -        | 5136         | 0.071                | AN        | 567        | 78       | 7.41     | 1.22     | -        | -            | -                    | SL        |
| 550        | 78       | 0.14     | 0.84     | -        | 7931         | 0.856                | CB        | 568        | 78       | 11.98    | 1.14     | -        | -            | -                    | CH        |
| 551        | 78       | 0.26     | 0.85     | -        | 7671         | 0.818                | CB        | 569        | 78       | 17.50    | 1.08     | -        | -            | -                    | CH        |
| 552        | 78       | 0.58     | 0.86     | -        | 7320         | 0.740                | CB        | 570        | 78       | 24.25    | 1.03     | -        | -            | -                    | CH        |
| 553        | 78       | 1.07     | 0.88     | -        | 6767         | 0.635                | CB        | 571        | 78       | 31.24    | 1.00     | -        | -            | -                    | AN        |
| 554        | 78       | 2.29     | 0.91     | -        | 5136         | 0.409                | SL        |            |          |          |          |          |              |                      |           |
| 555        | 78       | 5.02     | 0.92     | -        | -            | 0.232                | SL        |            |          |          |          |          |              |                      |           |
| 556        | 78       | 7.34     | 0.92     | -        | -            | 0.147                | SL        |            |          |          |          |          |              |                      |           |

# Appendix D

## Published Papers

# Experimental investigation of two-phase flow regime in an inclined pipe

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## ABSTRACT

Experiments were performed with propose of mapping the flow patterns in two-phase flow in an upward inclinable 60 mm ID and 6 m long Plexiglas pipe. Air and viscous oil were used as working fluids and degree of inclination changed from 10 ° to 78 °. Measurements includes pressure drop. Flow regime were recorded with high speed video cameras. Experimental results were compared with existing models by Barnea (1987) and with a commercial dynamic multiphase flow simulator (OLGA7.3<sup>®</sup>). Predictions with unified model had acceptable agreement with experimental data.

## 1. INTRODUCTION

The need of understanding two-phase gas-liquid flow has been increasing in the recent years, as well as the need of a technical solution for handling and controlling the flow behaviour. A correct prediction of multiphase flow dynamics is critical for the design of pipelines for deep-water riser and production tubing in offshore oil and gas field development, where parameters as pressure drop and liquid holdup are strongly dependent on the flow pattern. Generally, flow pattern in gas-liquid system can exist in a wide variety of forms, depending on the flow rate, physical properties of the phases, the geometry and inclination of the tube (McQuillan and Whalley, 1985).

For several years, extensive research on multiphase flow has been conducted. Most of these were aiming to either horizontal or flow in vertical pipe, since such pipe geometry and topology are quite common. Nowadays, exploration into deep-water and development of horizontal well drilling make it more actual for the pipe or flow channel with inclination between 10 ° to 85 °, little information on the flow in pipe with such inclination angle range is available.

Diverse classification of the flow pattern in the conduit exit, most of them based on individual interpretation of visual observation of the fluid distribution within the pipe flow (Barnea et al., 1980a). This has been a disadvantage in the industry, due to different visual interpretations reported under identical flow conditions. Therefore, many researches have proposed to classify the flow pattern quantitatively. Considerable numbers of correlation to predict the flow pattern, pressure drop and liquid holdup in either horizontal and vertical flow are available, but these correlations have not been satisfactory when applied to inclined flow. Beggs and Brill (1973) developed a model for predicting pressure gradient from correlation of liquid holdup and friction factor for two-phase flow in pipe at all angles for many flow conditions. Gould et al. (1974) presented a model to predict pressure distribution through vertical, horizontal and 45 ° inclined pipe.

Taitel and Dukler (1976) proposed a physical model that predicts the flow regime transitions in horizontal and near horizontal gas-liquid flow. Barnea et al. (1985) reported experimental data on flow pattern transitions for upwards flow of air-water in pipes having 0 to 90° of inclination. Later Barnea (1987) proposed a unified model to predict the steady-state transition boundaries for the whole range of pipe inclination for gas-liquid system. The model is an extension of the suggested model by Barnea (1986) where the transition from annular to intermittent flow and from dispersed flow were suggested and previously published models as Barnea et al. (1982a), Barnea et al. (1982b), (1980b) and Barnea et al. (1985).

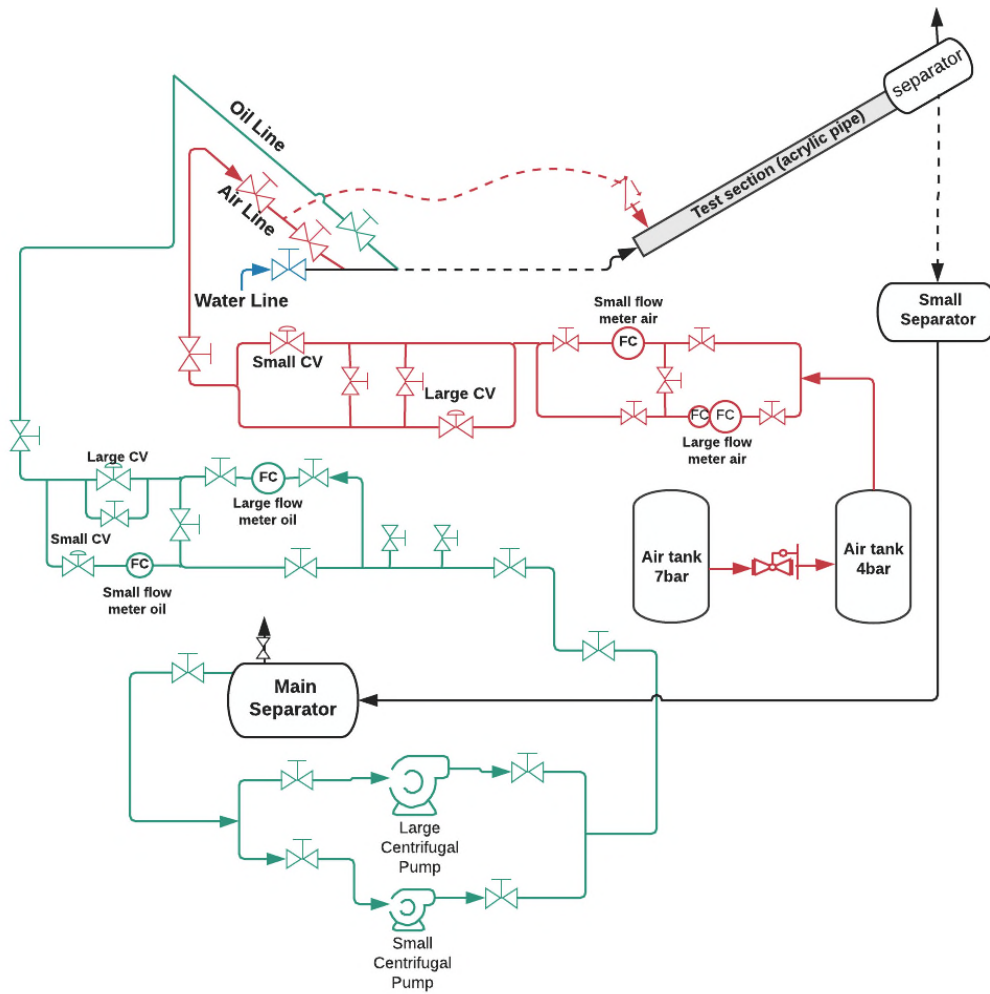
Zhang et al. (2003a) presented a unified model which predicts the flow pattern transition, pressure gradient, liquid holdup and slug characteristics in gas-liquid flow for all inclination angle ( $\pm 90^\circ$  from horizontal). The validation of the model were presented by Zhang et al. (2003b) were extensive experimental data acquired with different pipe geometry and fluid properties were used. Gokcal et al. (2008) experimentally studied the effect of high viscosity liquid on the flow pattern for oil-gas flow in horizontal pipe and later on Jeyachandra et al. (2012) extended the study using slightly inclined pipe ( $\pm 2^\circ$ ). They reported flow pattern and pressure drop, the results were then used to evaluate different flow pattern maps, model and two-phase flow correlation. There is variety of measuring techniques used in two-phase of which only few are used directly for flow pattern as void fraction fluctuation measurements, pressure gradient oscillations and conducted/capacitance probe techniques (Barnea et al., 1980a).

From the literature survey on two-phase gas-liquid flow in inclined pipes, it can be concluded that most of the experiment data available for comparing with existing correlations come from air-water solution as test fluids. Moreover, the data with viscous liquid phase and inclined pipe is limited. The first objective of this study was to obtain reliable data for the flow pattern identification having gas and viscous liquid system for inclination-angle range of  $10^\circ \leq \theta \leq 78^\circ$  from horizontal. Next, the performance of flow pattern using Barnea (1987) model and Multiphase flow simulator by SPT-Group (OLGA<sup>®</sup>7.3-hereafter referred to as OLGA) is evaluated using the data acquired in the experimental part of the study. Barnea (1987) model was selected to evaluate if the model is applicable for more viscous fluid since it was developed based on experimental data for air-water flow system.

## **2. EXPERIMENTAL SET UP AND PROCEDURE**

### **2.1 Test Section**

Experiments were carried out at the Multiphase Flow Laboratory at NTNU, which consists of several flexible test sections used for diverse proposed. The facility used comprised of a 6-m long, 60-mm ID transparent acrylic pipe for better visualisation. Inclination angles can be changed from 10° to 78° from horizontal. There were limitations on the variation of inclination range due to safety issues during the experiments. The inclined setup has two possible mixture sections. One is located before the test section where gas and liquid flow simultaneously through a flexible pipe and the other where each fluid is mixed at the test section inlet separately. The second mixture section were preferred in present investigation to prevent instabilities prior to the test section, which can be caused if the mixing occurs several meters before the test section. The two-phase flow propagates through the test section to a separator at the top of the pipe where the air is vented to the atmosphere and the liquid drained to a main storage separator. The schematic of the facility is given in Fig. 1.



**Fig. 1 Schematic of the test facility**

## 2.2 Fluid system

Experiments were carried out using compressed air as gas phase and oil as liquid phase. Air is supplied at 7 bar by the pressurized air network of the university and reduced to operational pressure of 4 bar. Oil is supplied through an oil line by centrifugal pump and is storage with water separated by gravity in the main separator located in the basement. Fluid flow rate were measured by mean of Coriolis meter. The properties of the fluids at 20°C and 1 atm are given in Table 1.

**Table 1. Fluid properties**

| Physical property           | Air   | Oil |
|-----------------------------|-------|-----|
| Density, kg.m <sup>-3</sup> | 1.22  | 840 |
| Viscosity, cP               | 0.018 | 25  |

## 2.3 Pressure gradient

Pressure gradient is calculated from the measure pressure of two pressure cells and two absolute pressure that were connected along the test section.

## 2.4 Experimental test matrix

The flow pattern in two-phase flow system depends on the geometry, physical properties and superficial velocities of the fluids. Effect of inclination angle on the flow patterns was the interest on this study. For every inclination 10°, 15°, 20°, 25°, 30°, 45°, 60°, 70°

and 78° (from horizontal), different combination of superficial liquid and gas velocity ( $v_{sl}$  and  $v_{sg}$ ) varied from 0.1 m/s to 1.2 m/s and 0.04 m/s to 10 m/s, respectively were used. The limits of  $v_{sl}$  were due to the accuracy of the flow meter and the centrifugal pump operation limits. In the case of air, the lower limit was due to accuracy of flow meter, while the higher was set after few experiments to verify at which velocity annular flow was identified.

## 2.5 Flow regime visualisation and characterisation

Flow regimes were identified by visual inspection, pictures and video were recorded using, three synchronised cameras installed in the test section. The camera was a Basler acA640 with the maximum resolution of 659x494 pixels in black and white. The videos were recorded at 120 frames per second and simultaneously acquired using a program written in LabVIEW2013<sup>®</sup> for the acquisition system. Stratified wavy (SW), elongated bubble (EB), cap bubble (CB), slug (SL), churn (CH) and annular (AN) flow pattern were observed. Dispersed bubble (DB) flow could not be observed due to limitations of oil flow rate during the experiments. Experimentally the identification if either the flow was annular, churn or stratified wavy by visual inspection was quite challenging, thus may have led to a poor flow pattern characterisation. Long time on the observations was considered and the most dominant flow regime over the time was classified as the final flow regime.

## 3. RESULTS AND DISCUSSION

In this section, experimental flow pattern observations were compared with predictions of Barnea (1987) model and simulations results from OLGA (Fig. 2 to Fig. 10). Pressure gradient were only compared with OLGA results, since the unified model is basically a set of equations and criteria solved for superficial velocities, void fraction and pipe geometry having no relation with pressure drop.

