Master's thesis 2019	Master's thesis
BEATRICE ISSARA	Norwegian University of Science and Technology Faculty of Engineering Department of Geoscience and Petroleum

**BEATRICE ISSARA** 

## Modeling of Oil-Water Flow Development Along the Pipe Downstream a Choke Valve

August 2019







### Modeling of Oil-Water Flow Development Along the Pipe Downstream a Choke Valve

**BEATRICE ISSARA** 

MSc. Petroleum Engineering Submission date: August 2019 Supervisor: Milan Stanko Co-supervisor: Heiner Schümann

Norwegian University of Science and Technology Department of Geoscience and Petroleum

### Abstract

The main objective of the thesis is to propose and test a way to model flow development downstream a choke valve.

Experiments were performed in the SINTEF medium scale flow loop in order to study oil-water flow development along the pipe. The test section was a horizontal, 10.91cm diameter, 220m long pipe with three 180° bends and inlet mixing valve at the beginning of the section. There were four 0.5m long transparent sections with video recordings, three traversing gamma densitometers and three droplet size distribution measurements (Canty Inflow Particle sizer) along the test section. The experiments in this setup were done in two campaigns with different oils. In June 2018, a mixture of Exssol D60 (density 789  $kg/m^3$  and viscosity 1.43cp) and tap water with Span 83 surfactant added to the oil was used. The mixture velocities tested were 1, 1.5 and 2m/s with water cuts between 0-75%. The second campaign in March 2019, tap water and a mineral oil blend of Primol 352 and Exxsol D80 (density 850  $kg/m^3$  and viscosity 35cp) was used with Span 80 surfactant added to the oil. The mixture velocities tested were 0.5, 1 and 1.5m/s for water cuts between 0-90%.

Flow patterns are identified by using the video recordings and phase fraction profiles from the gamma densitometers. The identified flow patterns include Stratified mixed (SM), Homogeneous oil continuous dispersion (Do-H), Inhomogeneous oil continuous dispersion (Do-I), Inhomogeneous water continuous dispersion (Dw-I), Oil continuous dispersion with a dense layer of water droplets (Do-DP), Water continuous dispersion with a dense layer of oil droplets (Dw-DP) and Oil continuous dispersion with a dense layer of water droplets and a water layer (Do-DP + w). The flow patterns identified are classified in flow pattern maps as functions of

either mixture velocity and water cut or superficial velocities of oil and water. The measured pressure gradients are related to the flow patterns. The phase inversion point is observed at a mixture velocity 1.5m/s with 25% water cut with a peak of 322 Pa/m pressure gradient.

The effect of pressure drop across the inlet mixing valve to the flow development along the pipe is analyzed in terms of pressure gradient and local dispersion factor. For both campaigns, the increase in pressure drop across the mixing valve leads to increase in the pressure gradient. For 2018 campaign, the pressure gradient along the pipe begins by increasing due to settling of droplets before it starts decreasing due to formation of free water layer. For 2019 campaign, the pressure gradient trend was a gentle decrease along the test section because the flow was dispersed throughout the test section. For experiments with the same water cut and pressure drop across the mixing valve, higher flow rate causes a delayed separation of phases along the pipe. Clear flow development and lower average pressure gradients are seen for the 2018 campaign compared to 2019 campaign; this is associated with higher oil viscosity in the 2019 campaign.

A dynamic model from Schümann (2016) is modified and used to predict the flow development along the pipe. The model consists of three sub-models named valve model for determining the initial droplet size, phase distribution model for determining the heights and areas of the oil, dispersion and water layer, and the pressure gradient model for calculating the pressure gradient along the entire test section. In this model, the mixture is assumed to be initially homogeneous dispersed with a single droplet size and the phase distribution considers two main mechanisms: droplet settling and coalescence. The results from the model compared to the experimental results show a satisfactory agreement in the interfacial tension positions and the droplet sizes. The pressure gradient model does not give the same trend as in the experiment but the average value of pressure gradient compares well with the experimental values.

## Acknowledgement

Foremost, I would like to thank Heiner Schumann for his valuable guidance as my supervisor. He set aside time for discussions and shared his brilliant knowledge in multiphase flow. His quick responses and support throughout this thesis is extremely appreciated.

My sincere thanks goes to Prof. Milan Stanko at the Norwegian University of Science and Technology (NTNU) for agreeing to be my supervisor and his substantial input in creating the framework of this thesis. His support and understanding throughout the duration of the thesis is greatly revered.

I would like to extend my profound gratitude to Equinor and the Norwegian University of Science and Technology (NTNU) for fully sponsoring my master's education. Without this support, it would have been hard to concentrate in my studies. My heartfelt thanks go to my family for their constant love and support. My father, mother and my siblings have been endlessly encouraging me during my studies.

I would like to thank my fellow students in the ANTHEI program. They have been like a second family to me. Special gratitude goes to Rehema Kivuyo and Mohammed Said for their constructive criticism on my work and constantly challenging me to improve my work.

# Contents

A	bstrac	et		i
A	cknow	ledgme	enti	iii
Ta	ble of	Conte	ats	vi
Li	st of H	ligures		ix
Li	st of 7	ables.		X
N	omeno	clature		iv
1	Intr	oductio	n	1
	1.1	Object	ives	3
	1.2	Organi	zation of the report	4
2	Lite	rature ]	Review	5
	2.1	Basic o	definitions in oil-water flow	5
	2.2	Flow p	patterns	6
		2.2.1	Classification of flow patterns	6
		2.2.2	Flow pattern Maps	2
		2.2.3	Factors affecting flow patterns	3
		2.2.4	Phase Inversion	17
	2.3	Pressu	re Gradient	8
		2.3.1	Pressure Gradient in Single Phase Flow	8
		2.3.2	Pressure Gradient in Liquid-Liquid Flow	9
	2.4	Drople	et Dynamics	21
		2.4.1	Droplet sizes and distribution	22

		2.4.2	Droplet Breakup	23
		2.4.3	Droplets Coalescence	24
3	Ехр	eriment	tal Description	26
	3.1	Setup.	- 	26
	3.2	Instru	nentation	27
		3.2.1	Pressure measurements	27
		3.2.2	Optical sections	28
		3.2.3	Traversing gamma densitometers	29
		3.2.4	Droplet size distribution measurements	30
	3.3	Fluid S	System	31
	3.4	Data Q	Quality	32
	3.5	Test M	Iatrix	33
4	Flov	v Patter	ns	35
	4.1	Identif	ied flow patterns	35
	4.2	Local	phase fraction measurements	41
	4.3	Flow F	Pattern Maps	44
	4.4	Flow F	Patterns and Pressure gradient	47
5	Flov	v Develo	opment Analysis	50
	5.1	Effect	of pressure drop across the mixing valve	50
		5.1.1	Local water fractions	50
		5.1.2	Pressure Gradient and Dispersion Factor	54
	5.2	Effect	of flow rate	64
	5.3	Effect	of viscosity	65
6	Mod	leling .		66
	6.1	Model	description	66
	6.2	Modifi	ications to the model	70
	6.3	Model	results	71
7	Unc	ertainti	es and Sources of Errors	74
	7.1	Bend e	effect	74
	7.2	Pipe cl	leanliness	75

	7.3	Calibra	tion and instru	ment errors	S	 	•		 •	 •				 77
	7.4	Errors	due to the natur	re of the flo	ow.	 	•		 •			 •		 77
	7.5	Humar	errors			 	•		 •	 •	 •	 •	•	 77
8	Con	clusion	and Recomme	ndations .		 	•		 •	 •	 •		•	 78
Bi	bliog	caphy.				 	•		 •	 •	 •		•	 81
Aj	opend	lices				 	•	 •	 •	 •			•	 85
A	Pipi	ng and	Instrumentatio	on Diagran	n.	 	•		 •	 •	 •		•	 85
B	Pha	se Fract	ion Profiles .			 	•		 •	 •	 •		•	 87
С	Flov	v Develo	opment			 	•		 •			 •	•	 103
	<b>C</b> .1	Pressu	re gradient vs w	ater cut		 	•		 •	 •		 •	•	 103
	C.2	Local	water fraction.			 	•		 •			 •		 105
	C.3	Pressu	re gradient vs d	ispersion .		 • •	•		 •	 •	 •	 •	•	 109
D	Mat	lab Cod	es			 	•		 •	 •	 •	 •	•	 113
	D.1	Dynam	nic model			 	•		 •	 •			•	 113
		D.1.1	Main code			 	•		 •	 •			•	 113
		D.1.2	Valve model .			 	•		 •			 •		 119
		D.1.3	Settling Veloc	ity model .		 	•		 •			 •		 120
		D.1.4	Phase distribu	tion model		 	•		 •	 •		 •		 120
		D.1.5	Pressure Grad	ient model		 	•		 •			 •		 123
		D.1.6	Sample results	s of the mo	del	 	•		 •			 •		 125

# **List of Figures**

2.1	Stratified flow patterns according to Elseth (2001)	8
2.2	Dispersed flow patterns according to Elseth (2001)	9
2.3	Flow pattern classification according to Arirachakaran et al. (1989)	10
2.4	Flow patterns according to Nädler & Mewes (1997)	11
2.5	Flow Patterns according to Trallero et al. (1997)	12
2.6	Flow patterns according to Schümann (2016)	13
2.7	Flow pattern map ( $U_{mix}$ vs WC) by Trallero et al. (1997)	14
2.8	Flow Pattern map ( $U_{sw}$ vs $U_{so}$ ) by Trallero et al. (1997)	15
2.9	Phase Inversion process for an oil-water dispersion flow (Arirachakaran et al.,	
	1989)	18
2.10	Pressure drop Vs Water cut by Elseth (2001)	20
2 1	SINTEE Madium coole flow loop	27
5.1 2.2	Sin IEF Medium scale now loop	21
3.2	Setup of the optical sections and an image from the camera 2 recording of Op-	20
2.2	December 2 and 4 at 100m and 218.0m respectively	28
3.3	Phase fraction profile from gamma densitometer. $U_{mix} = 1$ m/s, wC = 0.5,	20
2.4	$Dp_{valve} = 0$ bar	30
3.4	inustration of uncertainties in representative sampling of droplets for experi-	21
25		31
3.5		34
4.1	Homogeneous oil dispersion flow pattern; $U_{mix} = 1$ m/s, WC = 0.2, $Dp_{valve} =$	
	0.2bar	36
4.2	In-homogeneous oil dispersion flow pattern; $U_{mix} = 1$ m/s, WC = 0.2, $Dp_{valve} =$	
	0bar	37
4.3	In-homogeneous water dispersion flow pattern; $U_{mix} = 1$ m/s, WC = 0.6, $Dp_{valve}$	
	= 0bar	38

4.4	Oil continuous dispersion with a dense pack of water droplets and a water layer;	
	$U_{mix} = 1 \text{ m/s}, \text{ WC} = 0.3, Dp_{valve} = 0 \text{ bar} \dots \dots$	39
4.5	Water continuous dispersion with a dense pack of oil droplets; $U_{mix} = 1$ m/s, WC	
	$= 0.9, Dp_{valve} = 1 bar \qquad \dots \qquad $	40
4.6	Stratified flow pattern; $U_{mix} = 0.5$ m/s, WC = 0.5, $Dp_{valve} = 0$ bar	40
4.7	Local phase fraction for all water cuts at 218m; fluid system B; $U_{mix} = 0.5$ m/s,	
	$Dp_{valve} = 0$ bar	41
4.8	Local phase fraction for all water cuts at 218m; fluid system B, $U_{mix} = 1$ m/s,	
	$Dp_{valve} = 0$ bar	42
4.9	Local phase fraction for all water cuts at 218m; fluid system B, $U_{mix} = 1.5$ m/s,	
	$Dp_{valve} = 0$ bar	43
4.10	Flow pattern maps ( $U_{mix}$ vs $WC$ ) for four positions of gamma along the pipe	45
4.11	Flow pattern maps $U_{so}$ vs $U_{sw}$ for four positions of gamma along the test section	47
4.12	Pressure gradient vs water cut for $U_{mix} = 0.5$ m/s, 1m/s and 1.5m/s	48
5.1	Local water fraction distribution along the pipe for the bottom section of the	
	pipe; $U_{mix} = 1.0$ m/s, fluid system A	51
5.2	Local water fraction distribution along the pipe for the bottom section of the	
	pipe; $U_{mix} = 1.5$ m/s, fluid system A	52
5.3	Local water fraction distribution along the pipe for the bottom section of the	
	pipe; $U_{mix} = 1.0$ m/s, fluid system B	52
5.4	Pressure gradient and dispersion factor along the test section; $U_{mix} = 1m/s$ , WC	
	= 20%, $DP_{valve} = 0.1bar$ , fluid system B	54
5.5	Pressure gradient and dispersion factor along the test section; $U_{mix} = 1m/s$ , WC	
	= 20%, $DP_{valve} = 0.2bar$ , fluid system B	55
5.6	Pressure gradient and dispersion factor along the test section; $U_{mix} = 1m/s$ , WC	
	= 20%, $DP_{valve} = 0.35bar$ , fluid system B	56
5.7	Pressure gradient and dispersion factor along the test section; $U_{mix} = 1m/s$ , WC	
	= 20%, $DP_{valve} = 0.5bar$ , fluid system B	56
5.8	Pressure gradient and dispersion factor along the test section; $U_{mix} = 1m/s$ , WC	
	= 20%, $DP_{valve} = 1bar$ , fluid system B	57
5.9	Pressure gradient development along the pipe as a function of the $DP_{valve}$	58
5.10	Pressure gradient and dispersion factor development along the pipe; $U_{mix} =$	
	$1m/s$ , WC = 20%, $DP_{valve} = 0bar$ , fluid system A	59

5.11	Pressure gradient and dispersion factor development along the pipe; $U_{mix} =$	
	$1m/s$ , WC = 20%, $DP_{valve} = 0.2bar$ , fluid system A	60
5.12	Pressure gradient and dispersion factor development along the pipe; $U_{mix} =$	
	$1m/s$ , WC = 20%, $DP_{valve} = 0.35bar$ , fluid system A	60
5.13	Pressure gradient and dispersion factor development along the pipe; $U_{mix} =$	
	$1m/s$ , WC = 20%, $DP_{valve} = 0.5bar$ , fluid system A	61
5.14	Pressure gradient and dispersion factor development along the pipe; $U_{mix} =$	
	$1m/s$ , WC = 20%, $DP_{valve} = 1bar$ , fluid system A	62
5.15	Average dispersion factor vs pressure drop across the mixing valve for $U_{mix}=1$ m/s	
	and $U_{mix}=1.5$ m/s for the fluid system A	63
5.16	A comparison of pressure gradients and local average dispersion factor for fluid	
	system A to show the effect of flow rate	64
6.1	Geometry of the three layer model with model definitions for initially oil dis-	
	persed in water	69
6.2	Interfacial positions results from the model compared to experimental results	72
6.3	Critical diameters used in the model and the initial droplet sizes from the valve	
	model	73
7.1	Bend effect on the dispersion factor ; $U_{mix} = 1$ m/s, $DP_{valve} = 1$ bar, fluid system A	75
7.2	Wetting of pipe walls before and after cleaning of the pipe (Schümann, 2016) .	76
7.3	Comparison of pressure gradient measurements along the pipe for a cleaned and	
	dirty test section; Umix=0.5 m/s, fw=40% (Schümann, 2016)	76

# **List of Tables**

5.1	Results for the pressure gradient and local average dispersion factor along the	
	test section for fluid system B at $U_{mix} = 1m/s$ , WC = 20% and different pressure	
	drops across the mixing valve	54
5.2	Results for the pressure gradient and local average dispersion factor along the	
	test section for fluid system A at $U_{mix} = 1m/s$ , WC = 20% and different pressure	
	drops across the mixing valve	59

# Nomenclature

### Symbols and Variables

А	Cross-sectional area of the pipe $[m^2]$
$C_{disp}$	Droplets coalescence rate in the dispersed layer
Cinter	Droplets coalescence rate with the interface
Co	Contamination in oil [-]
Cv	Orifice coefficient (downstream) [-]
Cw	Contamination in water[-]
D	Internal pipeline diameter[m]
d	Droplet diameter [ $\mu m$ ]
DF	Local dispersion factor[-]
Е	Energy dissipation rate
f	Volumetric fraction [-]
fv	Valve opening fraction [-]
g	Acceleration due to gravity $[m/s^2]$
Ι	Intensity $[W/m^2]$
K <sub>L</sub>	Bend pressure drop coefficient [-]
L	Length [m]

LWF	Local water fraction [-]
Nwe	Weber group constant []
Р	Pressure [bar]
Q	Flow rate $[m^3/s]$
Re	Reynolds number []
V	Velocity [m/s]
WC	Water cut [-]
У	Position in pipe cross-section [m]
Δ	Difference
ε	holdup
μ	Viscosity [mPas or cp]
ρ	Density $[kg/m^3]$
σ	Interfacial tension
Φ	Dispersed phase fraction

### Subscripts

0	oil
W	water
с	continuous
dense	dense packed layer
max	maximum
mix, m	mixture
S	superficial
i	index

meas	Measured
perm	Permanent
valve	Inlet mixing valve
b	bottom
m	middle
t	top
f	fraction of droplets breaking in an orifice
nom	nominal

### Abbreviations

Do-DP	Oil continuous dispersion with a dense packed layer of water droplets
Do-H	Homogeneous oil dispersion
Do-I	Inhomogeneous oil dispersion
DP, dP	Pressure drop
DPvalve	Pressure drop across the valve
Dw-DP	Water continous dispersion with dense packed layer of oil droplets
Dw-H	Homogeneous water continuous dispersion
Dw-I	Inhomogeneous water continuous dispersion
O-W	Oil in water emulsion
W-O	Water in oil emulsions
PG	Plug flow
PMMA	Polymethyl methacrylate
SS, ST	Stratified smooth flow
SM, ST&MI	Stratified flow with mixing

SW Stratified wavy

## Chapter 1

## Introduction

Most conventional oil reservoirs contain three zones: a gas zone on top, an oil zone in the middle and a water zone at the bottom. During drilling, the well is positioned so that the oil, with associated gas, is produced first with the pressure in the gas zone assisting this production by expanding and pushing the oil out. In the later years of production, water coning occurs and as a result more water is produced together with oil. The mixture, in most oil fields is transported long distance to the processing facilities where separation of the phases is carried out. The high initial reservoir pressure of the fluids is often used as the mechanism of transport in early reservoir life but as pressure depletes installation of pumps/compressors may be necessary (Devold, 2006).

The flow behavior of oil and water mixture will be different from that of single phase oil. The most important difference is in the pressure gradient of the mixture. This can be explained by following reasons. First, the properties of the mixture like viscosity and density change depending on the individual properties and amount of each phase. Secondly, the way the two immiscible fluids are distributed geometrically in the pipe; this is known as the flow regimes or flow patterns. There are many types of flow patterns but the major ones for liquid-liquid flow are dispersed/mixed flow and segregated/stratified flow. Stratified flow is when both phases are continuous while dispersed flow is when droplets of one phase (dispersed phase) are distributed within another phase (continuous phase). In a long transportation line both types of flow might be present depending on the fluid properties and nature of the flow system. Because

most wellheads contain a choke valve, the flow always starts as a dispersion and then develops to a stratified flow if the route is smooth. The pressure gradient of the flow is dependent on the flow patterns for a particular fluid system. So, when the flow pattern transition to another, a change in pressure gradient occurs (Bratland, 2010).

Design of a transportation line requires the correct prediction of the pressure drop along the line. In order to correctly predict the pressure drop, the flow patterns must be accurately predicted together with the resulting properties of the mixture. For liquid-liquid flow, correct modeling has been achieved with the fully stratified flow. During dispersed flow, the size and distribution of the droplets change due to phenomenon such as droplet coalescence and break-up. Accurate modeling of dispersed flow has not been achieved, mostly due to lack of full understanding of the droplets dynamics (Vielma et al., 2008).

In oil fields, the dispersion starts during the flow in the reservoir. Production and transportation systems include restrictions e.g. tubing and valves, which induces pressure drop by accelerating the mixture and enhances the dispersion by breaking up the droplets. Several authors have proposed models explaining the effects of such restrictions including the mechanism of the droplet break up and the resulting droplet size distribution (Liao & Lucas, 2009). As the fluids continue to flow, droplets are likely to increase in size by coalescence. Coalescence is more complex compared to break-up and a lot of models are in existence which try to describe the phenomenon (Liao & Lucas, 2010).

In the early years of oil production, oil is produced in very low water cuts and a water-in-oil dispersion is likely to be formed. As the production continues, higher amount water is produced with oil and an oil-in-water dispersion will likely be formed. Separation of oil-water dispersion is part of every oil processing system. There are restrictions to the allowable water content in the oil. Also, the water has to be very clean because it will be released in the sea or re-injected in the well. Very small droplets and the presence of surface stabilizing chemicals (surfactants that might be a natural part of the crude oils or from added production chemicals) will lead to stable droplets. Depending on the droplets sizes, there are several phase separation techniques like setting tanks (droplet diameter bigger than  $60\mu$ m), Plate separators (low efficiency with droplet diameter) (Van der

Zande & Van den Broek, 1998). In order to choose an efficient separator for oil-water mixture, prediction of the oil-water droplet size distribution is important (Torres-Monzón, 2006).

This thesis is aimed at studying oil-water flow development downstream a choke valve including the flow patterns and the pressure gradients. The experiments were conducted at SINTEF Multiphase laboratory in a horizontal pipe containing a mixing valve at the inlet. Flow patterns and pressure gradients were observed at different points along the pipe. Droplets pictures were also taken in order to prepare a droplet size distribution for each experiment. Analysis of the experimental data was used to improve the Schümann (2016) simple dynamic model that predicts the droplet sizes, pressure gradients, local phase holdup and liquid-dispersion interface positions.

### 1.1 Objectives

The main objective of this thesis is to propose and test a way to model oil-water flow development along the pipe downstream a valve.

Data comprising of phase fraction profiles and video recordings for varying flow rates and pressure drops across the valve were provided. One secondary objective is to categorize the flow patterns from the provided flow data. The observed flow patterns will be related to the measured pressure gradients along the test section. The effect of oil viscosity in the flow development and the resulting pressure gradient will also be investigated.

A suitable dynamic flow model is selected from literature and implemented in Matlab. The model will then be changed and improved, as necessary, to improve the predictions by comparing it with the experimental data. The model will predict the flow development along the pipe including the pressure gradient and the positions of the interfaces between water, oil and dispersion layers.

This thesis is done in close collaboration with another student: Kivuyo (2019), by interchanging results from the experimental analysis and modeling work. In this way the modelling part of this

thesis will focus mainly on the dynamic development of the flow. The correct representation of different flow patterns will be subject of the modeling work of the collaborating student.

### **1.2** Organization of the report

The report is divided into 8 chapters covering a range of subject:

- Chapter 1: Introduces the general background on the multiphase flow and phenomena associated with it.
- Chapter 2: Covers the main concepts of the multi-phase flow that are covered in this thesis. Previous works on the flow patterns and maps are revisited. Other effects of the multiphase flow like pressure gradient, bend effect and droplet dynamics are covered as well.
- Chapter 3: Covers the set-up of the experiment whose data are analysed in this thesis. The chapter describes the instrumentation, fluids properties and a test matrix which lists the water cuts and velocities tested.
- **Chapter 4**: Presents the analysis of the flow patterns identified in the experiments. The flow pattern maps are established using the data and the effect of flow patterns on pressure gradient is discussed.
- Chapter 5: Flow development analysis is presented. The effects of pressure drop across the mixing valve, flow rate and viscosity on flow development are investigated.
- **Chapter 6**: The main parts of the dynamic model developed to describe the pressure gradient, droplet size, dispersion thickness and the interfaces positions are explained. Results from the model are compared to experimental results.
- **Chapter 7**: Possible sources of errors and uncertainty in the measurement and analysis of the data are discussed.
- Chapter 8: Summarizes the main findings of the analysis and recommends the way forward.

References used in this work are listed immediately after the conclusion. In the end, Several figures are attached as appendices to be referred whenever needed.

## Chapter 2

## **Literature Review**

### 2.1 Basic definitions in oil-water flow

Consider oil and water flowing simultaneously in a horizontal pipe with cross section area (A). The input volumetric flow rates of oil and water being  $Q_o$  and  $Q_w$  respectively. The input volumetric oil  $(f_o)$  and water  $(f_w)$  fractions are then given by

$$f_o = \frac{Q_o}{Q_o + Q_w} \qquad \text{and} \qquad f_w = \frac{Q_w}{Q_o + Q_w} \tag{2.1}$$

 $f_w$  is often called water cut.

Superficial velocity of a liquid is defined as the imaginary velocity of that liquid if it were to occupy the entire cross-section of the pipe. It is calculated by dividing the individual flow rate by the total cross-section area. For oil  $(U_{so})$  and water  $(U_{sw})$  flow they are given by

$$U_{so} = \frac{Q_o}{A}$$
 and  $U_{sw} = \frac{Q_w}{A}$  (2.2)

The mixture velocity  $U_{mix}$  is given by

$$U_{mix} = U_{so} + U_{sw} \tag{2.3}$$

The superficial velocities do not represent the true velocities of oil and water since each phase occupies an area smaller than the total cross-sectional area. The actual velocities of oil  $(U_o)$  and water  $(U_w)$  in the pipe are given by;

$$U_o = \frac{Q_o}{A_o}$$
 and  $U_w = \frac{Q_w}{A_w}$  (2.4)

where  $A_w$  and  $A_o$  are the areas occupied by water and oil respectively. Area fractions for oil ( $\varepsilon_o$ ) and water ( $\varepsilon_w$ ), also known as liquid holdup, are simply defined by

$$\varepsilon_o = \frac{A_o}{A}$$
 and  $\varepsilon_w = \frac{A_w}{A}$  (2.5)

### 2.2 Flow patterns

The geometrical distribution of present phases flowing in a pipe is known as the flow regime or flow pattern. This distribution depends on the properties of the phases such as the density ratio, the viscosities, wetting properties, surface tension and amounts of each fluid. Flow patterns, also, largely depend on the mixture velocity and pipe geometry.

#### 2.2.1 Classification of flow patterns

A fixed classification of flow patterns does not exist. This is because the flow patterns change with respect to fluid properties. An endless combination of oils and water can be used and will give different results. Also, the most used method of identifying flow patterns since the 1950's is through visual observation of the flow itself. Different authors who investigated horizontal oil-water flow have different classifications based on their observations. For the same observed flow pattern, different authors will give different names. Here the classical work of Arirachakaran et al. (1989) is presented together with Trallero et al. (1997), Nädler & Mewes (1997), Elseth (2001) and the more recent studies of Schümann (2016) and Amundsen (2016).

Elseth (2001) did a study on horizontal oil water flow with a low viscosity oil and water. The oil was Exxsol D60 with a density of 790  $kg/m^3$  and viscosity 0.00164 Pas. The experiments were

performed in a 10.21m long test section. The experiments were performed for various constant mixture velocities while varying the input water cut from 10% to 90%. For identification of flow patterns there was a 0.8m long transparent section followed by a gamma densitometer 1.5m downstream the transparent section. Elseth (2001) identified stratified and dispersed flow as the major flow patterns. He further categorized them as Stratified Smooth (SS), Stratified Wavy (SW) and Stratified Mixed (SM). Stratified smooth appeared at low mixture velocities and intermediate water cuts characterized by a smooth interface with no droplets and only small waves. With increase in mixture velocity, larger amplitude waves and droplets appeared at the interface; this was stratified wavy flow. For even higher flow rates, there are more and larger waves at the interface and more droplets form from break-up of the interfacial waves. The droplets remain near the interface as water dispersed in oil, oil dispersed in water or both; this was stratified mixed flow. Figure 2.1 shows the stratified flow patterns.

For high mixture velocities and high or low water cut, dispersed flow was observed. Elseth (2001) identified homogeneous water continuous and oil continuous dispersion (Dw-H & Do-H) as well as in-homogeneous water continuous and oil continuous dispersion (Dw-I & Do-I). These flow patterns were defined when the droplets were distributed across the pipe's entire cross-section, either homogeneously or in-homogeneously. For intermediate mixture velocities, the droplets appeared as a dense pack near the pipe wall. The dispersed droplets were so close and almost looked like a layer. This is because of the relatively low mixture velocity that the droplets avoid being distributed across the entire pipe cross-section. This flow pattern was called oil continuous dispersion with a dense packed layer of water droplets (Do-DP) and water continuous dispersion with a dense packed layer of oil droplets (Dw-DP), see Figure 2.2.

Arirachakaran et al. (1989) performed a number of experiments aiming to determine the effect of oil viscosity in oil-water flow. He identified the flow patterns and produced flow pattern maps using: a mixture of water and diesel in a 3.81cm diameter, 12.8m long steel pipe; and water with two refined oils in a 2.67cm diameter, 6.1m long pipe. The oil densities ranging from 868-898 kg/m<sup>3</sup> according to oil type and temperature.

With a 3.81cm diameter pipe, 612 experiments were performed with 4 oils whose viscosities are 4.7, 58, 84 and 115cp (at  $21^{\circ}$ C) by varying the mixture velocity between 0.5 - 3.66m/s. The



(a) Stratified Smooth (SS)



(c) Stratified Mixed with water droplets in the oil phase (SM)



(b) Stratified Wavy (SW)



(d) Stratified Mixed with oil droplets in the water phase (SM)



(e) Stratified Mixed with oil droplets in the water phase and water droplets in the oil phase (SM)

Figure 2.1: Stratified flow patterns according to Elseth (2001).

water fraction ranged between 5-90% while the testing temperatures were between  $10-37^{\circ}$ C. Using 2.54cm diameter pipe, 587 experiments were performed with viscosity of 237cp and 2116cp (at 21°C) by varying the mixture velocity between 1.5-3m/s. The water fraction ranged between 15-90% while the testing temperatures were between 22-37°C.

The flow patterns identified were: stratified flow possibly with some mixing at the interface, mixed flow with a separate layer of dispersion and free phase, annular flow with a core of one phase within the other, homogeneous dispersed flow and intermittent flow with phases alternat-



(a) Oil continuous dispersion with a dense packed layer of water droplets (Do-DP)



(c) In-homogeneous oil continuous dispersion (Do-I)



(e) Homogeneous oil continuous dispersion (Do-H)



(b) Water continuous dispersion with a dense packed layer of oil droplets (Dw-DP)



(d) In-homogeneous water continuous dispersion (Dw-I)



(f) Homogeneous water continuous dispersion (Dw-H)

Figure 2.2: Dispersed flow patterns according to Elseth (2001).

ing between free phase flow and fully dispersed flow. The illustration is shown in Figure 2.3.

Nädler & Mewes (1997) studied flow regimes and pressure drops in oil-water flow in a 5.84cm diameter, 48m long perspex pipe at varying temperatures between 18-30°C. They used water and white mineral oil with viscosity ranging between 22-35cp. The superficial liquid velocity were ranged between 0.1-1.6m/s while the water cuts were changed between 10-90%.



Figure 2.3: Flow pattern classification according to Arirachakaran et al. (1989)

They identified stratified flow, stratified with mixing on the interface, Unstable oil in water emulsion (O-W), Unstable water in oil (W-O), layers of water in oil dispersion and water (W-in-O), layers of dispersion (W-in-O and O-in-W) and water layer and, oil in water dispersion (O-in-W) above a water layer. The illustration is shown in Figure 2.4.

Trallero et al. (1997) used tap water and mineral oil at a constant temperature of  $25.6^{\circ}$ C in a 5.013cm diameter, 15.54m long transparent pipe. The oil density and viscosity were 884 kg/m<sup>3</sup> and 28.8cp respectively. The mixture velocity was ranged between 0.02 - 3.4m/s for the water cuts between 0-100%.

They reported six different flow patterns and classified them into major categories of dispersed and segregated flow. Segregated flow patterns included stratified flow (ST) and Stratified flow



Figure 2.4: Flow patterns according to Nädler & Mewes (1997)

with some mixing (ST & MI) at the interface. The dispersed flow could be water dominated or oil dominated. Water dominated flows were: a dispersion of oil in water over a water layer (Do/w & W); and an emulsion of oil in water (O-W). An emulsion of water in oil (W-O) and a dual dispersion (Do/w and Dw/o) were oil dominated flow patterns. Their sketches are presented in Figure 2.5.