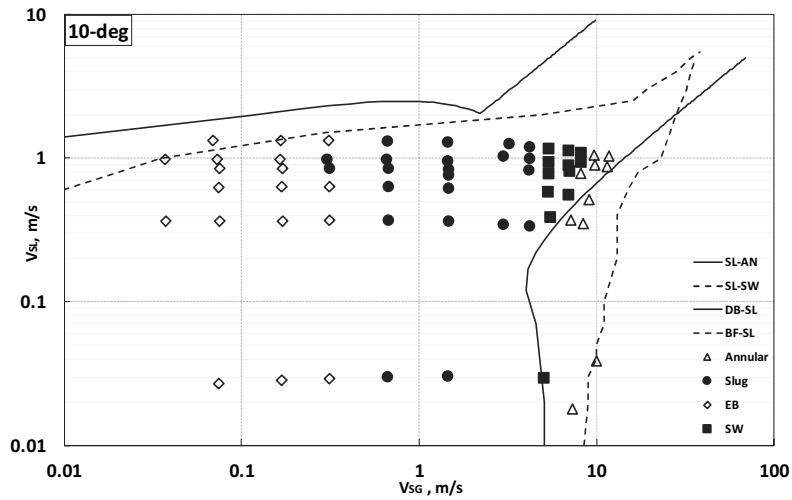
### 3.1 Flow pattern comparison

Barnea (1987) developed a model with the purpose of predicting flow pattern transition boundaries for the whole range of pipe inclination through operative equations and dimensionless maps, that incorporate the effect of flow rates, fluid properties, pipe size and pipe inclination. In Barnea et al. (1985) the classification of two-phase were defined into four main regions: stratified that was subdivide into *stratified smooth* and *stratified wavy*; Intermittent with *elongated*, *slug* and *churn flow*; annular with *annular* and *annular wavy* and dispersed bubble region.

Besides the flow pattern transition predicted through theoretical model, dynamic multiphase flow as OLGA are also used with the same proposed. Bendiksen et al. (1991) mentioned that flow regime transition identification in OLGA, is basic two flow regime classes distributed and separated. The distributed is where the contribution of bubble and slug flow are present, while separated including stratified and annular flow. In total, OLGA distinguish between four flow regimes: *stratified*, *bubble*, *slug* and *annular*. It should be mentioned that the stratified flow is classified either as smooth or wavy.

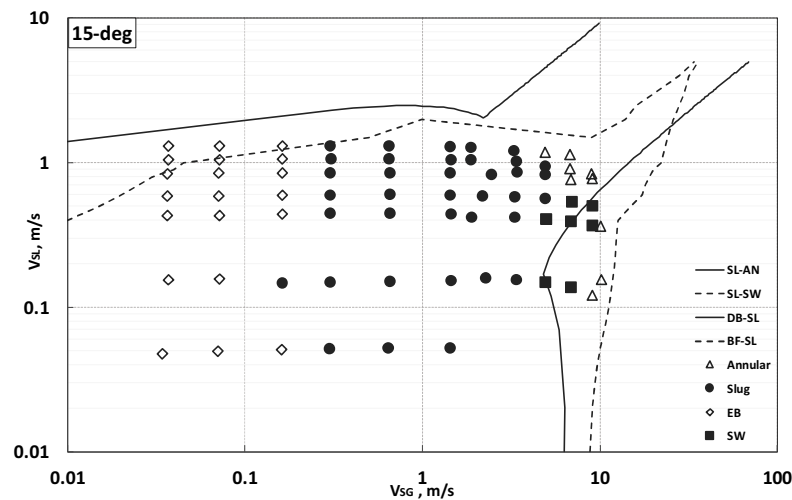
For all the inclination stratified smooth pattern were not experimentally observed neither predicted through unified model nor OLGA simulation. In Barnea et al. (1985) this flow pattern could be observed only for inclination angles less than 0.25°. Dispersed flow was not achieved in the experiments due to limitation on the liquid flow rate, which was confirmed with the theoretical transition line (DB-SL) located above the maximum superficial velocity of the liquid used in the experiments.





**Fig. 2 Flow pattern map 10° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation**

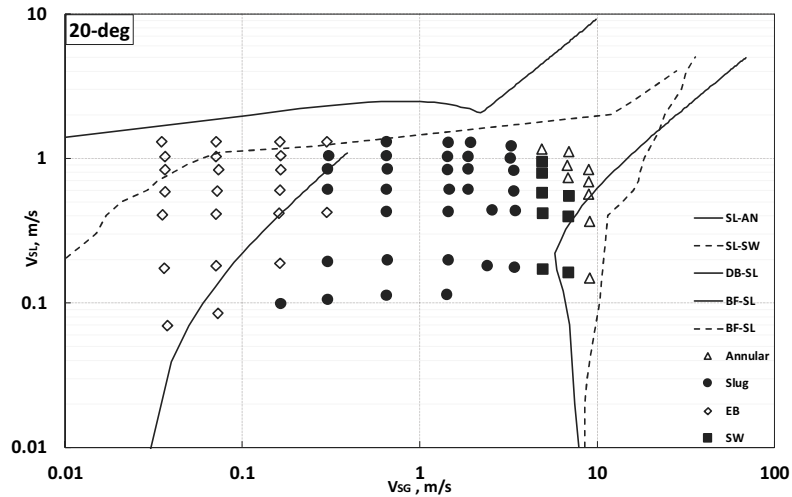
Fig. 5 - Fig. 10 stratified wavy flow was not identified. However, a transition boundary for SW predicted from Barnea (1987) was expected to appear at inclination angles below 20°, which could not be observed due to the lower liquid flow rates used in the model compared with the experiments. On the other hand, the transition boundary from slug to stratified wavy (SL-SW) predicted in OLGA was identified in most of the inclination except in Fig. 8 to Fig. 10. Experimentally elongated bubble flow region reduces with increasing inclination angle and cap bubble appears for inclinations above 30°. Similar condition as observed in Barnea et al. (1985) and Barnea (1987) where the elongated bubble disappeared at angles above 30° for upward inclined pipe and dispersed bubble flow take place. Due to the gas phase inlet location on the test section, cap bubble pattern was identified instead of dispersed bubble. Considering that, small bubbles of air injected in the system were flowing on the top of the pipe section creating a cap bubble flow.



**Fig. 3 Flow pattern map 15° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation**

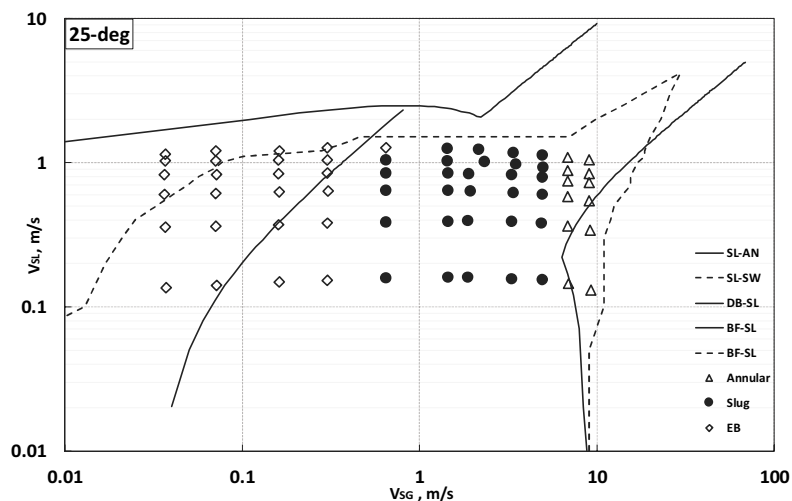
Bubble-slug transition curve (BF-SL) predicted from the model represented better the experimental data for inclination angles above 60°. The criteria set by the unified model used in this transition were not met for inclination angles 10° and 15°. In OLGA, bubble-slug transition curve moves to the right down when the inclination angle increase, hence

the experimental bubble flow region is better represented for inclination above 30°. This conclusion was based on the fact that, cap bubble and elongated bubble exists in the bubble flow region. Churn flow in the experimental data has a similar behaviour as the one verified by Barnea et al. (1985) where the first appearance of this pattern occurred at 70° inclination (Fig. 9). In Barnea et al. (1985) the range of  $v_{sl}$  at which the churn flow appeared increase with the pipe diameter, thus it was possible to observe this pattern for the velocities used in the experiment.



**Fig. 4 Flow pattern map 20° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation**

Slug-annular transition curve (SL-AN) in both theoretical and simulations predictions occurred at higher gas flow rates compared with the experiments. In OLGA, annular flow transitions for 10° inclination were observed for  $v_{sg}$  around 200 m/s. The required gas flow rate for annular flow to be seen, decreases as the angle increases around 50 m/s for 70° inclination. Thus, no SL-AN transition was observed for inclination angle below 60°. It should be mentioned that different naming between annular wavy and stratified wavy, the stratified-annular transition was not clear, which mean that experimentally flow pattern could be misinterpreted.



**Fig. 5 Flow pattern map 25° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation**

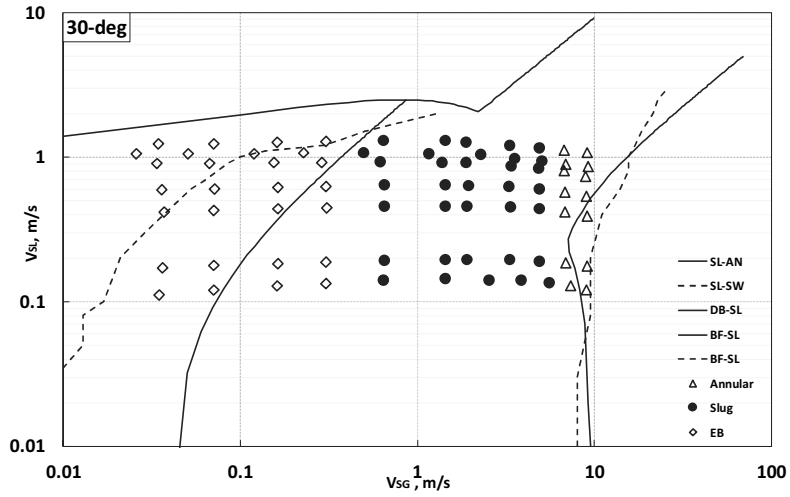


Fig. 6 Flow pattern map 30° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation

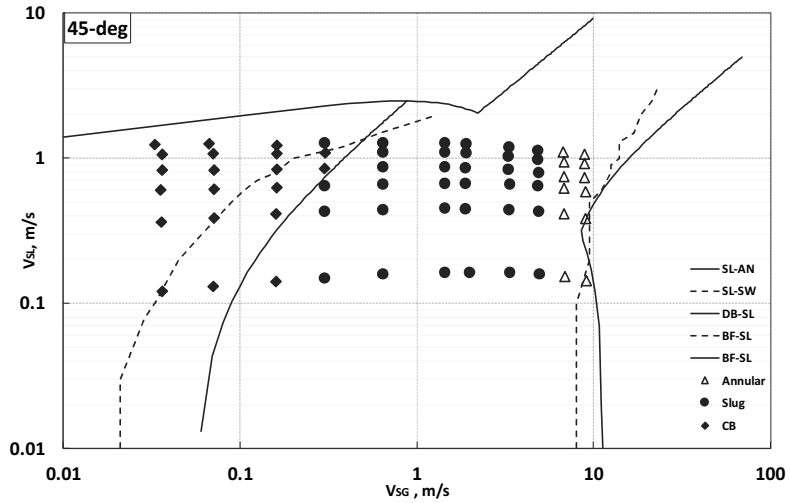


Fig. 7 Flow pattern map 45° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation

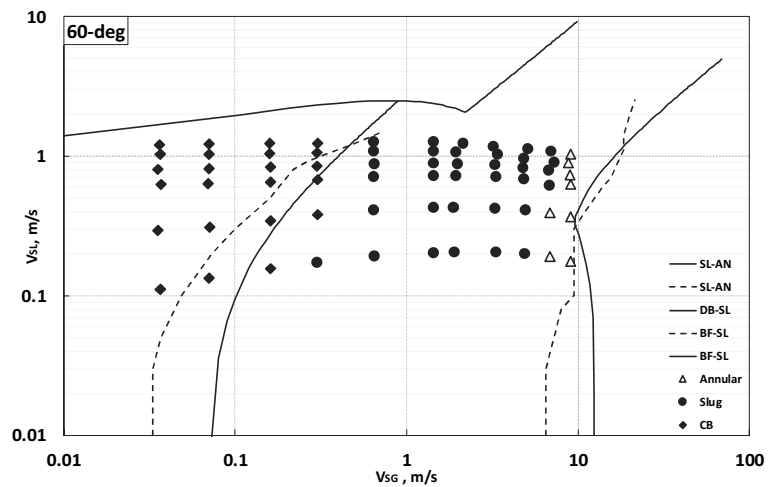
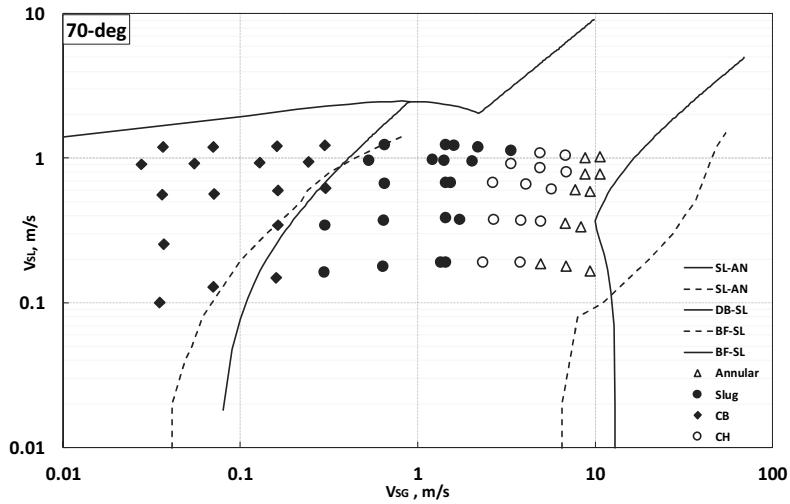
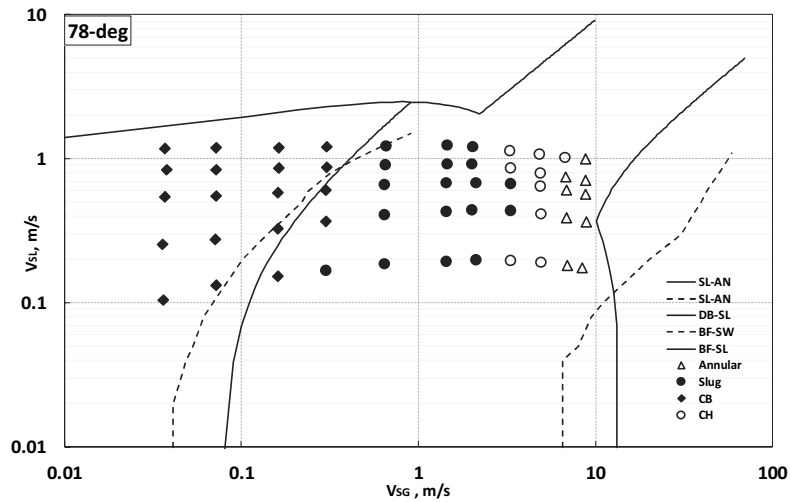