Amundsen (2016) used tap water and Exxsol D60 at atmospheric conditions using 5.08cm diameter, 13.2m long stainless steel pipe with water cut between 0-100% and mixture velocity between 1-3m/s. She identified flow patterns similar to Trallero et al. (1997) and Elseth (2001) but also observed plug flow (PG) pattern characterized by oil plugs flowing at the top of the pipe. She observed that the oil plugs disperses gradually until they disappear before re-appearing.

Schümann (2016) divided the flow patterns identified by Trallero et al. (1997) to better describe other patterns observed in his experiments, see Figure 2.6. He conducted his experiments using tap water and three sets of blends of Primol 352 and Exxsol D80 at 20°C in 10cm diameter, 25m long transparent PVC pipe. The oil densities were 866 kg/m<sup>3</sup>, 859 kg/m<sup>3</sup> and 853 kg/m<sup>3</sup> while the viscosities were 120cp, 60cp and 35cp respectively. The experiments were conducted using the water cuts of 0-100% and mixture velocities were changed between 0.1-1.1m/s.



Figure 2.5: Flow Patterns according to Trallero et al. (1997)

The list of the experiments above is not exhaustive but the flow patterns identified by other authors who did similar experiments mostly agree to the classifications above.

#### 2.2.2 Flow pattern Maps

The flow pattern maps are created for an easy comparison with other authors. These maps are mostly representing the flow patterns as a function of the mixture velocity and water fraction. Some authors prepare flow pattern maps as a function of the changing superficial velocities of the two phases. An example of the flow pattern maps is shown from the extensive experiments performed by Trallero et al. (1997) as seen in Figure 2.7. The figure shows the regions of water cut and  $U_{mix}$  associated with a specific flow pattern. Similarly, Figure 2.8 shows the flow pattern regions but this time, associated with the superficial velocity of water and oil.



Figure 2.6: Flow patterns according to Schümann (2016)

### 2.2.3 Factors affecting flow patterns

#### Mixture velocity and input water cut

Low mixture velocities allows the flow to fully develop very early hence the flow tends to be Stratified flow. Higher velocity tends to disperse flow. Dispersed flow may appear at low velocity when the water cut is very low or very high (Elseth, 2001).



Figure 2.7: Flow pattern map ( $U_{mix}$  vs WC) by Trallero et al. (1997)

#### Viscosity and Density

Viscosity does not have a large effect on the flow pattern. However, the range of flow conditions in which a particular flow pattern appear will change. This will make some flow patterns regions bigger or smaller on the flow maps. When the density difference between the phases is big, the flow will tend be stratified for higher mixture velocity and water cuts compared to liquids with similar density. This is due to the gravity effect on the flow. When fluid properties are very sensitive to the temperature and pressure, the flow patterns might also change significantly.

#### Flow geometry

The orientation and geometry of the flow is one of the determinant factor on the flow patterns. For horizontal flow, inlet design, pipe dimensions and bends affect the type of the flow observed. Constrictions settings e.g. inlet valve opening might easily produce dispersion even in low velocities. This effect is the subject of this thesis. Bends can also have impact on the type



Figure 2.8: Flow Pattern map ( $U_{sw}$  vs  $U_{so}$ ) by Trallero et al. (1997)

of flow pattern and pressure drop as described below.

#### **Bend Effect**

When fluids navigate a bend, extra force act on them: centrifugal force. The combination of the forces will create an extra pressure drop which, in case of the multiphase flow, depends on: streams and physical properties of the phases; void fractions of the phases; gravitational forces and geometric parameters of the bend i.e. diameter, bending angle and radius of curvature (Pietrzak & Witczak, 2013).

To quantify the liquid pressure drop across the bend, single phase models have been corrected for the multiphase effects like in Equation 2.6.

$$\Delta P_L = \frac{K_L \cdot \rho \cdot U^2}{2} \tag{2.6}$$

Coefficient  $K_L$  is read from appropriate plots.

Sharma et al. (2011b) developed a correlation to estimate the pressure drop across the U-bend

without the prior knowledge of the flow patterns as shown in Equation 2.7.

$$\Delta P_{bend} = 1.45 \cdot \rho_m \cdot U_m^2 \cdot f_w^{(430.5 - \frac{224800}{Re_m})} + 0.33 \cdot \rho_m \cdot U_m^2$$
(2.7)

The subscript m represent mixture. Mixture density, Reynolds number and mixture viscosity are given by Equation 2.8 to Equation 2.10 respectively. The volumetric water and oil fractions:  $f_w$  and  $f_o$  are given by Equation 2.1 and the mixture velocity  $U_{mix}$  is given by Equation 2.3.

$$\rho_m = \rho_o(1 - f_w) + \rho_w f_w \tag{2.8}$$

$$Re_m = \frac{D \cdot U_m \cdot \rho_m}{\mu_m} \tag{2.9}$$

$$\mu_m = \frac{1}{\left(\frac{1-f_w}{\mu_o} + \frac{f_w}{\mu_w}\right)} \tag{2.10}$$

Some researchers have used the air-liquid models to calculate the liquid-liquid bend pressure drop. However, caution is needed to only use the models that have been proven to work in liquid-liquid flow as there is no guarantee of correct results (Sharma et al., 2011a).

By comparing the average hold up upstream and downstream of the bend, Belfroid et al. (2010) demonstrated that the bends not only act as mixer of the phases, sometimes they act as the separator of the phases, especially with low mixture velocities. With separation and mixing, the bend effect might go as far as to change the flow pattern of the multiphase flow (Sharma et al., 2011b).

While air-liquid flow has received a considerable attention, there is a big gap in the literature for the liquid-liquid flow e.g. water-oil flow. Sharma et al. (2011b) studied the flow of low viscosity oil and water for different bend geometry, bend orientation and flow direction through the 180° return bends. With high water velocity, rectangular bend show water dispersed flow at the bend and downstream the bend. For low water velocity, oil dispersed flow was observed. Similar results were not seen in the U-bend under similar experimental conditions. This means that if the geometry of the bend is not taken into account, error in flow pattern identification can

occur. The rectangular bend has shown higher pressure drop compared to U type bend which can be attributed to the sudden change in flow direction.

Similar studies were done with high viscosity oil. Sharma et al. (2011a) reported that the direction of the flow through the bend influenced the flow pattern at the bend as well as downstream of it. Downward flow of the two phases enhanced the formation of annular flow while reversing the flow caused dispersed flow. In this case, however, the bend geometry did not influence the flow regimes at tested conditions. Like in low viscosity oil, rectangular bend caused higher pressure drops compared to U-bend under the same test conditions.

#### 2.2.4 Phase Inversion

A very important phenomenon that can occur in a two phase flow is called phase inversion. Phase inversion is defined as the change in continuity from one phase to another. In other words, phase inversion of two immiscible liquids can be defined as the transition of a phase from being dispersed to being continuous (Angeli & Hewitt, 2000).

For oil-water systems at low water cuts, water will be transported as droplets in the oil continuous phase. As the amount of water increases, it reaches a point where water becomes the continuous phase and oil is transported as droplets within the water phase; this is the phase inversion point, see Figure 2.9. At the inversion point, the viscosity of the system will be much higher than the individual fluids viscosity leading to increased pressure drop. After the inversion point, the pressure gradient falls rapidly when the mixture becomes an oil in water dispersion.

This behaviour is affected by velocity of the mixture, type of the pipe and type of dispersion. The pressure gradient peak is sharper and larger at high mixture velocities than at low ones (Arirachakaran et al., 1989) (Ioannou et al., 2005). The acrylic pipe shows a larger peak in pressure gradient compared to the steel pipe for similar experimental setup. The height of pressure gradient peak is smaller when the experiments start with water continuous dispersion than with oil continuous dispersion (Ioannou et al., 2005).

Increased pressure drop in long distance transportation is highly undesirable and hence it is very



Figure 2.9: Phase Inversion process for an oil-water dispersion flow (Arirachakaran et al., 1989)

important to predict exactly when phase inversion will occur so that transport can be arranged to take place far from the inversion point (Sanchez & Zakin, 1994).

### 2.3 Pressure Gradient

### 2.3.1 Pressure Gradient in Single Phase Flow

For a fluid flowing in a horizontal cylindrical pipe of length L with a volumetric flow rate Q, the main cause of pressure drop is friction. The Darcy-Weisbach Equation 2.11 can be used to calculate this pressure drop.

$$\frac{\Delta P}{L} = f \cdot \frac{\rho}{2} \cdot \frac{v^2}{D} \tag{2.11}$$

where  $\Delta P/L$  is the pressure drop per unit length (Pa/m), f is the Darcy friction factor,  $\rho$  is the
density of the fluid  $(kg/m^3)$ , v is the mean flow velocity measured as the volumetric rate (Q) per unit area (m/s), D is the internal pipe diameter (m).

The friction factor, f, for turbulent flow can be obtained by using the Swanee & Jain (1976) relation shown in Equation 2.12.

$$f = \frac{1.325}{\left(\log\frac{\varepsilon}{3.70} + \frac{5.74}{Re^{0.9}}\right)^2}$$
(2.12)

where  $\varepsilon$  is the surface roughness, Re is the Reynolds number which is given by Equation 2.13.

$$Re = \frac{\rho \cdot v \cdot D}{\mu} \tag{2.13}$$

where  $\mu$  is the viscosity of the fluid in  $Pa \cdot s$ .

The friction factors obtained using Equation 2.12 are within 1% absolute error margin when compared to Colebrook-White equation for  $10^{-6} \le \varepsilon/D \le 10^{-2}$  and  $5 \times 10^3 \le Re \le 10^8$ . There are several other correlations for the friction factor existing in the literature.

#### 2.3.2 Pressure Gradient in Liquid-Liquid Flow

The main cause for pressure drop in two phase flow is friction, just as in the single phase flow. But for two phase liquid-liquid flow, pressure drop is mainly dependent on the type of flow pattern. There are models that present each type of flow pattern to predict the pressure gradients in each case. These are such as the two-fluid model for stratified flow and the homogeneous model for dispersed flow (Arirachakaran et al., 1989). Schümann (2016) modified the two fluid model and presented a three layer model for calculating pressure gradient in dense packed layer flow.

From experiments, the effect of flow pattern on pressure gradient has been described by different authors. Stratified flows have been observed to have a low pressure gradient compared to dispersed flows. A peak in pressure gradient was observed by Elseth (2001) when the flow changed from stratified mixed to water continuous dispersion with dense packed layer of oil droplets. The formation of the dense packed layer of oil droplets led to increase in mixture viscosity, hence high pressure gradient. Elseth (2001) observed the peak in pressure gradient at velocities below 2m/s; with the peak appearing at a decreasing input water cut as the velocity increased. This is shown in the Figure 2.10.



Figure 2.10: Pressure drop Vs Water cut by Elseth (2001)

Arirachakaran et al. (1989) reported that pressure drop changes dramatically at the phase inversion point, and the magnitude of this change varies with the mixture velocity and the oil viscosity. For an oil-in-water dispersion, temperature and oil viscosity had small effects on the mixture pressure drop when oil viscosity is much higher than water viscosity. The pressure drop had the same order of magnitude as single-phase water pressure drop at the same flowing conditions. For a water-in-oil dispersion, pressure drop was highly affected by temperature, since the oil viscosity is very sensitive to changes in temperature.

Trallero et al. (1997) reported pressure gradients as a function of flow pattern transitions. The transition from the stratified region to the dispersed region was indicated by a small decline in

pressure drop. Transition from ST & MI to DO/W & W was also detected by a fall in pressure drop because of the loss of oil continuity. Pressure drop appeared to be insensitive to the transition from ST to ST & MI. Transition from W/O to DW/O and DO/W was reflected as a decrease in pressure drop. For large mixture velocities and moderate water cuts, the two phase pressure drop behavior approached that of a single phase water flow.

Amundsen (2016) presented normalized pressure gradients as a function of water cut. In horizontal flow for water cuts between 0-15%, she observed that the two phase pressure gradient was the same as that of pure oil pressure gradient. While the flow pattern is stratified flow and mixing (ST & MI), small peak in pressure gradient was observed between 15-35% water cut followed by a gentle increase in pressure gradient. A sudden increase that is 1.7 times that of pure oil was observed when the flow pattern changed from ST & MI to Dw/o & w at 80% water cut. The increase was explained by a formation of clusters of droplets which increase the effective viscosity.

Comparing the pressure gradient for oils with different viscosity, Schümann (2016) found that for oil continuous flow pressure gradients increased with increasing oil viscosity. Water continuous flow did not show a significant dependence on the viscosity of oil; also observed by Arirachakaran et al. (1989). The sudden increase in pressure was present when the flow was transitioning from water dispersion with oil on top (o & D) to Do/w & w at 40-50% water cut. This is because of the disappearance of the oil layer; same as reported by Trallero et al. (1997).

## **2.4 Droplet Dynamics**

Depending on the flow regime, liquid-liquid multiphase flows are often accompanied by the droplets dispersed in a continuous phase. Droplets may form as the result of the external conditions like flowing through the constriction or, the forces and mechanism within the fluid flow itself.

### 2.4.1 Droplet sizes and distribution

Development of the models for the droplets size distribution has been very difficult subject; partly because the experimental data needed to produce such models are very difficult to measure. Most of the data available have been measured in stirred beaker settings. Sample models for the droplet size include the Hinze (1955) model, Sleicher (1962) model, Levich (1962) model, Kubie & Gardner (1977) model, Angeli & Hewitt (2000) model and recently Kouba (2003) model. For the size distribution, the models include Rosin-Rammler distribution, Lognormal distribution and bi-normal distribution. No single model was found to be the most accurate all the time (Amundsen, 2016).

In general, however, the mean droplet size and distribution will depend on the physical properties of the fluids, phase velocities and piping system i.e. nature, configurations and dimensions. With droplets floating in another liquid, the size of the droplets will be influenced by:

- Flow regime: different authors report different results. While some report larger water droplets in water in oil emulsion compared to oil droplets in the oil in water emulsion e.g. Trallero et al. (1997), others e.g. Al-Wahaibi & Angeli (2008) have reported the opposite. Vielma et al. (2008) report that the difference between the droplets was very small.
- Flow velocity: the higher the velocity, the smaller the droplets sizes. The droplet sizes also increased with the increase in the dispersed phase velocity at the same level of turbulence (Vielma et al., 2008). Increasing water superficial velocity decreased the number of large droplets (Al-Wahaibi & Angeli, 2008).
- Piping system: with the same flow conditions, bigger droplets were formed in acrylic piping system compared to steel. Turbulent suppression may also occur when the droplet size is smaller than 10% of the pipe diameter (Angeli & Hewitt, 2000).

Once the droplets have been formed, surface forces (from the continuous phase) works in breaking up the droplets even further while the inertial forces: interfacial tension and the viscosity of the droplet, preserve it. The balance between these two type of forces determines what happens to the droplet.

### 2.4.2 Droplet Breakup

The breakup of the droplets is generally caused by four mechanisms (Liao & Lucas, 2009):

- **Turbulent fluctuation and collision**: caused by eddy collisions or turbulent pressure fluctuation along the surface of the droplet.
- Viscous shear forces: velocity gradient between the continuous phase and the droplets will cause shear stress that will deform the droplet and lead to the breakup.
- Shearing off and interfacial instability: also known as erosive breakage, where small droplets will break up from the larger one at the rim of the bigger droplet due to velocity gradient and interfacial tension.
- Interfacial instability: mostly observed when the continuous phase is stationary and the droplet is either settling or rising through it. When there is density difference, the breakup is governed by Rayleigh-Taylor instability, otherwise it will be governed by Kelvin-Helmholtz instability.

Mathematically, the breakup of the droplets is predominantly governed by Equation 2.14, known as the Weber group  $(Nw_e)$  equation.

$$Nw_e = \frac{\mu_c \cdot S_v \cdot d}{\sigma} \tag{2.14}$$

Where  $\mu_c$  is the absolute viscosity of the continuous phase, Sv is the maximum velocity gradient in the flow field, d is the droplet diameter and  $\sigma$  is the surface tension.