Fig. 8 Flow pattern map 60° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation



**Fig. 9 Flow pattern map 70° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation**

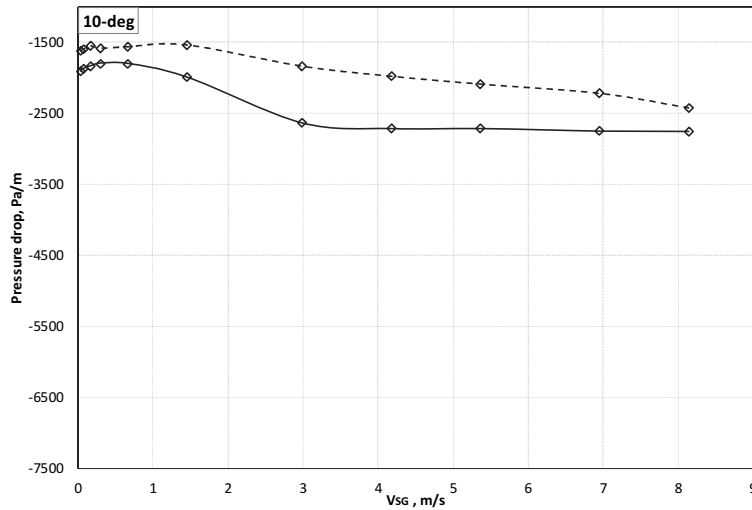


**Fig. 10 Flow pattern map 78° upward, 6 cm pipe: — Barnea (1987) model; --- OLGA simulation**

### 3.2 Pressure gradient and liquid holdup

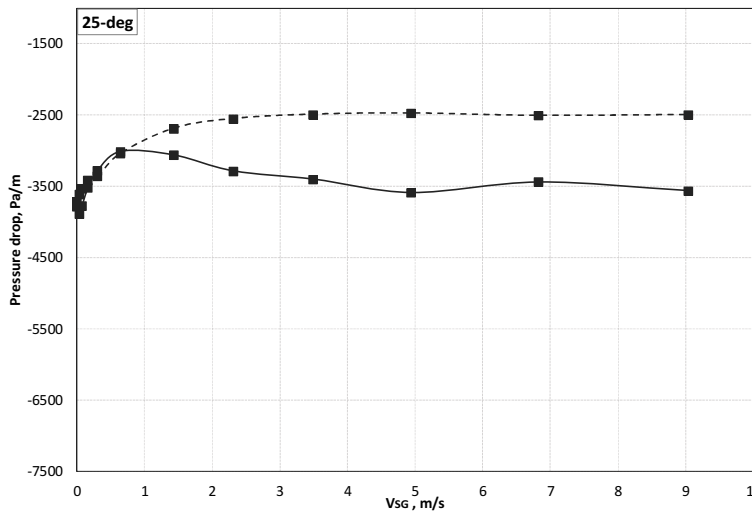
This section presents the pressure drop from experimental results compared to OLGA simulations results. Pressure drop in two-phase is more complicated and difficult to predict compared to single phase. Beggs and Brill (1973) developed an equation for the pressure drop when gas, liquid or both are flowing in a pipe. They also mentioned that in directional wells pressure are usually determined from vertical flow correlations.

In Fig. 11 to Fig. 15 total pressure drop versus superficial gas velocities given a constant superficial liquid velocity for different inclination are shown. Overall, it was observed that the pressure drop response changed with the flow pattern present in the test section and the inclination angles. Experimentally, two differential pressure transducers were used to measure the pressure drop in the test section. The output pressure signal (from LabVIEW®) was then processed and corrected for non-zero value at zero flow, during calibration.

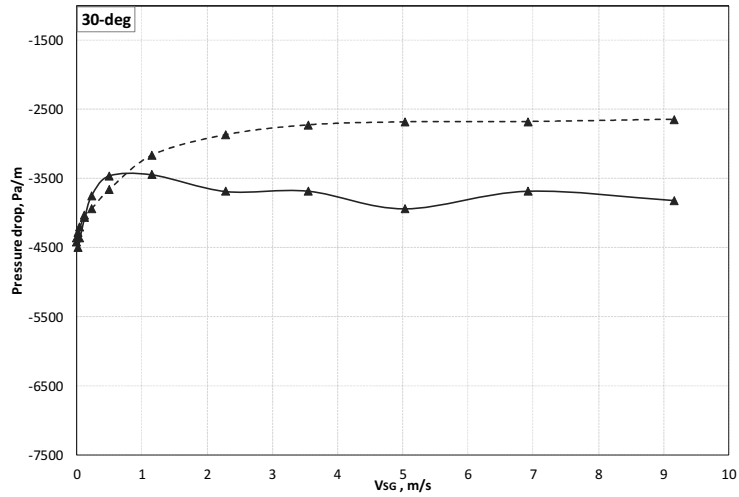


**Fig. 11 Pressure drop 10° upward, U<sub>sl</sub> = 1m/s: — experimental data; --- OLGA simulation**

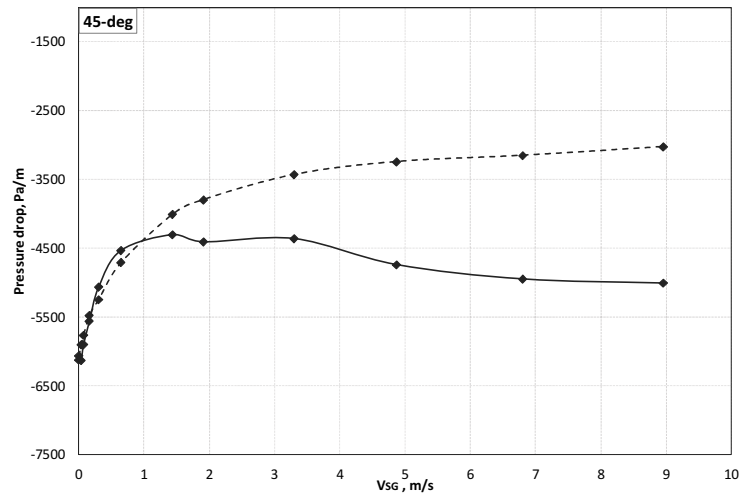
On Fig. 11 to Fig. 15 it was observed that the total pressure drop reached a minimum point for lower gas flow rates and a further increase in gas flow rates resulted in larger pressure drop for all inclinations. In the area of high gas flow rates, the frictional losses are more dominant. Although OLGA and experiments data show the same trends, the lines for total pressure gradients deviates a lot, especially for high gas flow rates when the inclination angle increases.



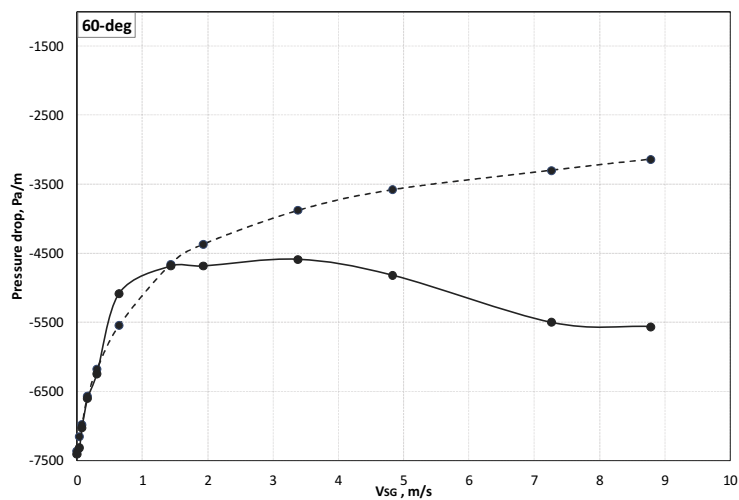
**Fig. 12 Pressure drop 25° upward, U<sub>sl</sub> = 1m/s: — experimental data; --- OLGA simulation**



**Fig. 13 Pressure drop 30° upward,  $U_{sl} = 1\text{m/s}$ : — experimental data; --- OLGA simulation**



**Fig. 14 Pressure drop 45° upward,  $U_{sl} = 1\text{m/s}$ : — experimental data; --- OLGA simulation**



**Fig. 15 Pressure drop 60° upward,  $U_{sl} = 1\text{m/s}$ : — experimental data; --- OLGA simulation**

#### 4. SUMMARY AND CONCLUSION

Experimental results were collected for two-phase flow air-oil system 60 mm ID upward inclined pipe and flow patterns were identified. Experimental flow patterns were then compared with flow patterns predicted using Barnea (1987) model and multiphase flow simulator. Experimentally, the flow regime consisted of stratified wavy at 10°-20°, churn flow at 70°-78°, while bubble flow (elongated bubble and cap bubble), slug and annular flow were observed for the entire range of inclination. A comprehensive conclusion of the experimental study was that variation on the inclination angle had a major effect on the flow pattern. Comparison of experimental flow patterns with Barnea (1987) model indicated that the unified model, which was obtained based on two-phase air-water to predict flow patterns, shows a good agreement with the experimental measurements. Most of the flow pattern regions defined by Barnea et al. (1980a), Barnea et al. (1980b), Barnea et al. (1985) and Barnea (1987) were observed also in our study.

In general, flow pattern prediction in OLGA was not in successful agreement with the measured data. OLGA patterns were sufficient similar for the slug flow at 70°-78°, but failed on the slug-annular transition flow for the same inclination. Experimental results for pressure drop were also compared with the simulation results. It was shown total pressure gradient measured agreed quite well on the behaviour with the predictions in OLGA for the tested inclination angles.

Future work is focusing on evaluating Barnea (1987) model on two-phase flow system with viscous liquid for vertical and horizontal geometries.

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## **Applicability of Models for Liquid Loading Prediction in Gas Wells**

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### **Abstract**

Liquid loading phenomenon is known as the inability of the produced gas to carry all the co-produced liquid to the surface. Under such condition, the non-removed liquid accumulates at the wellbore resulting in reduction of the production and sometimes cause the death of the well. Several studies were carried out and correlation were developed based on field and experimental data with the aim to predict the onset of liquid loading in a gas well. However, each model provides different indication on the critical gas velocity at which the liquid loading exists. Thus, to have a clear understanding on the difference between most used models, experiments were performed in an upward inclinable pipe section. The 60-mm diameter test pipe was positioned at angles of 30°, 45° and 60° from horizontal. The fluids used were air and light oil. Measurements include fluid velocities and fluid reversal point. High-speed video cameras were used to record the flow conditions in which the onset of liquid loading initiated. Experimental results were compared with existing models by Turner et al. (1969), Barnea (1986), Belfroid et al. (2008), Luo et al. (2014), Shekhar et al. (2017) and with a commercial dynamic multiphase flow simulator from SPT-Group (OLGA2017.1.0®). Prediction using the liquid film models presented acceptable agreement with experimental.