When the surface forces overcome the viscous forces, the droplets will break up. Matching the two forces will give the maximum diameter of the droplet above which the droplets will break. Several models exist in the literature to calculate the  $d_{max}$  e.g. Equation 2.15 and Equation 2.16 gives  $d_{max}$  formula for the Hinze (1955) model (not to be used when droplets size is greater than 0.1D) and, Kubie & Gardner (1977) model respectively.

$$d_{max} = 0.725 \cdot \left(\frac{\sigma}{\rho_c}\right)^{0.6} \cdot \left(\frac{2f_c \cdot U_c^3}{D}\right)^{-0.4}$$
(2.15)

$$d_{max} = 5.53 \left( \frac{\sigma}{f_c \cdot \rho_c \cdot Uc^2} \right) \tag{2.16}$$

Where the subscript c represent continuous phase.

#### 2.4.3 Droplets Coalescence

Three important models have been proposed on the mechanism of the coalescence (Liao & Lucas, 2010).

- **Drainage model**: When two droplets come close, they are separated by a thin film of the continuous phase. Attraction force between the droplets will drain the film until it is too thin to hold up and breaks. The two droplets will then coalesce (Shinnar & Church, 1960).
- Energetic collision model: The fact that the drainage model includes attraction forces gave birth to energetic collision model. The attraction force, which is molecular in nature, is too weak to drive the film out (Howarth, 1967). This model proposes that coalescence will occur between two droplets when they collide with large enough velocity to instantaneously merge the two droplets. This model improves on the drainage model due to the fact that it does not employ molecular attraction forces (too weak). It also does not require long time for the coalescence to occur unlike drainage model which requires certain amount of time for the droplets to be in contact so as to drain the film out; which may or may not be the case.
- Critical approach velocity model: Based on empirical evidence, this model proposes that when a droplet approaches another droplet with relatively small velocity, higher coalescence rate is achieved (Lehr et al., 2002).

The studying the above models, two important concepts in the coalescence phenomenon have been introduced: collision rate/frequency and coalescence efficiency. Collision of the droplets is caused by (Liao & Lucas, 2010):

- motion induced by turbulent fluctuations in the continuous phase
- motion induced by the velocity gradient in the flow

- droplets rising/settling induced by buoyancy and gravitational forces
- capturing of the droplets in the flow eddies
- wake interactions

The coalescence efficiency is controlled by the coalescence mechanisms/models described above.

# Chapter 3

# **Experimental Description**

## 3.1 Setup

The experiments were performed at the SINTEF multiphase laboratory at Tiller. A medium scale flow loop with a total test section length of 220m including three  $180^{\circ}$  bends with a bend radius of 2.25m was used. A piping and instrumentation diagram of the flow loop is shown in Appendix A. After each approximately 50m there was a bend, and after the second bend the pipe goes on top of the first section. This was present due to restricted space in the test room. The pipe was made of stainless steel 316L with an inner diameter of 10.91cm and a thickness of 0.26cm. The test section was inclined by  $0.1^{\circ}$  which for this study is considered horizontal flow. See Figure 3.1.

The oil and water feed lines pumped from the separator were mixed in a simple Y-junction followed by an inlet mixing valve. Both the oil and water feed line into the mixing point had a tap where fluid samples were collected. The tap on the oil feed line was also used as an injection point for surfactant. After surfactant injection the fluids were circulated well before taking measurements. The surfactant concentration in the oil can be assumed to be as homogeneously distributed as possible by circulation. No additional surfactant was added to the flow during the experiment, meaning that the total amount of surfactant in the flow loop was constant.



Figure 3.1: SINTEF Medium scale flow loop

# 3.2 Instrumentation

The main instrumentation in the test section included, four optical sections with video recording, three traversing gamma densitometers, nine pressure transducers and two temperature transmitters.

### **3.2.1** Pressure measurements

The pressure drop over the inlet mixing valve was measured between the water feed tap and a tap access point 40cm downstream of the mixing valve. There were 9 pressure transducers in the test section. 8 pressure transducers were placed at beginning and end of each of the 4 straight sections: 3.6m, 47.86m, 59.51m, 103.72m, 116.39m, 160.65m, 173.32m and 217.53m from the mixing valve. One was placed 14.09m from the mixing valve. The pressure transducers in the test section measured the pressure relative to the atmospheric pressure in the test room. All

pressure transducers were Fuji Electric FCX-AII series and were calibrated using Beamex MC5 pressure calibrator. The transducers were accepted with calibration errors within 0.1% of span.

### **3.2.2** Optical sections

There were four 0.5m long optical sections made of PMMA tubes. The diameter was 10.91cm same as the pipe diameter and thickness was 0.5cm. Optical section 1, 2, 3 and 4 were positioned 1.6, 106, 113.9 and 218.6 meters from the inlet mixing valve, respectively. Since the two loops of the test section pipe were placed on top of each other, the optical sections were placed in pairs on top of each other. There were two video cameras, camera 1 recording optical sections 1 and 3 simultaneously and camera 2 recording optical sections 2 and 4 simultaneously, see Figure 3.2. The optical sections were illuminated with a strong LED panel, used as back-light.



Figure 3.2: Setup of the optical sections and an image from the camera 2 recording of Optical Sections 2 and 4 at 106m and 218.6m respectively.

#### 3.2.3 Traversing gamma densitometers

Gamma densitometers were used to measure the vertical density profiles. There were three gamma densitometers in the test section. Since the two loops of the pipe section were on top of each other, each traversing gamma was used to scan points in both flow loops. Traversing gamma 1 was placed at 1.82m & 114.61m, traversing gamma 2 at 48.88m & 161.67m, and traversing gamma 3 at 106.06m & 218.85m.

The working mechanism of the gamma densitometer is explained in simple terms. A radioactive source is collimated to produce an incident unidirectional photon flux normal to the test section. The beam is then attenuated through the pipe wall, the oil-water mixture and the opposite pipe wall before it is received by the detector collimator before the detector itself (Elseth, 2001). The rate of attenuation of the incident beam is proportional to the density of the medium and the intensity of the beam itself. Calibrating the gamma ray with a variety of known flow geometries can lead to prediction of holdup for other flow geometries. Water holdup from gamma densitometry is calculated by Equation 3.1

$$\varepsilon_{w} = \frac{ln(I/I_{o})}{ln(I_{w}/I_{o})}$$
(3.1)

Where I is the measured intensity for a given oil/water mixture,  $I_o$  is the calibrated intensity for oil and  $I_w$  is the calibrated intensity for water. The calculation assumes a thin collimated beam with a uni-directional photon flux normal to the test section and does not require any prior knowledge of the pipe wall (Amundsen, 2016).

The traversing gammas were regularly calibrated against a fully water and oil filled pipe. For all mixtures of oil and water the intensity of the gamma beam was measured. The resulting vertical density profiles or otherwise called phase fraction profiles are presented as water fraction vs normalized pipe position at the cross-section. The bottom of the pipe is at y/D = 0. An example given in Figure 3.3 shows a case of  $U_{mix} = 1$ m/s, WC = 0.5 and a fully open inlet valve. The profile shows the upper part of the pipe for all positions except 1.82m has zero water fraction, which means it's a clean layer of oil. The lower part of the pipe for the same positions has a unity water fraction which means there is clean water. The region in the middle where the fluid

changes from clean oil to clean water has a gentle slope at around y/D = 0.5 indicating the flow is nicely stratified. The curve for 1.82m shows a partially dispersed flow because of turbulence at the beginning of the flow section.



Figure 3.3: Phase fraction profile from gamma densitometer.  $U_{mix} = 1$ m/s, WC = 0.5,  $Dp_{valve} = 0$ bar

### **3.2.4** Droplet size distribution measurements

A particle-sizing camera (CANTY InFLow<sup>TM</sup>) mounted in a bypass of the main flow was used to capture videos for characterization of droplet sizes. There were 3 cameras located at 0.7m, 106.51m and 219.3m from the inlet mixing valve. These measurements were taken for the experiments with a significant pressure drop across the inlet mixing valve. The fluids were led through the Canty to capture pictures of the dispersion by feeding lines of inner diameter 6mm and approximately 2m long. The sampling was through a bent 8 mm inner diameter pipe, with the opening facing the oncoming flow.

Representative sampling is often a challenge when determining droplet size distributions. Unless the flow is homogeneously dispersed there will be uncertainties with regards to representative sampling since gravity and buoyancy will cause a stratification of droplets. This also depends on the pressure drop over the valve and the water cut. Figure 3.4 shows the uncertainty of representative droplet sampling due to water cut. To capture variations of droplet sizes with height in this campaign, the sampling point was variable. For most experiments sampling was done in three different heights: 3cm, 6cm and 8cm from the bottom of the pipe.



Figure 3.4: Illustration of uncertainties in representative sampling of droplets for experiments with different water cuts

## 3.3 Fluid System

There were two experimental campaigns that were run in the SINTEF medium scale flow loop. The first campaign was done in June 2018 and the second was done in March 2019. The experimental setup and instrumentation described above was used for both experiments. The only exception is that the traversing gamma densitometer 2 placed at 48.88m & 161.67m was faulty for the second experimental campaign. The fluids used in the two campaigns were different. All experiments were conducted at room temperature (approximately 20°C) without temperature control.

#### 2018 experimental campaign fluid system

The fluid system consisted of 6  $m^3$  of Exxsol D60 and 4  $m^3$  tap water. Exxsol D60 is a light mineral oil with a measured density,  $\rho_{oil} = 789 \text{ kg/m3}$  and a theoretical viscosity of 1.43 mPa·s at experimental conditions. The measured water density was  $\rho_{water} = 998 \text{ kg/m}^3$  and viscosity

of 1 mPa·s. Approximately 80ppm of Span 83 was used as surfactant in the oil phase. The biocide IKMCC-80 was added to the water phase at a concentration of 1000 ppm (4 liter in total) to prevent organic growth. The biocide was not found to be droplet stabilizing. Throughout this report, the 2018 fluid system will be called fluid system A.

#### 2019 experimental campaign fluid system

The fluid system consisted of 6 m<sup>3</sup> of a mineral oil blend containing Exxsol D60 and Primol 352 tested together with 4 m<sup>3</sup> tap water. The mineral oil blend had a measured density of 850 kg/m<sup>3</sup> and a theoretical viscosity of 35 mPas at experimental conditions. The measured water density was 999kg/m<sup>3</sup> and viscosity of 1 mPas. Span 80 was used as surfactant in the oil phase, its concentration was not clearly known but it was around 100 ppm. The biocide IKMCC-80 was added to the water phase at a concentration of 1000 ppm to prevent organic growth. Throughout this report, the 2019 fluid system will be called fluid system B.

## 3.4 Data Quality

In a flow loop, fluid system quality control is necessary. This is to ensure that before mixing the feed lines contain pure oil and pure water from the separator. One method that was used to make sure clean fluids were obtained was to increase the retention time in the separator.

Coriolis meters were used to measure the densities of oil and water in their respective feed lines. Since the fluids had already been in circulation, there were small droplets of oil in water and small droplets of water in oil that were not removed in the separator. These are termed as contamination in water ( $C_w$ ) and contamination in oil ( $C_o$ ) and are given by Equation 3.2.

$$C_o = \frac{\rho o\_meas - \rho o\_pure}{\rho w\_pure - \rho o\_pure} \qquad C_w = \frac{\rho w\_meas - \rho w\_pure}{\rho w\_pure - \rho o\_pure}$$
(3.2)

Where  $\rho_{o\_meas}$  is the measured oil density,  $\rho_{o\_pure}$  is the density of clean oil,  $\rho_{w\_meas}$  is the measured water density,  $\rho_{w\_pure}$  is the density of clean water.

Contamination leads to a change in the actual value of water cut. The oil droplets in water decrease the nominal water cut and the water droplets in oil increase the nominal water cut. The resulting real water cut can be found from Equation 3.3 where  $WC_{real}$  is the real water cut in the test section,  $WC_{nom}$  is the nominal water cut.

$$WC_{real} = WC_{nom}(1 - C_w) + C_o(1 - WC_{nom})$$
(3.3)

Two criteria were set to secure the quality of the data. The absolute contamination, Co and Cw should not exceed 2%, and the change in water cut due to contamination should not exceed 2%. During the experiments it was not always possible to meet the fluid quality requirements. However, experiments were still conducted if the qualities appeared to be stable and did not change over time.

### **3.5** Test Matrix

Figure 3.5 shows the combination of mixture velocities and water cuts for the experiments performed in both campaigns.



Figure 3.5: Test matrix

# Chapter 4

# **Flow Patterns**

## 4.1 Identified flow patterns

Flow patterns in both campaigns were identified visually from the video recordings and from the vertical density profiles from gamma densitometers (phase fraction profiles). The videos were recorded at four 0.5m transparent pipe sections and had a duration of about 5-10 seconds. There were six positions along the pipe section with gamma measurements for the 2018 campaign and four positions in the 2019 campaign. The flow patterns that were identified are very similar to those identified by Elseth (2001) as discussed in Section 2.2.

For the 2018 campaign (fluid system A), the flow patterns observed were exactly the same as observed by Elseth (2001) except for stratified smooth(SS) and Homogeneous water dispersion (Dw-H). The observed flow patterns include Stratified Wavy (SW), Stratified Mixed (SM), Homogeneous oil dispersion (Do-H), Inhomogeneous oil dispersion (Do-I), Inhomogeneous water dispersion (Dw-I), Oil continuous dispersion with a dense packed layer of water droplets (Do-DP) and Water continuous dispersion with a dense packed layer of oil droplets (Dw-DP).

For the 2019 campaign (fluid system B), the same flow patterns as 2018 campaign were observed. However an additional flow pattern was observed: oil continuous dispersion with a dense packed layer of water droplets and water layer (Do-DP + w).

In this chapter, all the results presented are for the fluid system B. Earlier work by the author covers the results for the fluid system A (Issara & Kivuyo, 2018).

#### Characteristic phase fraction profiles for identified flow patterns

Gamma measurements were taken for all experiments with very few exceptions. The phase fraction profiles that contain the water cut versus normalized position for all experiments are found on Appendix B.

Measurements of local phase fractions were placed over selected still frames from video recordings to show the typical phase fraction profiles for the identified flow patterns. The y-axis is fitted to the pipe inner diameter on the picture. However, the quality of the pictures were not good enough to allow visibility of the small droplets dispersed in a continuous phase, although such droplets could be clearly seen from the video files.



Figure 4.1: Homogeneous oil dispersion flow pattern;  $U_{mix} = 1$  m/s, WC = 0.2,  $Dp_{valve} = 0.2$ bar

Figure 4.1 shows a homogeneous oil dispersion. The picture doesn't show much because there is high droplets concentration of very small size distributed uniformly across the entire cross section. The gamma phase profile is almost a straight line at a local water fraction of 0.2. This corresponds to the input water cut of 20% in the experiment.



Figure 4.2: In-homogeneous oil dispersion flow pattern;  $U_{mix} = 1$  m/s, WC = 0.2,  $Dp_{valve} = 0$  bar

The in-homogeneous oil dispersion (Do-I) is characterized by a fairly straight line at the top of the pipe and a steep gradient at the bottom of the pipe as seen in Figure 4.2. The picture shows the top part as if it contain no water droplets while the bottom of the pipe shows the presence of droplets. The non-uniform distribution of the droplets is because the larger droplets settle at the bottom together with the small droplets. The water concentration being greater than zero at the top is a proof that there is water in the form of small invisible droplets.

Figure 4.3 shows an in-homogeneous water dispersion. This is quite similar to Do-I except that the continuous phase is water and not oil and the dispersed phase is oil. Because of density, the oil droplets are concentrated more at the top unlike the water droplets in oil which concentrate at the bottom. Therefore, as shown in Figure 4.3 and Figure 4.2, the slope of curve increases



Figure 4.3: In-homogeneous water dispersion flow pattern;  $U_{mix} = 1$ m/s, WC = 0.6,  $Dp_{valve} = 0$ bar

from top to bottom in Dw-I and decreases from top to bottom in Do-I.

Figure 4.4 shows an oil continuous dispersion with a dense packed layer of water droplets and a water layer (Do-DP + w). The curve shows a water fraction close to zero at the top of the pipe because the oil is almost clean. the dense packed layer of the water droplets appears just after the clean oil and below it a clean layer of water is observed.

When there is a dense packed layer of oil droplets in a water continuous dispersion, the droplet layer is seen on top of the pipe. This flow pattern is known as Dw-DP and is seen in Figure 4.5. In the figure it is unfortunate that the droplets are not clearly seen because of the poor picture quality. The phase fraction profile shows almost unity water fraction with some variations for the lower part of the pipe. In the upper part of the pipe the water fraction drops significantly because of the dense layer of oil droplets but it does not reach zero since water is still the continuous phase in the oil droplets densed pack layer.



Figure 4.4: Oil continuous dispersion with a dense pack of water droplets and a water layer;  $U_{mix} = 1$ m/s, WC = 0.3,  $Dp_{valve} = 0$ bar

For low mixture velocities, the flow was observed as stratified where both oil and water were continuous and segregated by gravity. Figure 4.6 shows stratified flow observed in Umix=0.5m/s and water cut of 50%. The flow pattern was identified as Stratified mixed (SM) and not stratified smooth as the picture might aspire. This is because of the presence of droplets and waves along the interface, and the presence of water droplets in the oil phase.



Figure 4.5: Water continuous dispersion with a dense pack of oil droplets;  $U_{mix} = 1$ m/s, WC = 0.9,  $Dp_{valve} = 1$ bar



Figure 4.6: Stratified flow pattern;  $U_{mix} = 0.5$ m/s, WC = 0.5,  $Dp_{valve} = 0$ bar

## 4.2 Local phase fraction measurements

Although the local water fraction were taken in several places, only local phase fractions at 218m are presented here for all experiments with no mixing at the inlet mixing valve. This is the last position of gamma densitometer on the test section where the maximum possible development of the flow is observed. The local phase fraction measurements are presented for different input water cut at constant mixture velocities.



Figure 4.7: Local phase fraction for all water cuts at 218m; fluid system B;  $U_{mix} = 0.5$ m/s,  $Dp_{valve} = 0$ bar

For 0.5 m/s all curves have similar gradients with a clean oil layer at the top and clean water layer at the bottom as shown in Figure 4.7. The interfaces are located at normalized positions value close to the input water cut value. The 10% input water cut shows a little difference with the other because of the small amount of water; which for slightly higher mixture velocity could be dispersed. This shows that 0.5m/s mixture velocity is characterized by stratified mixed flow.



Figure 4.8: Local phase fraction for all water cuts at 218m; fluid system B,  $U_{mix} = 1$ m/s,  $Dp_{valve} = 0$ bar

For 1 m/s mixture velocity, an oil dispersion is seen between 10% to 30% input water cuts as seen in Figure 4.8. For the 90% water cut, the curve is a typical water dispersion curve while intermediate water cuts curves show the stratified mixed flow .

For higher mixture velocity of 1.5m/s, Figure 4.9 shows that the 90% phase fraction curve indicates an in-homogeneous water dispersion. Intermediate input water cuts from 40-75% show the behavior of a water dispersion with a dense pack of oil droplets. For 20% and 30% water cuts, the curves indicate an oil dispersion with a dense pack of water droplets and a water layer. '

#### **Local Average Dispersion Factor**

The local dispersion factor is a term that quantifies the local dispersion present at any pipe position using local water fraction. In this work, dispersion factor was calculated for three positions.



Figure 4.9: Local phase fraction for all water cuts at 218m; fluid system B,  $U_{mix} = 1.5$ m/s,  $Dp_{valve} = 0$ bar

The bottom of the pipe i.e. 0-0.0164cm, the middle of the pipe i.e. 0.0164-0.0655cm and at the top of the pipe i.e. 0.0655-0.1091cm; where the average local water fraction (LWF) was read from the phase fraction profile for each section.

The local dispersion factor at the top layer is given by Equation 4.1.

$$DF_t = 1 - \frac{WC - LWF}{WC} \tag{4.1}$$

At DF = 1, the flow is fully dispersed and DF = 0 means the flow is fully stratified. The local dispersion factor at the middle layer is given by Equation 4.2.

$$DF_m = 1 - \frac{LWF - WC}{0.525 - WC}$$
(4.2)

The constant 0.525 in the formula was determined from the LWF boundary for separated flow

in the experiment without pressure drop across the valve.

The local dispersion factor at the bottom layer is given by Equation 4.3.

$$DF_b = 1 - \frac{LWF - WC}{1 - WC} \tag{4.3}$$

The Local Average Dispersion factor is the average of the top, middle and bottom local dispersion factors. This term is used in Section 5.1.2 to show the effect of pressure drop across the mixing valve along the pipe.

## 4.3 Flow Pattern Maps

Flow pattern maps are plots showing the type of flow pattern as a function of mixture velocity and water cut for experiments with the same pressure drop across the inlet mixing valve. Sometimes they are plotted for superficial velocity of water against superficial velocity of oil. Flow pattern maps are constructed for better visualization of results and also for comparison with those found in the literature.

The flow patterns in this work are identified from four positions with gamma vertical density profiles and videos from four transparent 0.5m pipes in the test section. Flow pattern maps with  $U_{mix}$  vs WC and  $U_{so}$  vs  $U_{sw}$  are prepared for all four positions along the pipe length. The flow pattern maps with  $U_{mix}$  vs WC for all experiments without pressure drop across the inlet mixing valve are discussed in this chapter. The four different positions are of great importance in showing how the flow develops along the test section.

At 1.82m from the inlet valve, the flow is segregated for all water cuts with mixture velocity 0.5m/s. For mixture velocity of 1 m/s, there is an inhomogeneous oil continuous dispersion for input water cuts of 10-25%. Increase in water cut to 30%, an oil continuous dispersion with a dense pack of water droplets and a water layer is formed. Further increase in water cut up to 60%, the dispersion changes continuity from oil to water and becomes a water continuous dispersion with a dense pack of oil droplets. For higher water cuts, 75% and above, the dense



Figure 4.10: Flow pattern maps ( $U_{mix}$  vs WC) for four positions of gamma along the pipe

pack of oil droplets disappears and the droplets are distributed non-uniformly across the pipe. The flow pattern is called inhomogeneous water continuous dispersion. For 1.5 m/s mixture velocity, input water cut of 10% shows a homogeneous oil continuous dispersion. Increased water cuts between 20-30% are characterized with inhomogeneous oil continuous dispersion. Increase to 35% water cut causes the continuity of the dispersion to change from oil to water and form a dense pack of oil droplets. Further increase of water cut from 40-90% causes the oil droplets to be distributed unevenly in the water phase and form an inhomogeneous water continuous dispersion. Simply, the flow pattern for 1.5 m/s mixture velocity is dispersed for all water cuts but phase inversion occurs between 25-30% water cut.

At 106m downstream the mixing valve, see Figure 4.10b, the flow is still stratified for all water cuts with a mixture velocity of 0.5 m/s. For a mixture velocity of 1 m/s, the flow is an inhomogeneous oil continuous dispersion for 10% input water cut. With increase in water cut from 15-30% a dense pack of water droplets is formed in the oil continuous dispersion together with a thin water layer at the bottom. Higher water cuts from 40-75% show a development to stratified flow. For input water cut of 90% the flow is still a water continuous dispersion but a dense pack of oil droplets is formed. For 1.5 m/s mixture velocity the flow is still dispersed same as for 1.82m downstream the mixing valve.

At 114m from the inlet mixing valve, see Figure 4.10c, segregated flow is seen for the full range of water cut for a mixture velocity of 0.5 m/s and 40-75% water cut for a mixture velocity of 1 m/s. Dispersed flow is observed as oil continuous dispersion for mixture velocities of 1 and 1.5 m/s at 10-30% water cuts. For 1.5 m/s the oil continuous dispersion at this range is inhomogeneous. For 1 m/s mixture velocity the oil dispersion starts as inhomogeneous at 10% water cut and then a dense pack of water droplets and a thin water layer are formed for 15-30% water cuts. Water continuous dispersions are observed from 40-90% water cuts for 1.5m/s and at 90% water cut for 1m/s where it contains a dense pack of oil droplets.

Towards the end of the test section at 218m downstream the inlet mixing valve, see Figure 4.10d, the flow is the same as observed at 114m downstream the mixing valve except for 10% water cut at 1m/s mixture velocity. At this point the flow changes from an inhomogeneous oil continuous dispersion to an oil continuous dispersion with a dense pack of water droplets and a water layer. The pattern maps with  $U_{so}$  vs  $U_{sw}$  for the four positions are shown in Figure 4.11. They show the same trends as for  $U_{mix}$  vs WC.



Figure 4.11: Flow pattern maps  $U_{so}$  vs  $U_{sw}$  for four positions of gamma along the test section

# 4.4 Flow Patterns and Pressure gradient

The flow patterns identified and discussed above were reflected in the pressure gradients for all the velocities tested in the experiments with fluid system B. The flow patterns are shown in a plot of pressure gradient versus water cut at 218m downstream the mixing valve. See Figure 4.12.

With 0.5m/s, the flow is SM with the smallest pressure gradient at around 39 Pa/m for 10% water cut. The pressure gradient increases to 42 Pa/m at 30% water cut and then drops to 31



Figure 4.12: Pressure gradient vs water cut for  $U_{mix} = 0.5$  m/s, 1m/s and 1.5m/s

Pa/m at 90% water cut.

Lower water cuts from 10-30% with  $U_{mix} = 1$ m/s show an oil continuous dispersion with small free water layer at the bottom of the pipe which has an approximate constant pressure gradient of average 108 Pa/m. The pressure gradient increases to 124 Pa/m when the flow changes to SM flow around 40% water cut. Increase of water leads to pressure gradient increases to a peak of 150 Pa/m at 50% water cut. For further increase of water cut, the flow pattern becomes a water continuous dispersion and the pressure gradient drops to 79 Pa/m at 90% water cut. The increase in pressure drop within the stratified flow pattern can be explained by formation of a dense layer of droplets when the phases start to separate. As the flow develops, the phases get cleaner and the pressure gradient drops.

Increasing the velocity to 1.5m/s, for 10-30% water cut, the flow is dispersed with oil being continuous phase. The pressure gradient starts at 248 Pa/m at 10% water cut then drops to 240 Pa/m at 20% water cut. The pressure gradient then increases to a peak value of 322 Pa/m at 25% water cut which is the phase inversion point. From 30-75% water cuts, the flow pattern is water

continuous dispersion with a dense layer of oil droplets. The pressure gradient in this range of water cut decreases due to decreasing size of the dense layer of droplets. At 90% water cut the flow is in-homogeneous water dispersion and has the lowest pressure gradient of all water cuts at  $U_{mix} = 1.5$ m/s at 160 Pa/m.

The pressure gradients for all water cuts with  $U_{mix} = 1.5$ m/s are larger compared to  $U_{mix} = 1$ m/s case which are also larger than  $U_{mix} = 0.5$ m/s. Similar patterns are found in earlier positions at the test section at the 2m, 105m and 115m as seen in Figure C.1, Figure C.2 and Figure C.3 in Appendix C.1 respectively. However, the effect/shape of the 1.5m/s mixture velocity is less elaborate at the 2m due to closeness to the mixing valve.

Schümann (2016) used a blend of Exxsol D80 and Primol 352 oil with 35mPas viscosity (same as fluid system B) for 0.1 to 1.1m/s mixture velocities and 0-100% water cuts. He did not observe the phase inversion point for this range because of smaller mixture velocities tested. This is consistent with the results presented here as the phase inversion point is observed only in higher mixture velocity of 1.5m/s.

The phase inversion point for fluid system A was observed at a smaller velocity: 1m/s, at the water cuts between 50-60% due to the change in the density ratios, viscosity ratios and interfacial tensions between oils and water. However, because the pressure gradient measurements were not taken for all water cuts and for all mixing velocities, the phase inversion point comparison for the 1.5m/s cases between fluid systems A and B could not be done.

# Chapter 5

# **Flow Development Analysis**

## 5.1 Effect of pressure drop across the mixing valve

In both campaigns, a number of experiments were performed with varying pressure drop across the mixing valve. For fluid system A, both experiments with  $U_{mix} = 1$ m/s (WC between 20-40%) and  $U_{mix} = 1.5$ m/s (WC = 20%) were tested for 0.2, 0.35, 0.5 and 1bar pressure drop across the mixing valve. For fluid system B, experiments with  $U_{mix} = 1$ m/s and water cut of 20% were tested for 0.1, 0.2, 0.35, 0.5 and 1bar pressure drop across the mixing valve.

#### 5.1.1 Local water fractions

The amount of mixing at the inlet valve, quantified by the pressure drop across it, affect the local distribution of water. To see the effect, local water fraction measurements for different pressure drops across the mixing valve are presented.

To appreciate the phase distributions, the pipe cross-section was divided into three horizontal sections measured from the bottom of the pipe: the bottom (0-0.0164cm), middle (0.0164-0.0655cm) and the top (0.0655-0.1091cm). The average local water fraction profiles at the pipe bottom for the velocity of 1 and 1.5m/s (for fluid system A) and 1m/s (for fluid system B)

for different pressure drops across the valve are presented. The curves for the top and middle positions are found in Appendix C.2.



Figure 5.1: Local water fraction distribution along the pipe for the bottom section of the pipe;  $U_{mix} = 1.0$ m/s, fluid system A



Figure 5.2: Local water fraction distribution along the pipe for the bottom section of the pipe;  $U_{mix} = 1.5$  m/s, fluid system A



Figure 5.3: Local water fraction distribution along the pipe for the bottom section of the pipe;  $U_{mix} = 1.0$ m/s, fluid system B

With more phase separation along the pipe, it is expected that the local water fraction for the bottom section of the pipe become bigger with the distance. Since higher pressure drop across the mixing valve causes higher dispersion, the local water fraction for the bottom positions must increase with the decreasing pressure drop across the valve i.e. less dispersion. Which is exactly the general trend seen in Figure 5.1, 5.2 and 5.3. The local water fraction also increases with the distance from the mixing due to settling of the water droplets at the bottom of the pipe.

When Figure 5.1 is compared to Figure 5.2, the increase in water fraction is seen to be delayed in the former compared to the later. This is result of the higher velocity and hence more turbulence which carries the droplets in dispersion for a longer distance before settling occurs.

Similar trends are found for the middle and top positions profiles as seen in the Figure C.4 to Figure C.9 in Appendix C.2. It can be seen that the local water fractions decrease with the distance from the bottom of the pipe. For the top positions, the reader should not be confused with the reverse of the trend since oil should be increasing i.e. water decreasing. The top profiles show the formation of clean oil in the fluid system A and not for fluid system B.

Comparing Figure 5.3 with Figure 5.1 (i.e. same velocity, different fluid systems), it can be seen that the maximum local water fractions of the former always end up smaller compared to the later for the same pressure drop across the valve. For example, for 0.35bar the average local water fraction at almost the end of the pipe section for Figure 5.1 is 80% while that of Figure 5.3 is merely 43%. It is important to note that Figure 5.3 is for fluid system B and hence water droplets are kept in suspension more because of the higher viscosity of the continuous phase (oil) and therefore settle less compared to fluid system A.

The same conclusion can be reached when comparing the middle position average local water fractions. The middle sections of the fluid system A seem to have lower average local water fraction compared to the high viscous counterparts. Unlike the previous positions, the top positions local water fraction are higher for the fluid system B compared to the fluid system A.

### 5.1.2 Pressure Gradient and Dispersion Factor

Pressure gradients as a function of pipe length were calculated using the experimental data and plotted as seen in Figure 5.4 to Figure 5.8 in Table 5.1 for the valve pressure drops of 0.1-1bar respectively. The mixture velocity of 1m/s and water cut of 20% for fluid system B data are reported. Average local dispersion factor (see Section 4.2) of the pipe was also calculated using the local water fractions and were included in the plots.