### **Introduction**

In most gas wells at an early stage the reservoir pressure is sufficiently high to achieve gas production rates that can transport any existing co-produced liquid up to surface, which makes the well produce at stable condition. As the pressure decrease, the gas velocity drops as well as its capacity of lifting the liquid. Under this condition, the non-removed liquid accumulates in the wellbore (liquid loading), creating a backpressure against the formation resulting in further accumulation of liquid and reduction of the production or even causing a premature abandonment of the well. To counteract this phenomenon and maintain production, the operator must have an accurate prediction of the onset of liquid loading. However, liquid loading behaviour and prediction of critical gas rate remain questionable. Over the past years, many methods, correlations and equations were proposed, based on field and experimental data to determine the critical superficial gas velocity in gas wells and the onset of liquid loading. Almost all these analyses indicated the existence of two theories for liquid removal in gas wells:

### Droplet model

The droplet model also known as the liquid droplet reversal model. It assumes that the liquid is transported as droplets entrained in the high velocity gas core, and that the main cause of liquid loading is falling droplets. Turner et al. (1969) proposed a model based on force balance of a droplet. It calculates a minimum gas velocity needed to lift the larger droplet present in the gas core. Due to simplicity, the model has been widely used in the industry. Turner's model for critical superficial gas velocity (m/s):

$$v_{sg,critical} = 5.463 \left[ \frac{(\rho_l - \rho_g)\sigma}{\rho_g^2} \right]^{0.25} \quad (1)$$

They adjusted the original coefficient by 20% to match their field data during validation of the model. Therefore, the 5.463 changed to 6.560. Several modifications and refinement to better match different set of data and conditions, to the Turner et al. (1969) model was made by Coleman et al. (1991), Nosseir et al. (1997), Li et al. (2001), Flores-Avila et al. (2002), Guo et al. (2005), Belfroid et al. (2008) and Veeken et al. (2010). Belfroid et al. (2008) proposed an improved droplet model. They adapted Turner's equation with a function from Fiedler et al. (2004) to account for well inclination. The equation for critical gas superficial velocity (m/s):

$$v_{sg,critical} = 5.463 \left[ \frac{(\rho_l - \rho_g)\sigma}{\rho_g^2} \right]^{0.25} \frac{(\sin(1.7\theta))^{0.38}}{0.74} \quad (2)$$

### Liquid film model

The liquid film model also known as liquid film reversal. It assumes that liquid is transported as a film moving along the walls of the pipe to the surface. Zabaras et al. (1986) conducted an experimental study on the liquid film for vertical upwards concurrent annular gas-liquid flow. They concluded that at low gas flow rates the film motion was controlled by a switching mechanism designated as churn flow. Several subsequent authors have shown that liquid loading is accompanied by flow regime transition from annular to intermittent flow. Barnea (1986, 1987) proposed models to predict flow patterns transition in two-phase gas-liquid flow in pipes for the complete range of inclination angles. The models incorporated the effect of fluid property and pipe size, and assumed no variation in film thickness around the pipe for all inclination angles. The annular-intermittent transition model of Barnea is widely used for the onset of liquid loading in deviated pipes. Paz (1994) performed experimental and theoretical investigations on two-phase annular flow focused on the effect of inclination angle on the liquid film thickness distribution around the circumferential of the pipe. He concluded that inclination angle strongly affected the liquid film thickness distribution ( $\delta$ ), proving Barnea assumption wrong. Luo et al. (2014) developed a correlation that took into account the non-uniform film thickness (Eqn. 3) and used Barnea (1986) methodology to predict the onset of liquid loading. Different from the Barnea model they used Fore et al. (2000) interfacial friction factor correlation instead of Wallis (1969). The model was validated with field and experimental data, showing an improvement on the prediction of onset of liquid loading compared to Barnea model and liquid droplet models:

$$\delta(\varphi, \theta) = (1 - \alpha \theta \cos \varphi) \delta_c \quad (3)$$

$$\alpha = \begin{cases} 0.0287, & 0 \leq \theta < 30 \\ 0.55\theta^{-0.868}, & 30 \leq \theta \leq 90 \end{cases}$$

Shekhar et al. (2017) proposed a new set of empirical correlation keeping the same concept of film thickness variation with the deviation angle ( $\theta$ ) of the pipe (Eqn. 4). In addition, they modified Wallis (1969) interfacial friction factor ( $f_i$ ) and proposed a correlation that is dependent on the inclination angle (Eqn. 5).

$$\delta(\varphi, \theta) = \left[ 1 - \left( \frac{1 - e^{-0.088\theta}}{1 + e^{-0.088\theta}} \right) \cos \varphi \right] \delta_L \quad (4)$$

$$f_i = 0.005 \{ 1 + [340(1 + \cos \theta)(\widetilde{\delta}_L)] \} \quad (5)$$

The motivation of this work is to evaluate the applicability of the liquid droplet model proposed by Turner et al. (1969) and Belfroid et al. (2008), along with liquid film model by Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017). Beside the prediction through theoretical models, a commercial dynamic multiphase flow simulator from SPT-Group (OLGA7.3® - hereafter referred to as OLGA) was also evaluated. Experimental data acquired at the Multiphase flow laboratory were used to evaluate the model's applicability.

## Experimental setup

The 60 mm inner diameter (ID) inclinable test section at the multiphase flow laboratory at NTNU was used for this study. The test section was 6 m long, transparent acrylic pipe mounted in a steel beam connected to a lift system. A schematic of the testing section is shown in Figure 1.

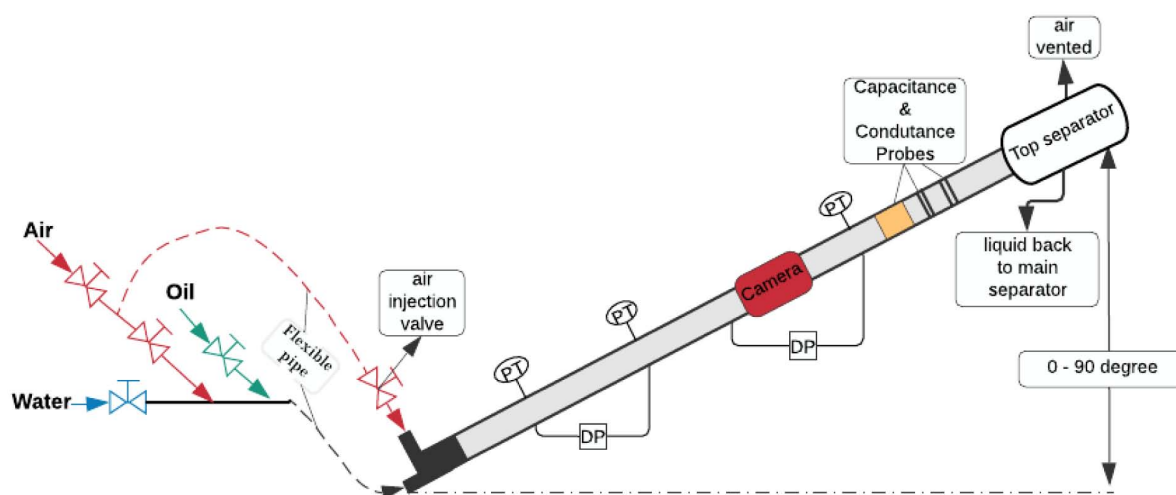


Figure 1—Schematic of inclinable test section

Modifications were made so the section could fully incline from horizontal to vertical. However, experiments were performed on 30°, 45° and 60° from horizontal due to safety issues. Mineral oil (Exxsol D80) and compressed air were used as fluid test. Air was supplied by the university ventilation network at approximately at 7 bar and reduced to operation condition of 4 bar. Air flow rate were measured by Vortex and converted to flow rate at atmospheric pressure, using readed values of a pressure transducer installed next to the flow meter. Oil was pumped from the main separator located in the basement and flow rate were measured by Coriolis flow meter. Both fluid entered the test section through a mixing section located at the bottom. Air injection in the test section was was controlled manually by a ball valve.

After entering the test section the the two-phase flowed through the pipe and then were separated at the top, where air was vented to atmosphere and oil circulated back to the main separator. Fluid properties at 20° C and 1 atm are given in Table 1.

Table 1—Fluid properties

| Fluid      | Density [kg/m <sup>3</sup> ] | Viscosity [cP] | Surface tension [N/m] |
|------------|------------------------------|----------------|-----------------------|
| Exxsol D80 | 800                          | 1.8            | 0.025                 |
| Air        | 1.2                          | 0.018          | -                     |

Two differential pressure transducers (DPT) and three absolute pressures were installed in the test section which enabled multiple pressure measurements. Daily calibration was performed on the DPT to ensure acceptable accuracy. The test section had capacitance and conductance probe rings for estimating the liquid hold up. Laboratory instrumentation were connected to a data acquisition system and controlled by a main program written in LabVIEW® where output signals were provided. A camera (GoPro Hero 6 Black®) was installed in the test section, and videos were recorded to support the identification of the transition point. The camera was set to record at 120 frames per second and high resolution in order to capture when the liquid started to flow in counter-current with the gas core. Preliminary tests were carried out to define the test matrix of the annular to intermittent transition region. Limitations of the quantity of fluid available, pump capacity and flow meter range also defined the test matrix too. Different combinations of superficial liquid and gas velocities ( $v_{sl}$  and  $v_{sg}$ ) were defined; varying from 0.01 m/s to 0.1 m/s and from 5 m/s to 50 m/s respectively. The interval of variation for the superficial gas velocity was not the same since the injection was controlled manually. Onset of liquid loading was defined through visual observations.

## Experimental results

Experimental data was collect at three inclinations of 30°, 45° and 60° and several superficial velocities of gas and liquid. Visually experimental data results were subdivided in three groups; *Loaded* (blue points) for cases were the flow was defined as full intermmitent (slug), *onset liquid loading* (black points) when the liquid started to go counter-current to the gas flow direction and *Unloaded* (red points) for cases were annular flow was visible. Experimental data are presente in Figure 2 to Figure 4.

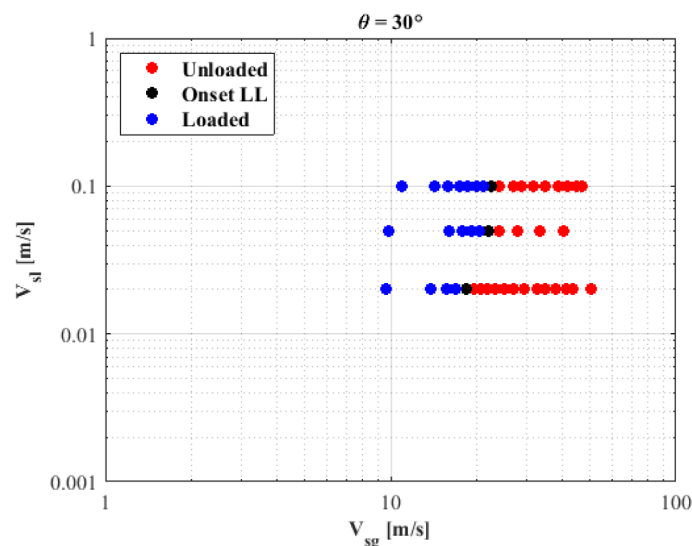


Figure 2—Experimental results for air- light oil system at STP conditions for 30° inclined pipe

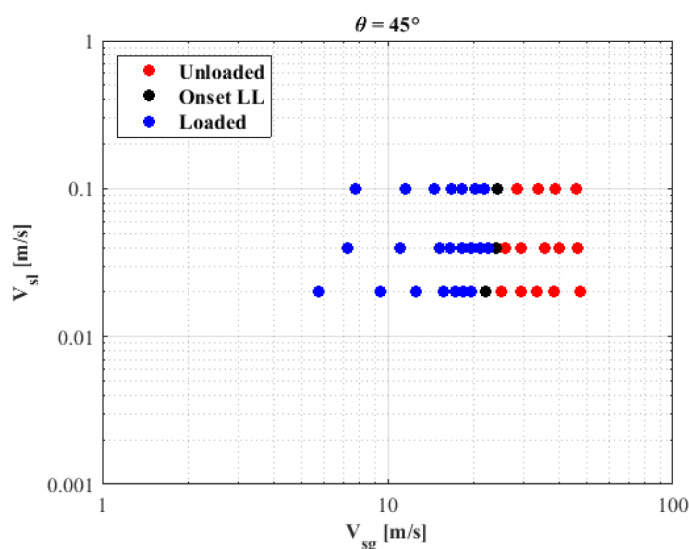


Figure 3—Experimental results for air- light oil system at STP conditions for 45° inclined pipe

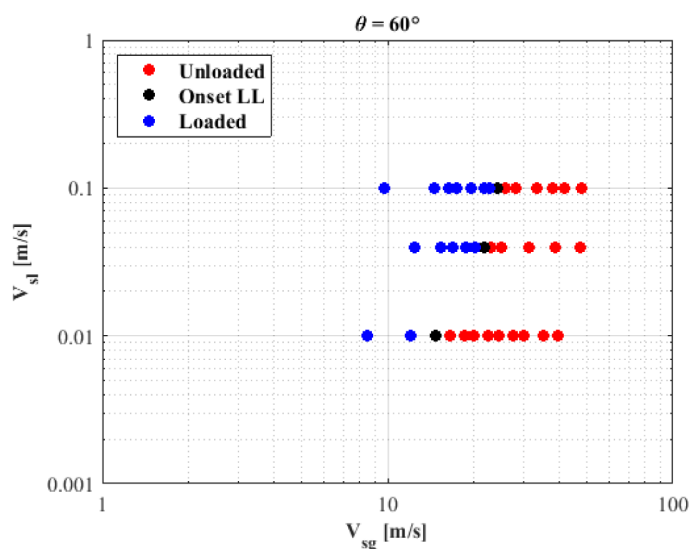


Figure 4—Experimental results for air- light oil system at STP conditions for 60° inclined pipe

In Figure 2 to Figure 4 it can be seen that the interval of variation of superficial gas and liquid velocity are equally distributed for all the inclination angle tested. This was due to insufficiency of oil available in the lab and manual injection of the gas flow in the test section.

## Model comparisons

Experimental data for air-light oil system results were compared with the model predictions. Multiphase flow simulator (Olga), Droplet models of Turner et al. (1969) and Belfroid et al. (2008), along with liquid film model by Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017) models were evaluated.

Figure 5 through Figure 7, onset of liquid loading points represent the critical gas velocity values from the experiments, continuous and dashed line are the liquid film and liquid droplet model respectively. Beside the prediction through theoretical models. Simulation results from OLGA were also presented as dashed point line.