Table 5.1: Results for the pressure gradient and local average dispersion factor along the test section for fluid system B at  $U_{mix} = 1m/s$ , WC = 20% and different pressure drops across the mixing valve



Figure 5.4: Pressure gradient and dispersion factor along the test section;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 0.1bar$ , fluid system B

Continued	on	next	page
-----------	----	------	------

#### **Explanation**

The pressure gradient consistently and gradually decrease by approximately 70Pa/m along the test section. It is caused by the settling of large droplets formed by small pressure drop (large valve opening) at the mixing valve and hence phase separation. This explanation is further supported by the fact that the dispersion factor profile decrease sharply from approximately 80% dispersion at the inlet of the test section to approximately 35% at the end; which means that there was significant phase separation.
Table 5.1 – continued from previous page

#### Figures



Figure 5.5: Pressure gradient and dispersion factor along the test section;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 0.2bar$ , fluid system B

#### Interpretation

Comparing to Figure 5.4, Figure 5.5 pressure gradient is relatively flat with the mean pressure gradient of approximately 180Pa/m. Due to the shape of the pressure gradient profile, it can be concluded that there was not so much phase separation and the mixture remain dispersed through out the test section. With larger pressure drop across the mixing valve, droplets of smaller sizes are formed; whose sizes are too small to overcome viscosity forces and fall towards the bottom of the pipe. The droplets will coalesce until they are big enough for the gravity to work on them and settle them at the bottom of the pipe. Due to this reason, the dispersion factor profile remain relatively flat compared to Figure 5.4 and only decreases from approximately 90% to merely 70%.

Continued on next page



Table 5.1 – continued from previous page

Figure 5.6: Pressure gradient and dispersion factor along the test section;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 0.35bar$ , fluid system B



Figure 5.7: Pressure gradient and dispersion factor along the test section;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 0.5bar$ , fluid system B

Continued on next page

Interpretation

The trends shown in Figure 5.5 is closely replicated in Figure 5.6. The pressure gradient remains relatively flat and so is the dispersion factor profile. Same explanation as of the Figure 5.5 is applicable here.

Similar trends as of Figure 5.5 is observed and hence the same explanation is applicable.



Table 5.1 – continued from previous page

Figure 5.8: Pressure gradient and dispersion factor along the test section;  $U_{mix} = 1m/s$ , WC

= 20%,  $DP_{valve} = 1bar$ , fluid system B

Similar trends as of Figure 5.5 is observed and hence the same explanation is applicable. The measured pressure gradient lies on top of the average pressure gradient, which means the pressure gradient throughout the test section was almost constant.

In general, the following can be concluded/observed from the results of Table 5.1:

- Dispersion remains fairly high, above 70%, for all pressure drop across the mixing valve with the exception of the Figure 5.4; hence all the experiments show the dispersed flow patterns.
- The dispersion factor increases with the increased pressure drop across the valve.
- The higher the mixing at the inlet valve, the higher the average pressure gradient of the flow. This is due to the increased mixing at the mixing valve with the increasing pressure drop across the valve. For the Obar, the average pressure gradient is slightly below that of single phase water. Increasing pressure drop across the mixing valve, the average pressure gradient becomes greater than the single phase water pressure gradient.

Figure 7.1 shows an increase of pressure gradient with increasing pressure drop across the mixing valve, except for 0.5bar. The 0.5bar curve shows a pressure gradient larger than that for

Interpretation



1 bar at earlier pipe distance which drops rapidly to the value close to that of 0.35bar pressure drop across the mixing valve.

Figure 5.9: Pressure gradient development along the pipe as a function of the DPvalve

In order to show the effect of viscosity, similar results of pressure gradient and dispersion factor for different pressure drops across the valve are presented for the fluid system A in Table 5.2.

Table 5.2: Results for the pressure gradient and local average dispersion factor along the test section for fluid system A at  $U_{mix} = 1m/s$ , WC = 20% and different pressure drops across the mixing valve



Figure 5.10: Pressure gradient and dispersion factor development along the pipe;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 0bar$ , fluid system A

#### Explanation

With the valve fully open, water and oil mixing comes only when they meet at the test pipe's inlet. The two fluids quickly segregate and stabilize which renders the dispersion factor curve relatively flat from the 50m point onwards.

The 2-phase pressure gradient starts to go higher initially due to settling of the drops, with no free water. It continues to increase probably due to the free water layer formation.

The rising of the pressure gradient profile after the 115m is hard to explain. It is possible that it is caused by the bend effect, more breaking up and subsequent settling of the droplets after breaking up at the bend, experimental errors or combinations of the above factors. Similar trend is observed in Figure 5.11. but disappear with large pressure drops across the mixing valve.

Continued on next page

 Table 5.2 – continued from previous page



Figure 5.11: Pressure gradient and dispersion factor development along the pipe;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 0.2bar$ , fluid system A





 $C_{mix} = 1m/s$ , WC = 20%,  $DI_{valve} = 0.550ar$ fluid system A

Continued on next page

#### Interpretation

With the pressure drop across the valve 0.2bar (42% of valve opened) more mixing of the droplets happens compared to Figure 5.10 above. The initial average dispersion factor is bigger for more than 12%. The separation of the two fluids will therefore take longer to reach a constant value as seen in the dispersion factor curve i.e. slower.

With more dispersion, the initial pressure gradient is higher in 0.2bar case compared to 0bar case. However, the shape of the curves are similar; with similar explanation.

With more mixing at the inlet valve, the dispersion is more homogeneous and hence relatively constant dispersion factor (also known as coalescence phase) at the start of the pipe until 105m. During this phase coalescence of the droplets happens until the droplets reach the critical settling size. Once the critical size is reached, rapid settling occurs and the average dispersion starts to decrease.

The shape and explanation of the pressure gradient curve is the same as for the above figures.





More dispersion is observed (94%) with 0.5bar with longer coalescence phase. Similar phenomenon happens in this case as previous ones.

Figure 5.13: Pressure gradient and dispersion factor development along the pipe;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 0.5bar$ , fluid system A

Continued on next page

 Table 5.2 – continued from previous page



Figure 5.14: Pressure gradient and dispersion factor development along the pipe;  $U_{mix} = 1m/s$ , WC = 20%,  $DP_{valve} = 1bar$ , fluid system A

Interpretation

With the highest pressure drop, there is hardly separation and the average dispersion remains relatively constant along the entire section of the testing pipe.

The shape of the pressure gradient curve is different from the rest of the Figure 5.10 to Figure 5.13. The explanation for this trend is still unclear.

In general, the following can be concluded/observed from the results of Table 5.2:

- Pressure gradient along the pipe begins by increasing due to settling of the droplets and starts to decrease due to formation of the free water layer.
- With higher mixing, the dispersion is more homogeneous and separation of the phases takes longer. This is because the droplet sizes are small so settling does not start until far downstream the mixing valve when the critical diameter has been reached.
- With increasing pressure drop across mixing valve, the average dispersion at the end of the pipe is higher, meaning the flow doesn't develop in the test section length.
- The higher the mixing at the inlet valve, the higher the average pressure gradient. For 0 bar, the average pressure gradient is between the single phase water and single phase oil values. With increasing pressure drop across the mixing valve, the pressure gradient

becomes higher than the single phase water pressure gradient.

• The initial pressure gradient increased from approximately 83 to approximately 90Pa/m when the pressure drop across the mixing valve is increased from 0 to 1bar. There is a trend where the smaller the pressure drop across the mixing valve, the lower the initial pressure gradient. This could be explained by the droplet sizes formed after mixing valve; with more constriction, the droplets are smaller and hence higher pressure gradient. However, this hypothesis has to be confirmed with separate experiments.

Comparing fluid system A and B, e.g. Figure 5.11 vs Figure 5.5, the dispersion factor changes less significantly in fluid system B compared to fluid system A for the same pressure drop across the valve and mixture velocity. Initially there is slightly less dispersion in fluid system B compared to fluid system A, yet at the end of the test pipe, the dispersion factor has dropped to mere 70% compared to 17% for fluid system B and A respectively. This is caused by formation of smaller droplets in the fluid system B due to high viscosity of the continuous phase and the fact that the water droplets needs to overcome higher viscous force to settle. For both cases, the average pressure drop is very close to that of pure water although very different in scale i.e. 84Pa/m for the fluid system A compared to 180Pa/m for the fluid system B. This is due to difference in viscosity and density of the oil.

In general, the average dispersion factor and the pressure drop across the mixing valve display a proportionate trend as seen in Figure 5.15 below.



Figure 5.15: Average dispersion factor vs pressure drop across the mixing valve for  $U_{mix}=1$ m/s and  $U_{mix}=1.5$ m/s for the fluid system A

### 5.2 Effect of flow rate

When the velocity is changed from 1 to 1.5m/s as Figure 5.16a and Figure 5.16b shows similar explanations as that shown in Table 5.2 can be observed. However, the following were observed when comparing the two figures:



Figure 5.16: A comparison of pressure gradients and local average dispersion factor for fluid system A to show the effect of flow rate.

- The pressure gradients are significantly higher when the mixture velocity is 1.5m/s compared to 1.0m/s; this is to be expected since the flow rate has changed. However, for the 1.5m/s and fully open valve, the average pressure gradient is lower compared to that of single phase oil.
- For similar pressure drop across the mixing valve, take 0.35bar as an example, see Figure 5.16, the average dispersion factor is higher in 1.5m/s. This is because of the extra turbulence caused by the increased liquid velocity.
- When present, the coalescence phases are longer with 1.5m/s compared to 1.0m/s experiments e.g. for 0.35bar pressure drop across the valve, the end of coalescence phases are approximately 160m and 105m for the mixing velocity of 1.5m/s and 1.0m/s respectively.

## 5.3 Effect of viscosity

Although the effect of viscosity has been mentioned throughout the report, the following is the summary:

- Comparing the Local water fractions at the bottom, middle and the top part of the flow suggests that the higher viscosity continuous phase (fluid system B) will have more stable dispersion compared to less viscous one (fluid system A). The high viscosity oil system seems to have bigger water concentration at the top compared to the low viscosity system. One possible explanation for this is that the droplet sizes are smaller in the high viscosity oil compared to less viscous one (Carrillo De Hert & Rodgers, 2018) and hence kept in suspension better.
- The pressure gradient of the fluid system B is higher compared to the fluid system A under the same experimental conditions.

# Chapter 6

# Modeling

In order to reproduce the experimental results, a simple dynamic model was implemented. This model was adopted from the model by Schümann (2016).

### 6.1 Model description

The model was developed in order to predict the full development length of an oil water flow downstream a choke valve. It was divided into three main sections: valve model, phase distribution model and pressure gradient model.

The valve model was put to find the initial size of the droplets downstream the valve. The valve was modeled as a restriction in the pipe diameter similar to an orifice. The mechanism of droplets break-up was acceleration in the restriction. Percy & Sleicher (1983) defined a droplet size  $d_f$  as a function of a fraction f of droplets breaking in an orifice. This means for an upstream droplet size called  $d_{90}$ , 90% of the droplets will break up in the orifice and  $d_0$  means that the droplets will pass through the orifice without breaking. Equation 6.1 shows the correlation for the upstream droplet size ( $d_f$ ) as given by Percy & Sleicher (1983).

$$d_f = C_f \sqrt{\frac{D_o \sigma}{\Delta P}} \tag{6.1}$$

Where  $D_o$  is the orifice diameter,  $\sigma$  is the interfacial tension and  $\Delta P$  is the pressure drop over the orifice.  $C_f$  is a coefficient which depends on the restriction of the pipe and the fraction of broken droplets f. Schümann (2016) assumed the downstream droplet size will be proportional to  $\sqrt{1/\Delta P}$  as the upstream droplet size. This is as seen in Equation 6.2.

$$d_{\nu} = C_{\nu} \sqrt{\frac{1}{\Delta P}} \tag{6.2}$$

where  $C_v$  is a characteristic variable considering the fluid properties and valve geometry.

The phase distribution model for low superficial velocities was made considering the effect of droplet growth and settling. Settling velocity was computed from Stokes law as shown in Equation 6.3.

$$V_s = \frac{2g}{9} \cdot \left(\frac{\rho_d - \rho_c}{\mu_c}\right) \cdot \left(\frac{d_v}{2}\right)^2 \tag{6.3}$$

 $\rho_d$  and  $\rho_c$  are the densities of the dispersed phase and the continuous phase respectively and  $\mu_c$  is the continuous phase viscosity.

It was assumed that there no slip between the phases occurs, so the oil and water layer can be calculated directly before settling and coalescence takes place. New layer areas were calculated at each time step by considering settling and coalescence.

It was assumed that settling movement is reduced as the dispersed layer compacts. The dispersed phase fraction inside the dispersed layer ( $\Phi_{mix}$ ) was calculated by taking the area of oil in dispersed phase over the total area of dispersion (when oil is the dispersed phase). See Equation 6.4.

$$V_{c} = V_{s} \left( 1 - \frac{0.2}{1 - \Phi_{mix}} \right) \qquad \Phi_{mix} = \frac{A(1 - f_{w}) - A_{o}}{A - A_{o} - A_{w}}$$
(6.4)

where A is the total pipe cross sectional area and  $A_o$  and  $A_w$  are the cross sectional areas of the oil and water layer respectively. When the  $\Phi_{mix}$  exceeds 0.8, settling will stop.

Coalescence was considered in two main forms. Coalescence of droplets with other droplets and coalescence of droplets with interface of the initially dispersed phase. Coalescence of droplets

with other droplets leads to growth of droplets size. The rate of droplets coalescence depends on the concentration of droplets in the dispersion. This is shown in the Equation 6.5 where  $\Delta t$ is the time step between *i* and *i* + 1 and  $C_{disp}$  describes the growth rate constant. The settling velocity, however, only considered the initial droplet size.

$$d_i = d_{i-1} (1 + C_{disp} \cdot \Phi_{mix} \cdot \Delta t) \tag{6.5}$$

The volume flux from the dispersion layer to the continuous layer of the initially dispersed phase was given by Equation 6.6 where  $I_i$  is the interface between dense packed layer and oil, and  $C_{inter}$  is a coalescence rate constant.

$$Q_{flux_i} = C_{inter} \cdot I_i \cdot d_i^3 \tag{6.6}$$

For pressure gradient, the two fluid model by Arirachakaran et al. (1989) was modified. The two fluid model which takes into account two clean continuous phases was taken as a starting point. A third layer representing the dense packed droplet section was added. The geometry of the dense packed layer is as seen in Figure 6.1.

As a simplification, it was assumed that the dispersed phase fraction is constant within the dense packed layer. The local phase fractions of water and oil were set equal to those required for phase inversion. It was also assumed the amount of entrained liquid is known. The effective viscosity of the dense layer was found from the effective viscosity model by Pal & Rhodes (1989) shown in Equation 6.7.

$$\mu_{mix} = \mu_c \left[ 1 + \frac{0.8415\Phi/\Phi_{\mu_r=100}}{1 - 0.8415\Phi/\Phi_{\mu_r=100}} \right]$$
(6.7)

 $\mu_c$  is the viscosity of the continuous phase.  $\Phi_{\mu_r=100}$  is the dispersed phase fraction when the mixture viscosity exceeds hundred times that of the continuous phase.  $\Phi_{\mu_r=100} = 0.765$  was proposed by (Søntvedt and Valle, 1994). The mixture density was calculated by Equation 6.8.

$$\rho_{dense} = \rho_o \cdot \varepsilon_{o\_dense} + \rho_w \cdot \varepsilon_{w\_dense} \tag{6.8}$$

The partial pressure loss is computed for every phase as if the phase would occupy the entire



Figure 6.1: Geometry of the three layer model with model definitions for initially oil dispersed in water

cross-section. The total pressure loss is computed as the sum of the partial pressure gradients for each phase multiplied with the perimeter fractions wetted by the respective phase as seen in Equation 6.9

$$\left(\frac{dP}{dz}\right)_{total} = \frac{S_o}{S} \left(\frac{dP}{dz}\right)_o + \frac{S_{dense}}{S} \left(\frac{dP}{dz}\right)_{dense} + \frac{S_w}{S} \left(\frac{dP}{dz}\right)_w$$
(6.9)

The single phase pressure gradients are given by Equation 6.10

$$\left(\frac{dP}{dz}\right)_{i} = \frac{f_{i} \cdot \rho_{i} \cdot U_{i}^{2}}{2D}$$
(6.10)

The friction factor  $f_i$  is obtained by solving the Hagen-Poiseuille equation for laminar flow or the Colebrook equation if the flow is turbulent, with the Reynolds number given by equation 6.11

$$Re_i = \frac{f_i \cdot \rho_i \cdot U_i}{\mu_i} \tag{6.11}$$

The mixture velocity  $U_{mix}$  was used in place of all the layer velocities.