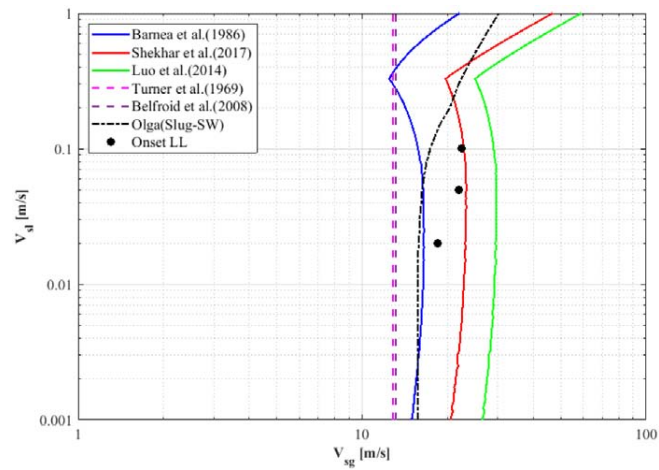


Figure 5—Comparison between experimental data with prediction models for 30° inclined pipe

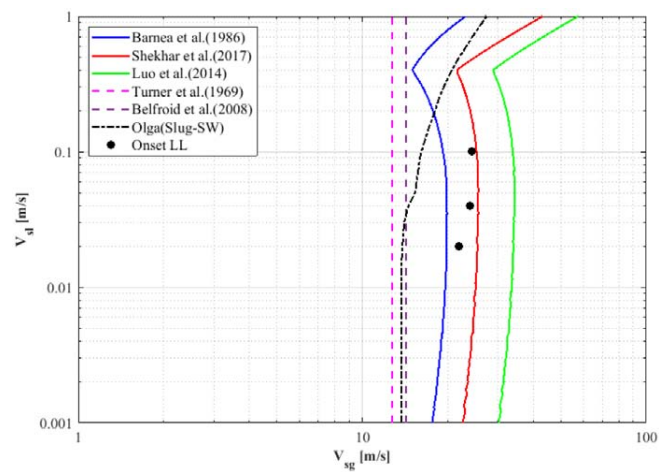


Figure 6—Comparison between experimental data with prediction models for 45° inclined pipe

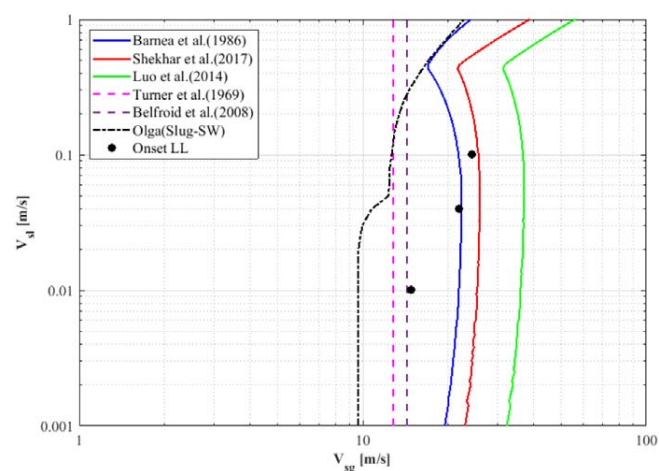


Figure 7—Comparison between experimental data with prediction models for 60° inclined pipe

Flow regime transitions in OLGA are distinguished between four flow regime: Stratified (smooth or wavy), annular, slug and bubble flow. Our focus was to identify the transition from slug to annular flow, then use the transition line to compare with experimental data. For all tested inclination, the slug-annular



transition was not observed. However, a transition for slug to stratified wavy (SW) line was observed and it seems to be close to the experimental data result as shown in Figure 2 to Figure 4. Note that annular flow in pipes with lower inclination angles could also be classified as stratified wavy.

It can be observed from Figure 2 and Figure 3 that Shekhar et al. (2017) predicts values close to the onset liquid loading observed experimentally. However, the same cannot be seen in Figure 4, where the Barnea (1986) transition line seems to have a better performance. Both liquid droplet model from Turner et al. (1969) and Belfroid et al. (2008) under-estimate the critical gas velocity for all the inclination angles. Luo et al. (2014) on the other hand over-estimate the predicted velocity for onset of liquid loading.

To support the conclusions done through visual perception of the Figure 2 to Figure 4 a percentage deviation was calculated using Eqn. 6.

$$\varepsilon(\%) = \frac{100}{N} \sum \left( \frac{v_{sg,model} - v_{sg,onset LL}}{v_{sg,onset LL}} \right) \quad (6)$$

For each inclination angles, the models and OLGA prediction results were compared with the onset of liquid loading experimentally observed. The deviation results are presented in Figure 8.

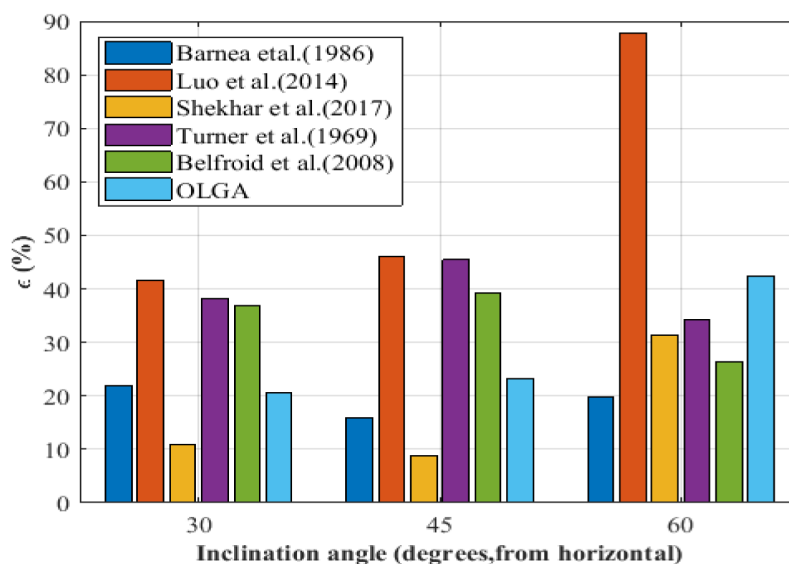


Figure 8—Deviation comparing all the model predictions for experimental data

It can be seen in Figure 8 that at 60° of inclination Barnea's model presents a better approximation to the experimental data compared to the other models. It is known that the model of Shekhar et al. was proposed to account for the inclination effect on the film thickness, which at the bottom of the pipe increases with the decrease of inclination. Analysing the deviation for inclinations of 30° and 45°, Shekhar et al. model provides a better prediction, this may be due to the fact that for such inclination the film thickness effect has a high influence on the critical gas velocity estimation.

### Comparison with other data

Vieira et al. (2018) performed an experimental study on flow pattern characterization in gas-liquid two-phase system in an inclined pipe using viscous oil (25 cP) using a 60-mm diameter pipe. They performed experiments for a wide range of well inclination (10° to 78° from horizontal) for different  $v_{sl}$  and  $v_{sg}$  values. They used the collected data to evaluate the performance of Barnea (1986) model with respect to viscous fluid. The data was published at 4 bar operational pressure condition and changed here to STP for better comparison with other data. In their publication, the superficial liquid velocity varied from 0.1 m/s to 1.2

m/s. Since liquid loading was not main, propose of their study, the points of onset of liquid loading were not identified. Thus, an interval from when they observed the transition from slug to annular flow was selected and is presented in [Table 2](#).

**Table 2—Experimental data for viscous oil-water, 60 mm ID at STP conditions [Vieira et al. \(2018\)](#)**

| Pipe inclination (degree) | $V_{sl}$ (m/s) | $V_{sg, slug}$ (m/s) | $V_{sg, annular}$ (m/s) |
|---------------------------|----------------|----------------------|-------------------------|
| 30                        | 0.12           | 20.55                | 26.69                   |
|                           | 0.20           | 17.72                | 24.49                   |
|                           | 0.44           | 17.67                | 24.41                   |
|                           | 0.61           | 17.66                | 24.34                   |
|                           | 0.88           | 17.47                | 24.18                   |
|                           | 1              | 18.23                | 24.79                   |
| 45                        | 0.14           | 17.75                | 24.56                   |
|                           | 0.42           | 17.64                | 24.47                   |
|                           | 0.64           | 17.55                | 24.37                   |
|                           | 0.82           | 17.62                | 24.38                   |
|                           | 1.04           | 17.55                | 24.28                   |
| 60                        | 0.18           | 17.62                | 24.36                   |
|                           | 0.38           | 17.68                | 24.52                   |
|                           | 0.67           | 24.33                | 31.78                   |
|                           | 0.83           | 24.03                | 31.65                   |
|                           | 1.02           | 25.82                | 30.86                   |

From the slug and annular data points, a transition area was defined. [Vieira et al. \(2018\)](#) concluded in their work that the [Barnea \(1986\)](#) model had a good agreement with the data. Therefore, the model of [Shekhar et al. \(2017\)](#) was evaluated, since the model showed to be good for the case of light oil.

[Figure 9](#) through [Figure 11](#) shows the comparison between the experimental data for air and viscous oil with the models. To evaluate the models, the transition line predicted by the models, were compared with the transition area, i.e., if the transition line from the model is located in the transition area then it means that the model has a better chance of predicting the correct velocity, otherwise oif the transition line from the model is.



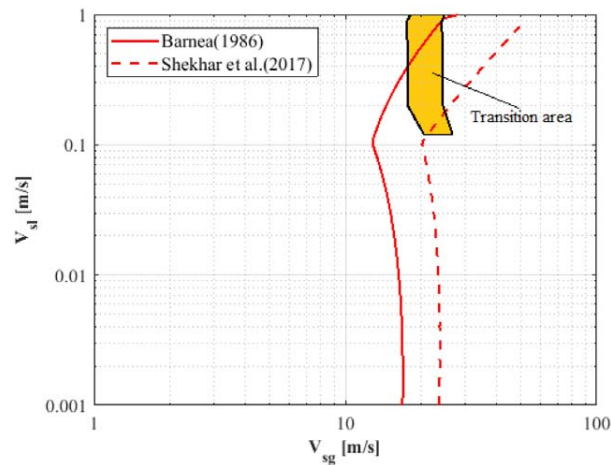


Figure 9—Comparison between experimental data with prediction models for 30° inclined pipe

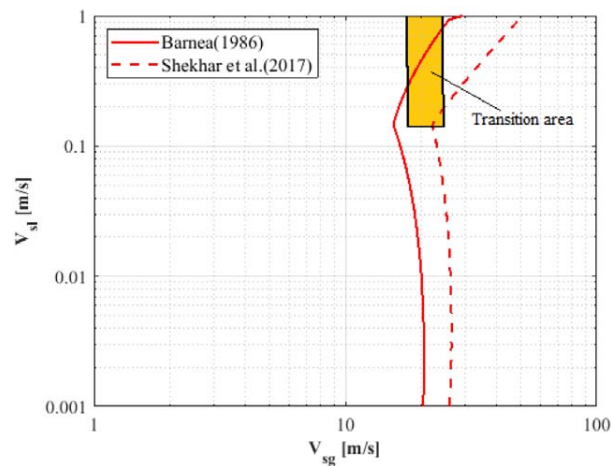


Figure 10—Comparison between experimental data with prediction models for 45° inclined pipe

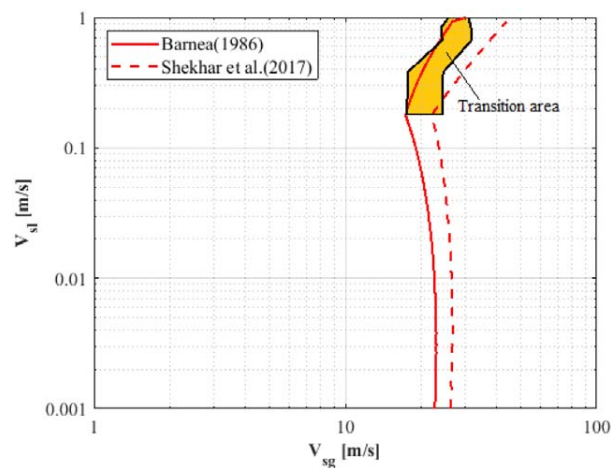


Figure 11—Comparison between experimental data with prediction models for 60° inclined pipe

It can be observed in Figure 9 that Barnea's model has a better prediction than Shekhar's model, since the line pass through a bigger part of the area, this can also be observed on Figure 10 and Figure 11.

Experimental data from air-water flow system were used in this study. The data were collected from a work done by Vieira et al. (2019) and presented in Table 3.