#### 6.2 Modifications to the model

The model described in Section 6.1 was modified to reproduce the results from the two SIP experimental campaigns.

- The experiments that were being reproduced by the model were initially oil continuous dispersions. So the model was changed from water continuous with oil droplets to oil continuous with water droplets. The minimum continuous phase fraction in the dispersion layer was set to 50%.
- The valve model that was used by Schumann was derived from Percy and Sleicher's equation for droplet size upstream an orifice. In this model, the main mechanism of droplet break-up was stated to be acceleration in the restriction. The size of the droplets is proportional to  $(\sqrt{1/\Delta P})$  where  $\Delta P$  is the pressure drop across the restriction. The valve model was changed to another model by Van der Zande & Van den Broek (1998) as presented by Fossen & Schümann (2017).

Van der Zande & Van den Broek (1998) found that contrary to acceleration in the restriction, it is mainly the geometry downstream of a restriction that influences the evolving droplet size distribution instead of the geometry of the entrance region. The results indicated that breakup happens due to turbulence in the downstream region. The equation proposed is

$$d_{max} = \left(\frac{\sigma}{\rho c}\right)^{0.6} \cdot E^{-0.4} \tag{6.12}$$

Where E is the energy dissipation rate which was approximated by the mean energy dissipation given in Equation 6.12.

$$E = \frac{\Delta P_{perm} \cdot U_p}{\rho_c \cdot \Delta x_{perm}} \tag{6.13}$$

•  $\Delta P_{perm}$  is the permanent pressure drop,  $U_p$  is the accelerated velocity,  $\rho_c$  is the density

of the continuous phase, and  $\Delta x_{perm}$  is the "dissipation length". In the implementation of the model, the  $\Delta P_{perm}$  was set to be the pressure drop across the valve. The accelerated velocity was set to the mixture velocity divided by the valve opening. The dissipation length,  $\Delta x_{perm}$ , was not measured in our setup, therefore, the value of 2.5 pipe diameters as determined by Van der Zande & Van den Broek (1998) was used as input.

- In the original Schümann (2016) model, once characteristic initial droplet size was found by the valve model. This value was then used to calculate the settling velocity, which remained constant for all time steps. Droplet sizes are changing in the test section due to coalescence between droplets in the dispersion layer. A modification was made to include the effect of the changing droplet size in the settling velocity. So the settling velocity was recalculated with a new droplet size present at each time step.
- Tuning parameters were valve constant  $C_{\nu}$ , coalescence rate constant  $C_{inter}$  and growth rate constant,  $C_{disp}$ , same as in Schumann's model. While implementing the phase distribution model, it showed that settling was occurring early on test section than it was observed in the experiments. Because of this, a critical droplet diameter,  $D_{crit}$  was introduced. Here the assumption is that the turbulent forces in the flow are strong enough to distribute droplets up to certain critical size. For larger droplets the gravitational forces will dominate.

No changes were made in the pressure gradient model. This was a subject for a fellow student. The focus of this project was to reproduce the interface positions along the test section.

#### 6.3 Model results

The results from the model include the interface positions along the pipe and the pressure gradients along the pipe. The initial droplet sizes from the model that were close to the experimental values were obtained with  $C_v = 1.1$ . The best results for interface positions were obtained with:  $C_{inter} = 1.5 \times 10^6$  and  $C_{disp} = 0.0012$ . Figure 6.2 shows some comparisons for the experimental data and the model results for the fluid system A. The model was tuned for the fluid system A experiments because they show a more distinct and complete separation behaviour. However, only the experiments with water cut of 20% were used because of the availability of droplet



data analysis from Issara & Kivuyo (2018). Other similar figures are shown in Appendix D.1.6.

Figure 6.2: Interfacial positions results from the model compared to experimental results

The model was also tested for the fluid system B with satisfactory results. The pressure gradient model did not produce satisfactory results in terms of the trend of pressure gradient along the test section. The average values of the predicted pressure gradients, however, were close to the measured pressure gradients.

The size of droplets obtained from the valve model for the low viscosity oil (Exxsol D60 with visocsity 1.43 mPas) compared well with the maximum droplet size,  $D_{max}$  values that were obtained from droplet analysis. Figure 6.3 shows the comparison of the experimental droplets sizes and the model predicted droplet sizes. The values of critical diameter that are used in the model have been correlated with the pressure drop across the valve as shown in Figure 6.3b. The trend of the correlation suggests that there will be a minimum droplet size below which no settling will occur but will be carried in the suspension as the pressure drop across the mixing valve increases.



(a) Critical Diameters (Dcrit) values used in the model as a function of  $DP_{valve}$ .

(b) Comparison of droplet sizes from model with experimental sizes

Figure 6.3: Critical diameters used in the model and the initial droplet sizes from the valve model

# Chapter 7

# **Uncertainties and Sources of Errors**

Several phenomena could account for the errors and rogue data in the experiments. There are cases where either the data had to be ignored completely or used with precautions in order to have conclusions that are reliable. Some of these effects are discussed below:

### 7.1 Bend effect

There are three bends in the test section as described in the Section 3.1. Although a careful designing of the facilities was implemented to minimize the effect of the bends (see Section 2.2.3), the effect was considerable in some cases. The effects were bigger with the more viscous oil system because it takes longer for the effect to dissipate. When such effects were detected, the measurements after the bend were not included in the data analysis. Figure 7.1 below compare results of the dispersion factor for the fluid system A when the position influenced by the bend is included and when not included .

Local water fraction and Dispersion factor, which depends on the former, were two parameters that the bend effect was most observed.



Figure 7.1: Bend effect on the dispersion factor ; $U_{mix} = 1$ m/s,  $DP_{valve} = 1$ bar, fluid system A

### 7.2 Pipe cleanliness

Cleanliness/wetting of the pipe walls by the flowing fluids may affect the measurements during the experiments. When light and oxygen are available, bacteria and algae may start to colonize the test pipe. The bacteria may start to degrade oil and the together with the byproducts start to introduce unwanted effect. Some types of oils, like used in this experiment i.e. Exxsol, reacts with hoses and make them stiff. They also react with plastic pipes and make them brittle. In this experiment steel pipes were used to minimize the effect and Biocide IKMCC-80 was also added in the mixture to prevent organic growth.

The wetting of the pipe walls affects the measurement considerably. When the droplets stick to the walls the surface roughness of the pipe may change. Figure 7.2 below shows the transparent pipe section for the similar experiment before and after cleaning.

The dirty pipe walls may affect the shape and the values of the pressure gradients. Schümann (2016) investigated the effects of the clean pipe walls with mixing at the inlet valve between



Figure 7.2: Wetting of pipe walls before and after cleaning of the pipe (Schümann, 2016)

water and oil. He also investigated when no mixing is set and the two liquids enter the test section by simple Y junction. Figure 7.3 shows that when the pipe is clean, there is considerable pressure gradient decrease for both cases; the shapes of the profiles also are physically consistent when the pipes are clean.



Figure 7.3: Comparison of pressure gradient measurements along the pipe for a cleaned and dirty test section; Umix=0.5 m/s, fw=40% (Schümann, 2016)

To minimize the error, pipes were cleaned before experiments and if both oil and water fractions were increased, water fractions were increased first.

#### 7.3 Calibration and instrument errors

While care was taken to calibrate the instruments regularly, there might still be errors due to faulty calibrations or instrument malfunctioning. For the instrument that are dependent on the radioactive source, e.g. gamma densitometer, the natural fluctuation of the source could introduce errors. Also, same type of instruments may introduce some difference due to uneven calibrations. Another important source of error is the mounting of the pressure taps. If the small holes drilled into the pipe are not perfectly perpendicular to the pipe, there could be error in the pressure measurements which will increase with the increasing mixture velocity. Same effect can be caused if a small grade from drilling was left in the pipe.

#### 7.4 Errors due to the nature of the flow

Sometimes, the instrument will read correct value but the value of the data is not what was expected. For instance, sometimes the local water fraction will be lower further from mixing valve compared to close. This could be caused by the combination of the nature of the flow and measuring techniques. For example, with wavy flow pattern, it makes a difference if the average value recorded were at the time of the crest or trough and the measurement is instantaneous or average on time span. The wavelengths of waves could be as high as twice the diameter depending on the mixture velocity (Trallero, 1997), approximately 0.22m in this experimental setup. Therefore, the position of the instrumentation is of importance. In general, the higher the velocity, the higher the amplitudes of the waves, the higher the risk of incorrect data.

#### 7.5 Human errors

Some errors are traceable to technicians and researchers. It could be as basic as faulty installation of instrumentation. Some of the data presented, have been calculated from other data that were read from plots, e.g. average local water fraction, and hence subjective reading comes into play. Another good example is the identification of the flow patterns through eye visualization. Although aided with local water fraction profiles, yet there is always subjectivity when results are dependent on human decision.

# **Chapter 8**

## **Conclusion and Recommendations**

Studies on the effect of the pressure drop across the mixing valve on the flow development were performed using two oil-water fluid systems. The experiments were carried out in 2018 and 2019 with low viscosity oil (1.43cp) and a higher viscosity oil (35cp) respectively. The experiments were carried out by changing the water cut and the mixture velocity.

The flow patterns were identified visually and using phase fraction profiles from gamma densitometers. The identified flow patterns include Stratified mixed (SM), Homogeneous oil continuous dispersion (Do-H), Inhomogeneous oil continuous dispersion (Do-I), Inhomogeneous water continuous dispersion (Dw-I), Oil continuous dispersion with a dense layer of water droplets (Do-DP), Water continuous dispersion with a dense layer of oil droplets (Dw-DP) and Oil continuous dispersion with a dense layer of water droplets and a water layer (Do-DP + w). The flow pattern maps were produced to show the flow pattern regions as a function of superficial velocities of oil and water; and, mixture velocity and water cut. The flow patterns identified and flow pattern maps produced were in agreement with the Trallero et al. (1997) and Elseth (2001) classifications.

The dispersed flow patterns were found to have generally higher pressure gradients compared to the dispersed flow patterns. The higher pressure gradient is attributed to the mixture velocity and effective viscosity where the dispersed flow patterns appear at higher mixture velocities compared to stratified flows, and its effective viscosity is higher. A peak in pressure gradient

observed at  $U_{mix} = 1.5$  m/s at 25% water cut when the flow pattern changes from being an oil continuous dispersion to water continuous dispersion is identified as the Phase inversion point.

Along the test section, it was found that separation of phases is delayed with increase in pressure drop across the mixing valve due to formation of smaller droplets downstream the choke valve. The smaller droplets are transported within the continuous phase when coalescence is taking place before the droplets start settling. The coalescence stage was found to be longer when pressure drop across the valve is higher. For the same conditions, a higher mixture velocity will transport the droplets further downstream the mixing valve before settling and thus delay phase separation. Viscosity of the oil was found to affect the pressure gradient and the phase separation. The higher the viscosity of oil, the higher the pressure gradient along the test section and a more delayed phase separation.

A 3-layer dynamic model from Schümann (2016) which predicted the pressure gradient and interfacial positions between water, oil and dispersion layers was modified and used. The model was able to predict the interfacial positions with good accuracy. While the trend of the pressure gradient were not correctly predicted, the model values of pressure gradient compared well with the average pressure gradient from the experiments.

#### **Recommendations and further Work**

The following are recommended as further work

- Perform further experiments on longer test pipe sections, especially for the higher viscosity oil and other mixing valve pressure drops so that the full development length can be observed.
- Perform similar experiments with higher mixture velocities compared to the ones tested in this experiment.
- Further improve on the model by including other effects such as the bend effect.
- Modification of the pressure gradient model used so as to accurately depicts the shape of the pressure gradients

• Testing the proposed model on other fluid systems to ascertain its applicability.

## References

- Al-Wahaibi, T., & Angeli, P. (2008). Droplet size and velocity in dual continuous horizontal oil–water flows. *Chemical engineering research and design*, 86(1), 83–93.
- Amundsen, L. (2016). An experimental study of oil-water flow in horizontal and inclined *pipes* (Unpublished doctoral dissertation). Norwegian University of Science and Technology, Trondheim.
- Angeli, P., & Hewitt, G. (2000). Flow structure in horizontal oil-water flow. *International Journal of Multiphase Flow*, 26(7), 1117–1140.
- Arirachakaran, S., Oglesby, K., Malinowsky, M., Shoham, O., Brill, J., et al. (1989). An analysis of oil/water flow phenomena in horizontal pipes. In *SPE Production Operations Symposium*.
- Belfroid, S., Cargnelutti, M., Schiferli, W., & van Osch, M. (2010). Forces on bends and tjoints due to multiphase flow. In Asme 2010 3rd joint us-european fluids engineering summer meeting collocated with 8th international conference on nanochannels, microchannels, and minichannels (pp. 613–619).
- Bratland, O. (2010). Pipe flow 2: Multi-phase flow assurance. *Ove Bratland Flow Assurance Consulting, Chonburi, Thailand*.
- Carrillo De Hert, S., & Rodgers, T. L. (2018). On the steady-state drop size distribution in stirred vessels. part ii: Effect of continuous phase viscosity. *AIChE Journal*.
- Devold, H. (2006). Oil and gas production handbook. ABB Oil & Gas.
- Elseth, G. (2001). *Modeling of oil-water flow in horizontal and near horizontal pipes* (Unpublished doctoral dissertation). Telemark University College, Porsgrunn.

- Fossen, M., & Schümann, H. (2017). Experimental study of the relative effect of pressure drop and flow rate on the droplet size downstream of a pipe restriction. *Journal of Dispersion Science and Technology*, 38(6), 826–831.
- Hinze, J. (1955). Fundamentals of the hydrodynamic mechanism of splitting in dispersion processes. *AIChE Journal*, *1*(3), 289–295.
- Howarth, W. (1967). Measurement of coalescence frequency in an agitated tank. *AIChE Journal*, *13*(5), 1007–1013.
- Ioannou, K., Nydal, O. J., & Angeli, P. (2005). Phase inversion in dispersed liquid–liquid flows. *Experimental thermal and fluid science*, *29*(3), 331–339.
- Issara, B., & Kivuyo, R. (2018, December). *Development of surfactant stabilized oil-water flow* (Tech. Rep.). Trondheim: Norwegian University of Science and Technology.
- Kivuyo, R. (2019). Droplets Analysis and model development for oil water pipe flow experiments (Unpublished master's thesis). Norwegian University of Science and Technology, Trondheim.
- Kouba, G. E. (2003). Mechanistic models for droplet formation and breakup. In *Asme/jsme* 2003 4th joint fluids summer engineering conference (pp. 1607–1615).
- Kubie, J., & Gardner, G. (1977). Drop sizes and drop dispersion in straight horizontal tubes and in helical coils. *Chemical Engineering Science*, *32*(2), 195–202.
- Lehr, F., Millies, M., & Mewes, D. (2002). Bubble-size distributions and flow fields in bubble columns. *AIChE Journal*, *48*(11), 2426–2443.
- Levich, V. G. (1962). Physicochemical hydrodynamics.
- Liao, Y., & Lucas, D. (2009). A literature review of theoretical models for drop and bubble breakup in turbulent dispersions. *Chemical Engineering Science*, *64*(15), 3389–3406.
- Liao, Y., & Lucas, D. (2010). A literature review on mechanisms and models for the coalescence process of fluid particles. *Chemical Engineering Science*, 65(10), 2851–2864.
- Nädler, M., & Mewes, D. (1997). Flow induced emulsification in the flow of two immiscible liquids in horizontal pipes. *International journal of multiphase flow*, 23(1), 55–68.