Table 3—Experimental data for liquid loading air-water, 60 mm ID at STP conditions [Vieira et al. \(2019\)](#)

| Pipe inclination (degree) | $V_{sl}$ (m/s) | $V_{sg,slug}$ (m/s) | $V_{sg,onset LL}$ (m/s) | $V_{sg,annular}$ (m/s) |
|---------------------------|----------------|---------------------|-------------------------|------------------------|
| 30                        | 0.01           | 16.99               | 19.47                   | 21.57                  |
|                           | 0.02           | 18.85               | 22.40                   | 25.34                  |
|                           | 0.05           | 21.68               | 23.32                   | 25.24                  |
|                           | 0.1            | 21.78               | 25.32                   | 30.08                  |
|                           | 0.2            | 23.40               | 25.63                   | 29.65                  |
| 40                        | 0.01           | 16.73               | 19.80                   | 20.97                  |
|                           | 0.02           | 20.36               | 21.46                   | 23.73                  |
|                           | 0.05           | 24.27               | 25.19                   | 26.88                  |
|                           | 0.1            | 23.66               | 24.76                   | 26.95                  |
|                           | 0.2            | 23.40               | 24.69                   | 26.07                  |
| 60                        | 0.01           | 18.72               | 19.48                   | 20.20                  |
|                           | 0.02           | 20.72               | 21.72                   | 22.58                  |
|                           | 0.05           | 22.54               | 23.70                   | 27.09                  |
|                           | 0.1            | 23.99               | 25.57                   | 28.90                  |
|                           | 0.2            | 23.27               | 25.77                   | 25.77                  |

[Vieira et al. \(2019\)](#) studied the effect of droplet entrainment on the prediction of critical gas velocity in gas wells. They compared field data from the literature and performed an experimental study on two-phase flow for 60mm ID in an inclinable pipe. Air and water (998 kg/m<sup>3</sup>, 60mN/m) were used as test fluid. In their data they reported the loading, unloading and onset of liquid loading points. They concluded that for low inclination angles the effect of droplet entrainment on the prediction of critical gas velocity was considerable. They compared the observed onset of liquid loading point with the model prediction from [Barnea \(1986\)](#), [Luo et al. \(2014\)](#) and [Shekhar et al. \(2017\)](#).

The model showed to have an improvement on the critical gas velocity when the droplet entrainment were considered. In general, [Shekhar et al. \(2017\)](#) showed to perform well for lower inclination angles, while for inclination greater than 60°, the model of [Barnea \(1986\)](#) presented a better agreement with the data.

With the propose of seeing the effect of fluid properties of the onset of liquid loading, experimental data for air-water, air-light oil and air-viscous oil system were plotted and presented in [Figure 12](#) to [Figure 14](#).

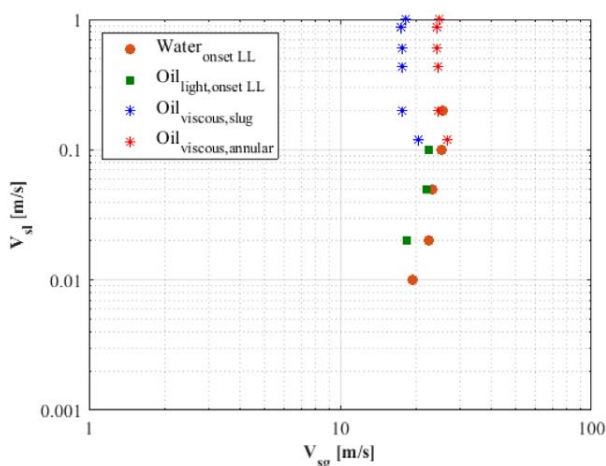


Figure 12—Experimental data for air-water, air-light oil and air-viscous oil system for 30° inclined pipe

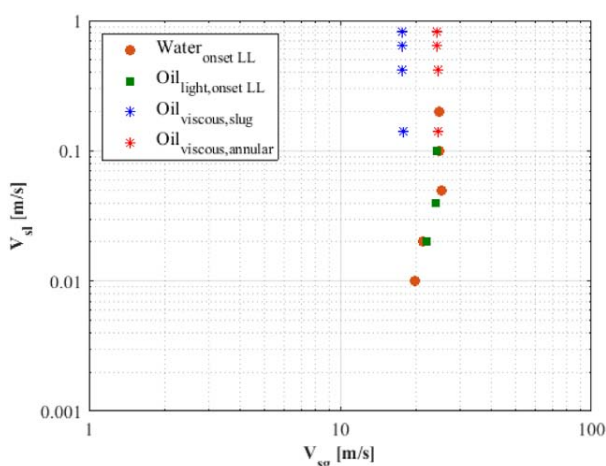


Figure 13—Experimental data for air-water, air-light oil and air-viscous oil system for 45° inclined pipe

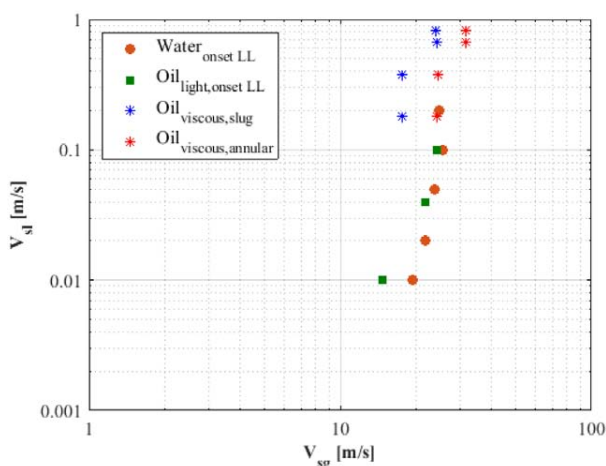


Figure 14—Experimental data for air-water, air-light oil and air-viscous oil system for 60° inclined pipe

It can be seen in Figure 12 to Figure 14, that the critical gas velocity predicted for water and light oil are almost the same for all inclination angles. This may be due to the fact that both fluid showed slight difference on properties. Due to this they presented the same behavior with the respect of model performance. In

the case of viscous oil where the superficial liquid velocities used were not small the behaviour observed was distinct. Note

## Conclusion

An experiment study on the applicability of the available model used to predict the critical gas velocity in inclined gas well has been conducted. Different liquid film and liquid droplet model were evaluated for air-water, air-light oil and air-viscous oil system in inclined pipe. From the work presented the following conclusion were derived:

- Droplet model under estimate the critical gas velocity for all the tested inclinations.
- The dynamic multiphase flow simulator do not predict the transition of intermittent (slug) to annular transition for inclination lower than 60 degrees. Instead, a transition from slug to stratified wavy flow was defined.
- Overall, Luo et al. (2014) model over estimate the transition of intermittent to annular flow, thus given a worse performance for the liquid film model group.
- On air-water and air-light oil the model presented by Shekhar et al. (2017) showed to perform well in inclinations lower than 60°, where the effect of film thickness is more relevant.
- At inclination above 60°, Barnea (1986) model showed to better prediction compared to Shekhar et al. (2017) model.
- For high liquid velocities Barnea (1986) model gives a better prediction than Shekhar et al. (2017) model for two-phase flow with viscous liquid for all the inclinations.
- Experimentally the critical gas velocity found for viscous oil was smaller comparing with the other fluids.

## Nomenclature

- $A$  = area,  $m^2$   
 $N$  = number of experimental points  
 $v_{sg}$  = superficial gas velocity,  $m/s$   
 $v_{gc}$  = critical gas velocity,  $m/s$   
 $v_{sl}$  = superficial liquid velocity,  $m/s$   
 $\rho_l$  = liquid density,  $kg/m^3$   
 $\rho_g$  = gas density,  $kg/m^3$   
 $\delta_l$  = liquid film thickness,  $mm$   
 $\theta$  = pipe angle of inclination, degrees  
 $\sigma$  = surface tension,  $N/m$   
 $\varphi$  = circumferential position in the pipe

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# Effect of droplet entrainment in liquid loading prediction

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## ABSTRACT

The present work investigate the effect of droplets entrainment on critical gas velocity, using the liquid film reversal model from Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017). Especial attention was given to the onset of liquid loading in gas well. Experimental and field data were considered for model evaluation. Field data were taken from published data (Turner et al., 1969, Belfroid et al., 2008 and Veeken et al., 2010). Experiments were performed at the multiphase laboratory (EPT-NTNU) in an upward inclinable pipe. The test section was 6 m long and 60 mm ID. Inclination angles varied from 30° to 70° from horizontal. The fluids used were air and water. Measurements included fluid velocities and reversal point. High-speed video cameras were used to record the flow regime transition (slug to annular) present in the system. Prediction using the film reversal models revealed that the model over-estimate the critical gas velocity compared to results where entrainment is neglected.

## 1 INTRODUCTION

Most gas wells produce liquid as co-produced fluid during well production. Liquid flows along with the gas core as droplets or liquid film on the tubing wall. At the beginning of the production, the gas rate is sufficient to carry all the produced fluid to the surface. However, the declining on the reservoir pressure, the gas production rate decreases until the current gas velocity is insufficient to lift the liquid to the surface. Once this condition is establish, fraction of the liquid starts to flow counter-current to the gas core and accumulates at the bottom of the well, creating a static column of liquid. This accumulation causes backpressure against the formation, which affect the production capacity of the well, making the well produce at unstable flow condition. If the well keep producing at unstable condition, it may lead to a premature abandonment of the well or in some case to wrong well test calculations due to slugging or churning of the liquid.

Several models were proposed to predict the inception of liquid loading in gas wells. Most models are based on two physical models for liquid removal in gas well first proposed by Turner et al. (1969):

**Droplet model** – the liquid is transported as droplets that entrained in the high velocity gas core.

**Liquid film reversal model** – the liquids transported as film moving along the walls of the pipe.

Although the two models are probably in continuous exchange between the gas core and liquid film, they are threated separately. Turner et al. (1969) stated that the droplet model predict liquid loading better. They concluded that there exists a minimum gas velocity required to remove the largest drops. The proposed equation was adjusted 20 percent to insure match with field data. Many researches, such Coleman et al. (1991), Nosseir et al. (1997), Li et al. (2001), Guo et al. (2005), Belfroid et al. (2008) and Veeken et al. (2010) made refinements and modifications to the Turner droplet model to better match different



set of data, with various degrees of success. Even though the droplet model is simple, easy to use and tune, there are some field and experimental evidence that shows limited predictability.

Different from the droplet model, the liquid film reversal model assumes that the liquid loading occurs when the liquid film along the pipe wall, can no longer be lifted to the surface. It has been extensively used and associated to flow pattern transition from annular to intermittent flow. Barnea (1986) proposed a unified model that predicts flow pattern transition for the whole range of pipe inclination for gas-liquid system. In the model, the transition from annular to intermittent flow is assumed to exist due to liquid film instabilities and gas core blockage. Luo et al. (2014) proposed a new model based on the Barnea (1986) model showing a better prediction result over droplet model. In the model they used Fore et al. (2000) equation instead of Wallis (1969) equation for the interfacial friction factor calculations and introduced a new equation for film thickness around the pipe. Barnea (1986) model the film thickness around the circumferential position of the pipe is assumed to be constant. However, studies done by Paz (1994) show that the liquid film structure and thickness varied with pipe inclination. With the change in inclination from vertical to horizontal. The film thickness at the top became thinner, and thicker at the bottom part of the pipe. The film thickness variation also resulted in variation of the deposition and entrainment rate (Shoham, 2006).

Chen et al. (2016) proposed a new model based on force balance of the liquid film and gas core. They developed a correlation term to compare the new model with the widely used Turner et al. (1969) model and evaluate the model using field data from Belfroid et al. (2008). They concluded that the prediction results from the new model had an improvement over the Turner model and for matching the Belfroid et al. data.

Riza et al. (2016), unlike other models, often used the wellhead flow conditions. They predicted flow regime across the entire production tubing to determine where the liquid loading initiates. Through field data, they observed that onset of liquid loading was more likely to occur at the bottom of the well. Shekhar et al. (2017) proposed an improved model for the prediction of onset of liquid loading in inclined pipes, based on the idea of Luo et al. (2014). They assumed a non-uniform film thickness and developed a new correlation for the interfacial friction factor. The model was compared with experimental data, showing a great improvement over droplet model and the Luo et al. (2014) model.

A literature review revealed that all the film reversal models were developed based on the assumption that liquid in the well is transported in the form of film, neglecting the droplets entrainment in the gas core. This assumption can overestimate the film thickness and therefore the critical gas velocity calculations. To evaluate the effect of droplet entrainment in the liquid film the field data from Turner et al. (1969), Belfroid et al. (2008), Veeken et al. (2010) and experimental data were used. To account the fraction of liquid droplet entering in the gas core ( $E$ ), empirical correlation developed from a regression analyse proposed by Oliemans et al. (1986) were used:

$$\frac{E}{1-E} = 10^{-2.52} \rho_L^{1.08} \rho_G^{0.18} \mu_L^{0.27} \mu_G^{0.28} \sigma^{-1.80} D^{1.72} v_{SL}^{0.70} v_{SG}^{1.44} g^{0.46} \quad (1)$$

Film liquid models from Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017) were preferred to be evaluated in this study, since they are widely used to estimate the annular – intermittent flow-transition for inclined pipes and for critical gas velocity prediction in gas wells.

## 2 EXPERIMENTAL SET UP

The experiments were carried out for two-phase flow using a 60 mm ID, 6 m long transparent acrylic pipe for visualisation. The test section was supported on a steel beam connected to a lift mechanism designed to vary angles of inclination. Experiments were performed with upward inclination angles of 30°, 45°, 60° and 70°. The phases are measured separately using a Coriolis and vortex flow meter. They entered the test section through a mixing tee at the bottom, flow through the pipe and separated primarily at the top where the gas phase was vented to the atmosphere and liquid phase was recirculated back to the main separator located in the basement. Compressed air, supplied by the university network, and water ( $\rho_w=998\text{kg/m}^3, \sigma=0.06\text{N/m}$  at 20°C and 1 atm) were used as test fluids. The water was stored with oil in the main separator. The surface tension of water appear to be lower than pure water (typically 0.072N/m), probably due to contamination by surface active agents coming from either the oil or small amounts of organisms living in the water. Further details of the experimental facility can be found in Vieira et al. (2018).

Preliminary tests were performed for each selected inclination in order to define the experimental matrix that covers annular to intermittent flow where liquid loading is expected to occur. Superficial gas and liquid velocities ranged from 55 to 5 m/s, and 0.01 to 0.2 m/s respectively. A high speed camera (GoPro Hero 6 Black®) was installed in the test section; videos supported the observed reversed point (onset liquid loading).

## 3 MODEL VALIDATION

Experimental data and field data from Turner et al. (1969), Belfroid et al. (2008) and Veeken et al. (2010) were used to confirm the ability of the liquid film models to predict the onset of liquid loading, assuming droplet entrainment in the gas core.

In addition to validate the models, a percentage deviation ( $\epsilon$ ) was calculated, using the following equation (2).

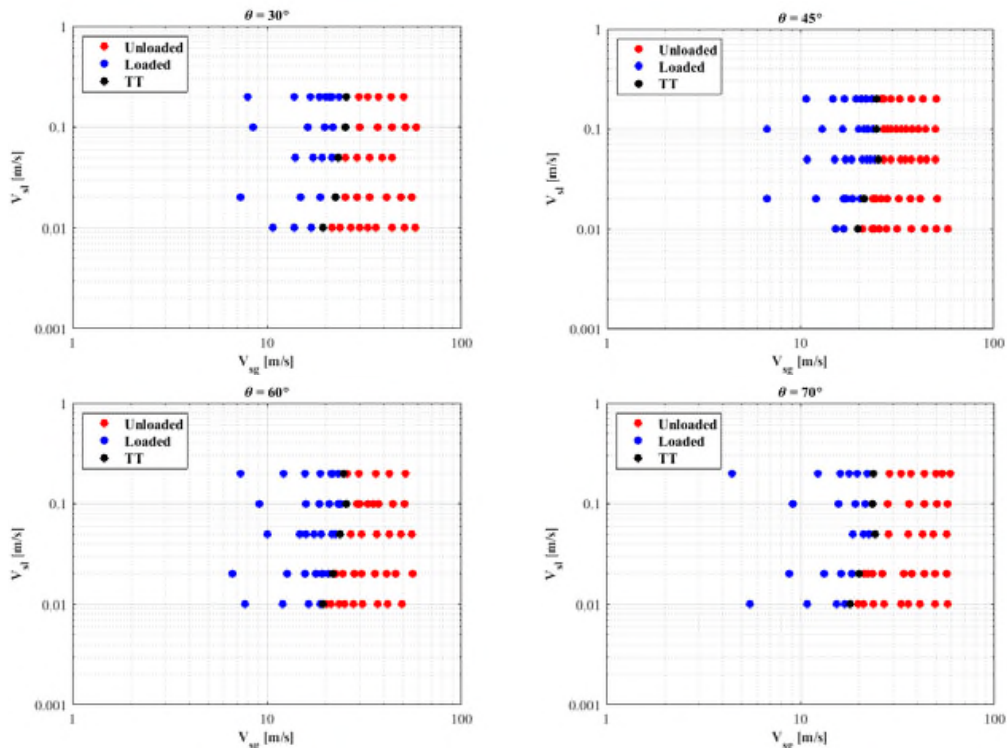
$$\epsilon(\%) = \frac{1}{N} \frac{100}{\sum \left( \frac{v_{sg,model} - v_{sg,observed}}{v_{sg,model}} \right)} \quad (2)$$

If  $\epsilon > 0$  the predicted critical gas velocity is higher than the observed, else  $\epsilon < 0$  the prediction values are lower. Therefore, if the deviation approaches zero it means there is a perfect match between the calculated and observed critical gas velocity.

### 3.1 Experimental data

The effect of droplet entrainment on critical gas velocity for predicting the onset of liquid loading was studied by considering four different inclination angles. For each inclination angle, five superficial liquid velocities, and for each liquid velocity, 14 superficial gas velocities were tested. Thus, significant amount of data points were collected. Experimental data points were subdivided into two groups; *Unloaded* in the case annular flow was observed and *loaded* for intermittent flow (see **Fig. 1**).





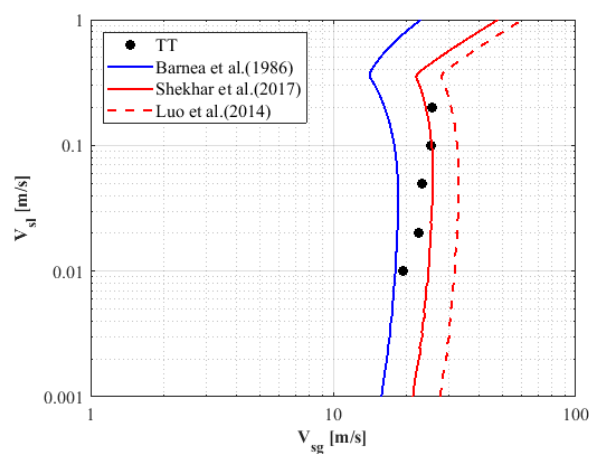
**Fig. 1** Experimental data for air-water system at STP for different inclinations

A true transition point (TT) was calculated by averaging the last loaded two point (right-most blue point) and the first unloaded (red) for each superficial liquid velocity.

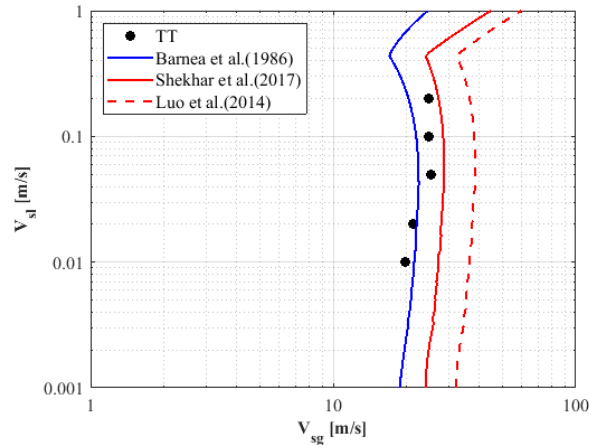
In **Fig. 2** through **Fig. 5**, true transition points represent the critical gas velocity values ( $V_{sg,critical}$ ) and continuous and dashed line represent the liquid film models, assuming no entrainment in the gas core.

It can be observed from **Fig. 2** that the Shekhar et al. model has a better approximation with the TT points than the two other models. However, in **Fig. 3**, **Fig. 4** and **Fig. 5** the transition line is best predicted by Barnea model.

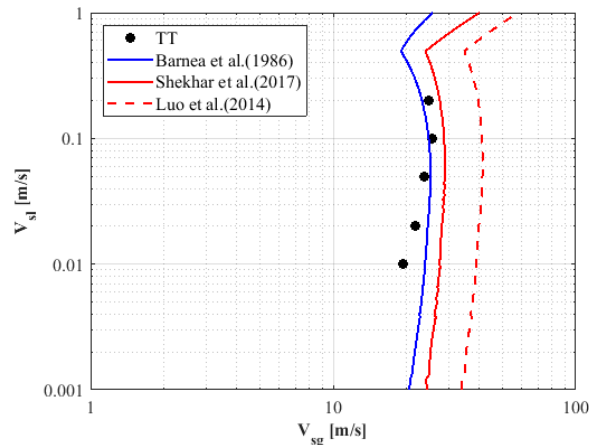
The similarity of both models on high inclination is due to the fact that the film thickness distribution around the inner pipe is almost constant. Thus, Shekhar et al. (2017) approaches Barnea (1986) model. Barnea assumes constant film thickness for all inclination angles.



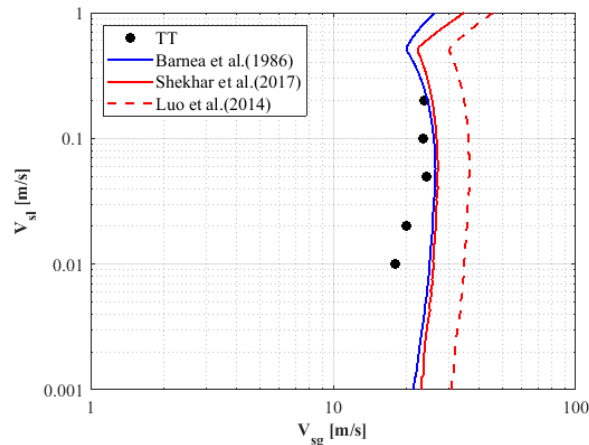
**Fig. 2** Experimental data for air-water system at STP for 30-degree inclination angle



**Fig. 3 Experimental data for air-water system at STP for 45-degree inclination angle**



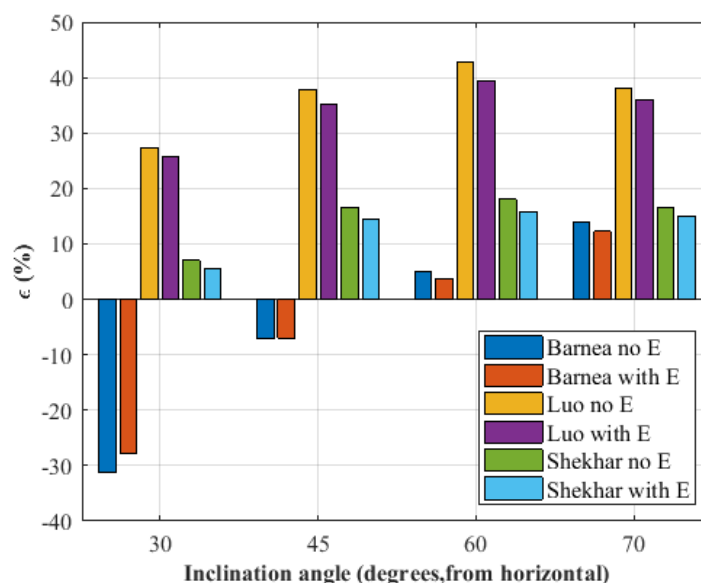
**Fig. 4 Experimental data for air-water system at STP for 60-degree inclination angle**



**Fig. 5 Experimental data for air-water system at STP for 70-degree inclination angle**

Overall, it is observed that the model proposed by Luo et al. (2014) over estimate the transition of annular to intermittent flow for all the inclination. Predictions of  $v_{sg,critical}$  using

the liquid film models, assuming droplet entrainment were also performed and compared with the laboratorial data, and the was presented as a percentage. In **Fig. 6** it can be observed that the prediction of critical gas velocities with droplet entrainment present slight better results in general.



**Fig. 6 Deviation for all the models prediction with and without entrainment for the laboratory data**

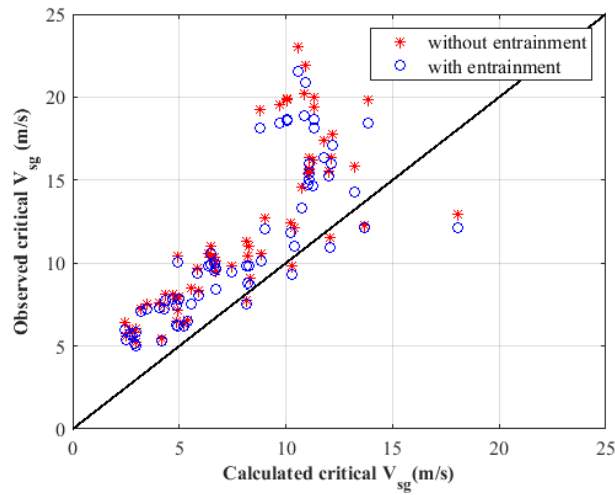
Barnea, 1986 model for lower inclination present negative deviation meaning that model predicted much lower velocities at which liquid loading occurs. This may also be, because of the film thickness that was considered constant in the model.

Values not lower that 10% of deviation were not observed through the experimental data comparison with the models, due to the fact that transition point were not always very clear, which mean that experimentally the transition could be misinterpreted.

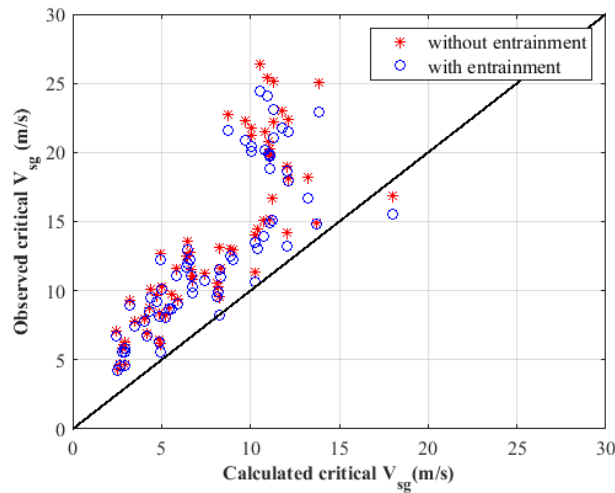
### 3.2 Field data

Three different set of field data were used to evaluate the importance of droplet entrainment during the prediction of onset of liquid loading. **Veeken et al. (2010)** published 67 gas wells from North Sea that were starting to experience liquid loading. The gas wells had from 2-6 inches of tubing diameter and included vertical and inclined pipe geometry (0 to 64° inclination angles from vertical). The liquids produced were condensate and water. Liquid gas ratio was assumed to be 5 bb/MMcf in the calculation as recommended by Luo et al. (2014). Veeken et al. (2010) reported the gas rate after the onset of liquid loading, which means that all the data should be located sight above the 45° line (loaded region) in the plot of calculated critical gas velocity ( $v_{sgc,model}$ ) and the observed gas velocity ( $v_{sgc,observed}$ ).

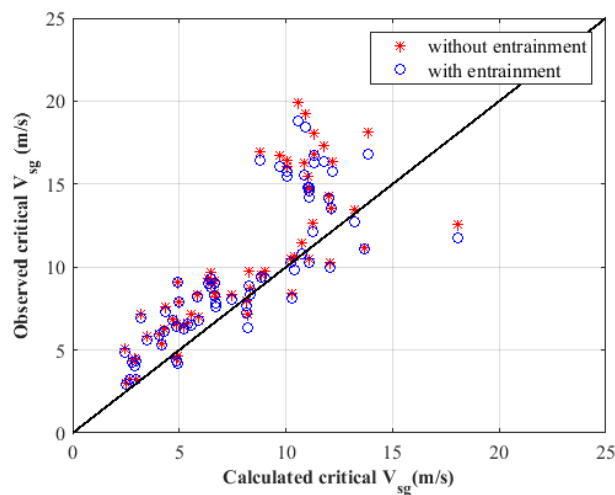
**Fig. 7 to Fig. 9** observed gas velocities of Veeken et al., 2010 were compared with critical gas velocities predicted by Barnea (1986), Luo et al. (2014) and Shekhar et al. (2017) models, with and without droplet entrainment. It can be seen that most of the wells are in the loaded region for both cases. It is also observed that when droplet entrainment are considered for the critical gas velocity calculation most of the points on the graphs are close to the 45° line, suggesting that the well have just started to load.



**Fig. 7 Veeken et al. (2010) data vs Barnea (1986) model prediction**



**Fig. 8 Veeken et al. (2010) data vs Luo et al. (2014) model prediction**



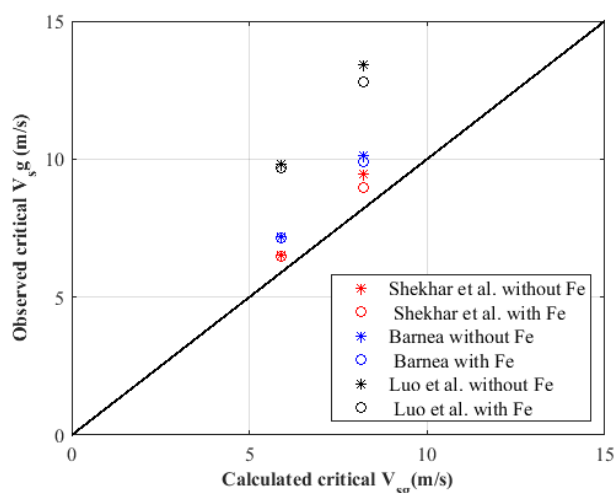
**Fig. 9 Veeken et al. (2010) data vs Shekhar et al. (2017) model prediction**

For an ideal model, the points have to be slight above the 45° line and the percentage deviation should be positive and close to zero. From **Table 1** result, it is clear that Shekhar et al., 2017 model, assuming entrainment presents best result, although the number of well predicted correct is the same.

**Table 1. Critical gas velocity prediction for Veeken et al. (2010) data**

| Model                 | Without Entrainment      |                | With Entrainment         |                |
|-----------------------|--------------------------|----------------|--------------------------|----------------|
|                       | Number of well predicted | $\epsilon(\%)$ | Number of well predicted | $\epsilon(\%)$ |
| Barnea (1986)         | 62/67                    | 32.40          | 62/67                    | 28.49          |
| Luo et al. (2014)     | 66/67                    | 40.78          | 65/67                    | 37.35          |
| Shekhar et al. (2017) | 57/67                    | 19.94          | 54/67                    | 16.71          |

**Belfroid et al. (2008)** published data for two gas wells, both had a deviation of 40 degree. One well had 0.112 m for the tubing diameter and observed critical gas rate of 90 000 Sm<sup>3</sup>/d, and the other 0.074 m for the tubing size and 45 000 Sm<sup>3</sup>/d for critical gas rate. For both well sufficient data were shared, which made possible the calculation. Since the well were also reported at critical condition, the predicted results is expected to be above the 45°-line, which can be seen in **Fig. 10**. The same as Veeken et al. data, **Table 2** shows that critical gas velocity prediction assuming droplet entrainment present improved having a positive and small value for the perceptual deviation.



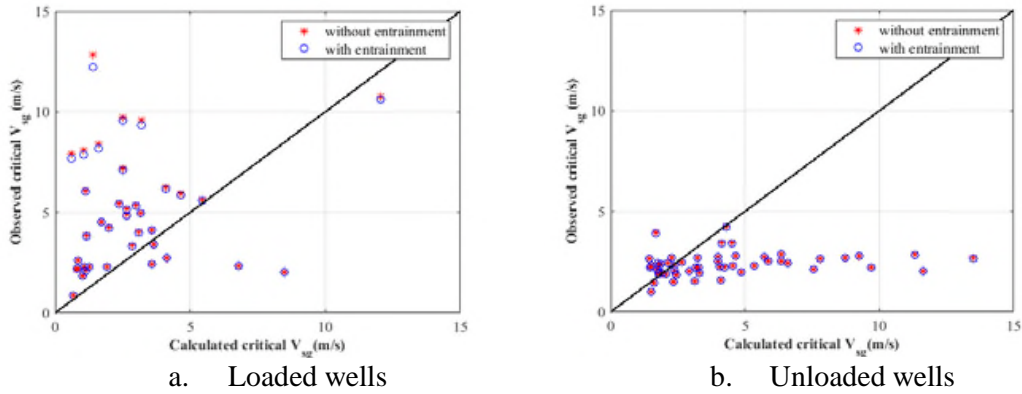
**Fig. 10 Belfroid et al. (2008) data vs liquid film models prediction**

**Table 2. Critical gas velocity prediction for Belfroid et al. (2008) data**

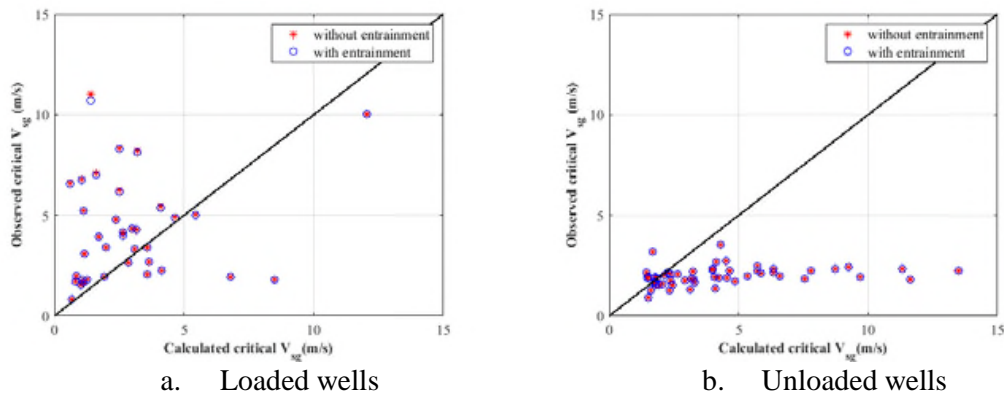
| Model                 | Without Entrainment      |                | With Entrainment         |                |
|-----------------------|--------------------------|----------------|--------------------------|----------------|
|                       | Number of well predicted | $\epsilon(\%)$ | Number of well predicted | $\epsilon(\%)$ |
| Barnea (1986)         | 2/2                      | 18.58          | 2/2                      | 17.32          |
| Luo et al. (2014)     | 2/2                      | 39.42          | 2/2                      | 37.42          |
| Shekhar et al. (2017) | 2/2                      | 11.41          | 2/2                      | 8.72           |

**Turner et al. (1969)** presented data for 90 gas wells, where 37 were experiencing liquid loading and 53 were producing at stable conditions (unloaded). All the wells were reported as vertical (0° inclination angle).

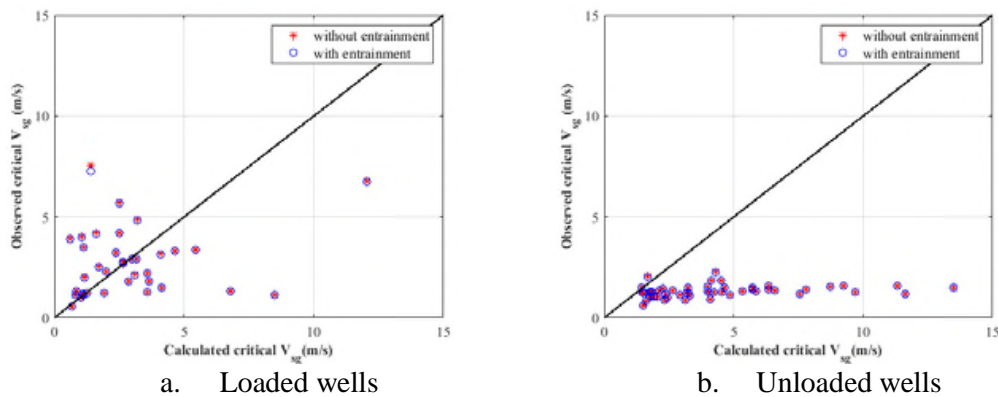
From **Fig. 11** to **Fig. 13**, observed critical gas velocity is compared with the calculated critical gas velocity using the model with and without entrainment. When the calculated velocity is higher than the observed the well is consider loaded. If the calculated velocity is is, lower than the observed the well is defined as unloaded. In case the well is unloaded the data point should be located slight below the 45° line in the plot. It can be that for Turner et al., 1969 data, droplet entrainment does not influence the prediction of critical gas velocity. Shoham (2006) mentioned that the film thickness variation changes the variation of the deposition and entrainment rate. Since the published well present vertical geometry, film thickness was considered constant.



**Fig. 11 Turner et al. (1969) data vs Barnea (1986) model prediction**



**Fig. 12 Turner et al. (1969) data vs Luo et al. (2014) model prediction**



**Fig. 13 Turner et al. (1969) data vs Shekhar et al. (2017) model prediction**

For all the model the prediction of unloaded well is accurate i.e., the data points are located below the 45° line. However, the percentage deviation calculated is high in the case of Luo et al. (2014) and Shekhar et al. (2017) as shown in **Table 3**. Although the film thickness correlation introduced in both model to account the effect of inclination do not have any effect, the interfacial friction factor used in the model overestimate the critical gas velocity in vertical gas wells. On the other hand Barnea (1986) model shows better prediction in both number of well and percentage deviation.

**Table 3. Critical gas velocity prediction for Turner et al. (1969) data**

| <b>Well at loaded condition</b>   |                          |                   |                          |                   |
|-----------------------------------|--------------------------|-------------------|--------------------------|-------------------|
| Model                             | Without Entrainment      |                   | With Entrainment         |                   |
|                                   | Number of well predicted | $\varepsilon(\%)$ | Number of well predicted | $\varepsilon(\%)$ |
| Barnea (1986)                     | 31/37                    | 26.01             | 31/37                    | 25.65             |
| Luo et al. (2014)                 | 28/37                    | 12.16             | 28/37                    | 12.02             |
| Shekhar et al. (2017)             | 20/37                    | -33.82            | 20/37                    | -33.97            |
| <b>Well at unloaded condition</b> |                          |                   |                          |                   |
| Barnea (1986)                     | 41/53                    | -82.06            | 40/53                    | -82.28            |
| Luo et al. (2014)                 | 46/53                    | -114.56           | 46/53                    | -114.49           |
| Shekhar et al. (2017)             | 51/53                    | -216.08           | 51/53                    | -216.17           |

#### 4 CONCLUSION

In the study, field and experimental data were compared with liquid film model, used to predict critical gas velocity in gas well. The proposed liquid film model assumes no entrainment of droplets in the gas core. Therefore, the present work was performed to verify the effect of entrainment on the liquid film model when critical gas velocity is predicted.

A comprehensive conclusion based on the data comparison with the models was that droplet entrainment had an effect on the accuracy of critical gas velocity predictions for the onset liquid loading.

Overall, Luo et al. (2014) model over estimates the transition from annular to intermittent flow for all cases studied.

The liquid film model of Barnea (1986) model was developed to predict the transition of annular to intermittent flow transition in both vertical and deviated pipe. However, in most of the case showed not be better than Shekhar et al. (2017) model, due to the assumption that the film thickness is constant for all pipe inclinations.

In the case of gas wells with vertical geometry, droplet entrainment does not have any effect on the critical gas velocity prediction. The film thickness is constant at such geometry and the variation of the deposition or entrainment rate in the gas core is negligible. Luo et al. (2014) and Shekhar et al. (2017) showed not to be a good model to be used when the well is vertical in case accurate critical gas velocity is crucial.

#### 5 ACKNOLOGMENTS

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## 6 NOMENCLATURE

|                  |  |
|------------------|--|
| ID               | pipe inner diameter (m)                        |
| E                | entrainment fraction(-)                        |
| g                | gravitational acceleration (m <sup>2</sup> /s) |
| N                | number of points or wells.                     |
| v <sub>sg</sub>  | superficial gas velocity (m/s)                 |
| v <sub>sgc</sub> | critical gas velocity (m/s)                    |
| v <sub>sl</sub>  | superficial liquid velocity (m/s)              |
| θ                | Angle of inclination from horizontal (degrees) |
| μ <sub>g,l</sub> | gas, liquid viscosity (Pa.s)                   |
| ρ <sub>g,l</sub> | gas, liquid density (kg/m <sup>3</sup> )       |
| σ                | surface tension (N/m)                          |

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