- Pal, R., & Rhodes, E. (1989). Viscosity/concentration relationships for emulsions. *Journal of Rheology*, 33(7), 1021–1045.
- Percy, J., & Sleicher, C. (1983). Drop breakup in the flow of immiscible liquids through an orifice in a pipe. *AIChE Journal*, 29(1), 161–164.
- Pietrzak, M., & Witczak, S. (2013). Multiphase flow mixture in 180 pipe bends. *Chemical and Process Engineering*, *34*(2), 227–239.
- Sanchez, L. E., & Zakin, J. L. (1994). Transport of viscous crudes as concentrated oil-in-water emulsions. *Industrial & Engineering Chemistry Research*, 33(12), 3256–3261.
- Schümann, H. (2016). *Experimental investigation of transitional oil-water pipe flow* (Unpublished doctoral dissertation). Norwegian University of Science and Technology, Trondheim.
- Sharma, M., Ravi, P., Ghosh, S., Das, G., & Das, P. (2011a). Hydrodynamics of lube oil–water flow through 180° return bends. *Chemical engineering science*, *66*(20), 4468–4476.
- Sharma, M., Ravi, P., Ghosh, S., Das, G., & Das, P. (2011b). Studies on low viscous oil–water flow through return bends. *Experimental Thermal and Fluid Science*, *35*(3), 455–469.
- Shinnar, R., & Church, J. M. (1960). Statistical theories of turbulence in predicting particle size in agitated dispersions. *Industrial & Engineering Chemistry*, *52*(3), 253–256.
- Sleicher, C. (1962). Maximum stable drop size in turbulent flow. *AIChE Journal*, 8(4), 471–477.
- Swanee, P., & Jain, A. K. (1976). Explicit equations for pipeflow problems. *Journal of the hydraulics division*, *102*(5).
- Torres-Monzón, C. F. (2006). *Modeling of oil-water flow in horizontal and near horizontal pipes* (Unpublished doctoral dissertation). University of Tulsa.
- Trallero, J., Sarica, C., Brill, J., et al. (1997). A study of oil-water flow patterns in horizontal pipes. *SPE Production & Facilities*, *12*(03), 165–172.
- Van der Zande, M. J., & Van den Broek, W. (1998). Breakup of oil droplets in the production system. In *Proceedings of asme energy sources technology conference and exhibition*, *houston* (pp. 2–4).

Vielma, M. A., Atmaca, S., Sarica, C., Zhang, H.-Q., et al. (2008). Characterization of oil/water flows in horizontal pipes. *SPE Projects, Facilities & Construction*, *3*(04), 1–21.

# Appendix A

# **Piping and Instrumentation Diagram**



Figure A.1: Piping and Instrumentation diagram for the Experimental Setup

# **Appendix B**

# **Phase Fraction Profiles**
































# **Appendix C**

## **Flow Development**





Figure C.1: Pressure gradient vs water cut at 2m for the  $U_{mix} = 0.5$  m/s, 1m/s and 1.5m/s



Figure C.2: Pressure gradient vs water cut at 106m for the  $U_{mix} = 0.5$  m/s, 1m/s and 1.5m/s



Figure C.3: Pressure gradient vs water cut for the  $U_{mix} = 0.5$  m/s, 1m/s and 1.5m/s



C.2 Local water fraction

Figure C.4: Local water fraction vs distance for the middle part of the cross-section;  $U_m ix=1m/s$ , less viscous oil



Figure C.5: Local water fraction vs distance for the middle part of the cross-section;  $U_m ix=1.5$  m/s, less viscous oil



Figure C.6: Local water fraction vs distance for the middle part of the cross-section;  $U_m ix=1m/s$ , high viscous oil



Figure C.7: Local water fraction vs distance for the top part of the cross-section;  $U_m ix=1$  m/s, less viscous oil



Figure C.8: Local water fraction vs distance for the top part of the cross-section;  $U_m ix=1.5$  m/s, less viscous oil



Figure C.9: Local water fraction vs distance for the top part of the cross-section;  $U_m ix=1$ m/s, high viscous oil

### C.3 Pressure gradient vs dispersion



Figure C.10: Pressure Gradient and dispersion for the fluid system with lower viscosity;  $U_{mix}=1.5$ m/s,  $dP_{valve}=0$ bar



Figure C.11: Pressure Gradient and dispersion for the fluid system with lower viscosity;  $U_{mix}=1.5$ m/s,  $dP_{valve}=0.2$ bar



Figure C.12: Pressure Gradient and dispersion for the fluid system with lower viscosity;  $U_{mix}=1.5$ m/s,  $dP_{valve}=0.35$ bar



Figure C.13: Pressure Gradient and dispersion for the fluid system with lower viscosity;  $U_{mix}=1.5$ m/s,  $dP_{valve}=0.5$ bar



Figure C.14: Pressure Gradient and dispersion for the fluid system with lower viscosity;  $U_{mix}=1.5$ m/s,  $dP_{valve}=1$ bar



Figure C.15: Average dispersion factor vs pressure drop across the mixing valve for  $U_{mix}=1$ m/s for the high viscous oil system

### **Appendix D**

### **Matlab Codes**

### **D.1** Dynamic model

#### D.1.1 Main code

```
1 %This is a modified dynamic model from Heiner's dynamic model;
2 % water droplets in oil
3 %% Inputs
4 Umix = 1;
                                 %mixture velocity [m/s]
5 fw = 0.2;
                                 %input water fraction [-]
6 D = 0.1091;
                                 %inner pipe diameter [m]
7 | visc_water = 0.001;
                                %water viscosity [Pa*s]
8 \text{ visc_oil} = 0.00143;
                                %oil viscosity [Pa*s]
9 \text{ rho}_water = 998.718;
                                %water density [kg/m3]
10 | rho_oil = 795.585;
                                %oil density [kg/m3]
11 | Conti = 'oil';
                                 % continuous phase can be water or
      oil
12 dt = 5;
                                %simulation time step [s]
13 n = 44;
14 Dcrit = 0.0002573;
                                %critical diameter
15
```

```
16 %Valve model data (Schummann and Fossen model)
17 \text{ DP}_valve = 34528;
                                %Pressure drop over valve [Pa]
18 Cv = 1.1;
                                 %valve constant considering
      restriction and a coefficient [-]
19 | ift = 0.04;
                                 %interfacial tension (N/m)
  fv = 0.35;
                                 %valve opening
20
21
22 %Settling model
                                 %gravitational constant [m/s2]
23 | g = 9.81;
24
  H_{-}limit = 0.5;
                                 %minimum continuous phase fraction
      in the dense packed layer
25
26 %Parameters
27 | R = D/2:
                                 %pipe radius
28 A = pi * R^2;
                                 %pipe cross-sectional area
  Afinal_o = A*(1-fw);
                                 %maximum area of oil layer
29
30 | Afinal_w = A - Afinal_o;
                                 %maximum area of water layer
31 syms alp;
32 \mid alpha = vpasolve(Afinal_o == (0.5 * R^2) * (alp-sin(alp)));
33 | hfinal_o = R*(1 - \cos(alpha/2));
   hfinal_w = D - hfinal_o;
34
35
  %experimental interface positions
36
  k=[2 47 105
                    115
                             160
                                     218];
                                                                %
37
      positions where measurements were taken along the pipe
   1 = [0.1091]
                    0.1091
                            0.1091
                                     0.1091 0.0466 0.0407];
38
                                                                 %
      positions of the oil-dispersion layer interface
  m=[0
           0.0026
                    0.0029
                            0.004
                                     0.0101
                                              0.01251;
                                                             %
39
      positions of the dispersion-water layer interface
40
41 %% MIXING MODEL
42 %Knowing the pressure drop over a ball valve, the produced
```

```
%droplet size can be modelled using A model presented by Fossen
43
      (2017)
  Dx = Valve_model_new( Conti, rho_water, rho_oil, DP_valve, D,
44
      fv, Cv, ift ,Umix);
   Ddrop = Dx;
45
46
47
  %%
      SETTLING VELOCITY MODEL
  %The model computes a constant for the settling velocity of
48
      droplets
49
  %It computes CVs which is equal to the settling velocity Vs
      divided by the
  %Square of the droplet size i.e. CVs=Vs/Ddrop<sup>2</sup> (to allow for
50
      the velocity
  %to be calculated with a new droplet size each timestep)
51
52
  CVs = Settling_velocity_mod ( Conti, visc_water, visc_oil, g,
53
      rho_water , rho_oil );
54
55
56
  %% DEVELOPMENT ALONG PIPE
57
                 %time after mixing [s]
  t = 0;
58
  x = t * Umix;
                %position downstream of mixer [m]
59
  h_{-}w = 0;
                 %water layer height
60
61 h_d = D;
                 %dispersion layer height
  h_{-}o = 0;
                 %oil layer height
62
  H_{-}d = fw;
                 %Homogeneous flow assumption after the valve
63
64
65 %Solution vectors
66 T = zeros(1, n);
                     %time
67 X = zeros(1, n);
                    %position
68 VEC_h = zeros(1, n);
                           %water layer height
69 VEC_{-}h_{-}o = zeros(1, n);
                           %oil layer height
```

```
70 VEC_h_d = zeros(1, n);
                            %dispersed layer height
71 VEC_H_d = zeros (1, n);
                            %emulsion layer holdup
72 VEC_DPDX = zeros(1,n); %Pressure gradient
73 VEC_V1 = zeros(1, n);
                            %settling velocity
74 VEC_Ddrop = zeros(1,n); %droplet diameter
75
76 % setting figures and axes titles
   figure (1)
77
78 hold on
79
   grid on
   grid minor
80
   ylabel('Interfacial position from pipe bottom [m]')
81
   xlabel('Position X downstream of the valve [m]')
82
83
84 figure(2)
   hold on
85
   ylabel('D_d_r_o_p')
86
   xlabel('Position X downstream of the valve [m]')
87
88
89
90 figure (3)
   hold on
91
   ylabel('-dP/dX [Pa/m]')
92
93
   xlabel('Position X downstream of the valve [m]')
94
95
   for i=0:n
96
97
       \%h_d \ge 0.001 %time steps
98
       i = i + 1;
99
       t = t + dt;
       x = t * Umix;
100
101
       %Downstream phase distribution
102
```

```
103
        [h_w, h_d, h_o, V1, Ddrop] =
            Phase_distribution_new_varyingVs( D, Ddrop, Dcrit, h_w,
             h_d, h_o, fw, dt, H_d, H_limit, hfinal_w, hfinal_o, CVs
           );
104
        %holdup in emulsion layer
105
106
        A_{0} = (R^{2}) * acos(1-h_{0}/R) - (R-h_{0}) * sqrt(2*R*h_{0}-h_{0}^{2});
        A_w = (R^2) * a \cos(1 - h_w/R) - (R - h_w) * s q r t (2 * R * h_w - h_w^2);
107
        H_{-d} = (A*fw - A_{-}w) / (A - A_{-}o - A_{-}w);
108
                                           %water holdup in dispersed
           layer
109
110
        %Downstream pressure gradient
111
        [DPDX] = ThreeLpressure_adp(D, Umix, h_o, h_w, h_d, H_d,
             rho_water, rho_oil, visc_water, visc_oil );
112
        %Write solution vectors
113
        T(i) = t;
114
115
        X(i) = x;
        VEC_h_w(i) = h_w;
116
        VEC_h_o(i) = h_o;
117
118
        VEC_h_d(i) = h_d;
119
        VEC_H_d(i) = H_d;
120
        VEC_DPDX(i) = DPDX;
        VEC_V1(i) = V1;
121
122
        VEC_Ddrop(i) = Ddrop;
123
    end
124
125
    figure (1)
126
    plot(X, VEC_h_w, b')
    plot(X, (VEC_h_d+VEC_h_w), 'r')
127
    plot(X, (VEC_h_o+VEC_h_d+VEC_h_w), 'k')
128
    plot(k,m, '*',k,l, '*')
129
130
```

```
131
    figure(2)
    plot(X, VEC_Ddrop)
132
133
134
    figure (3)
    plot(X,VEC_DPDX, 'r')
135
136
137
138
      %% EXPERIMENTAL PRESSURE GRADIENT
    load ('Results.mat')
139
    P = cell2mat(Results(3:end, [20:28, 11]));
140
   M = cell2mat(Results(3:end,29:37));
141
142
    [i, j] = size(P);
143
144
   Dp = [P(1:end, 1) - P(1:end, 2), P(1:end, 1) - P(1:end, 3), P(1:end, 2) - P
       (1: end, 3), P(1: end, 4) - P(1: end, 5), P(1: end, 6) - P(1: end, 7), P(1: end, 7))
       end, 8)-P(1:end, 9)];
   Dx = [M(1: end, 2) - M(1: end, 1), M(1: end, 3) - M(1: end, 1), M(1: end, 3) - M(1: end, 3)]
145
       (1: end, 2), M(1: end, 5) - M(1: end, 4), M(1: end, 7) - M(1: end, 6), M(1:
       end, 9)-M(1:end, 8)];
146
147
    %Calculates the pressure gradient in Pa
148
    dpdx = (Dp./Dx) * 1e5;
149
150
    for i=36
151
152
    plot ([M(i,1),M(i,2)],[dpdx(i,1),dpdx(i,1)], 'b',[M(i,1),M(i,3)]
       ],[dpdx(i,2),dpdx(i,2)],'b',...
153
         [M(i,2), M(i,3)], [dpdx(i,3), dpdx(i,3)], b', \dots
154
         [M(i,4), M(i,5)], [dpdx(i,4), dpdx(i,4)], b', \dots
         [M(i, 6), M(i, 7)], [dpdx(i, 5), dpdx(i, 5)], 'b', ...
155
156
         [M(i,8),M(i,9)],[dpdx(i,6),dpdx(i,6)],'b');
157
158
    end
```

#### **D.1.2** Valve model

```
function [ Dx ] = Valve_model_new( Conti, rho_water, rho_oil,
1
      DP_valve, D, fv, Cv, ift, Umix)
2 %The valve model is based on turbulence in the dissipation zone
       as the main
3 % contributor of droplet breakup. This is based on the model by
      van der
  %Zande (2000) as presented by Fossen and Schummann (2017).
4
5
6 % The model calculates the maximum size of the droplet
      downstrean a restriction (valve).
7 \% Up (accelerated velocity) = Umix/fv
  \% Dp_perm = permanent pressure drop = DP_valve,
8
9 % rho_conti = density of continuous phase ,
10 \% dx_perm = dissipation length = 2.5*D
11
12
   if strcmp(Conti, 'water')==1
13
       rho_conti=rho_water;
14
   else
15
       rho_conti = rho_oil;
16
   end
17
18
19 Dp_perm = DP_valve;
20 | Dx_perm = 2.5 * D;
   Up = Umix/fv;
21
22
  Dx = Cv * ((ift/rho_conti)^0.6) * ((Dp_perm * Up)/(rho_conti * Up))
23
      Dx_{-}perm))^{-}-0.4;
24
25
   end
```

#### D.1.3 Settling Velocity model

```
function [ CVs ] = Settling_velocity_mod( Conti, visc_water,
1
      visc_oil, g, rho_water, rho_oil)
  % This function computes CVs which is equal to the settling
2
      velocity Vs divided by the
  %Square of the droplet size i.e. CVs=Vs/Ddrop^2
3
4
5
  if strcmp(Conti, 'water')==1
                                           %checking the continuous
      phase
       visc_conti=visc_water;
                                           %assigning the viscosity
6
          of the continuous phase
7
  else
8
       visc_conti = visc_oil;
9
  end
10
  CVs = (2/9) * ((rho_water - rho_oil) / visc_conti) * g;
11
12
13
  end
```

#### **D.1.4** Phase distribution model

```
function [ h_w, h_d, h_o, V1, Ddrop ] =
1
     Phase_distribution_new_varyingVs ( D, Ddrop, Dcrit, h_w, h_d,
     h_o, fw, dt, H_d, H_limit, hfinal_w, hfinal_o, CVs);
 %The function computes the layer heights of the next time step.
2
 %The function takes a new droplet size each time step and re-
3
     calculates the settling velocity.
 %The coalescence rate is proportional to the interface area.
4
5
 %% SETTLING
6
7
      %Settling velocityy
      V1 = CVs*(Ddrop/2)^{(2)}*(1-((1-H_limit)/(1-H_d)));
8
```

```
9
      if Ddrop <= Dcrit
           V1=0;
10
      else
11
      end
12
13
        %maximum possible settling height
14
        R = D/2;
15
        A = pi * R^2;
16
        A_w = (R^2) * a \cos(1 - h_w/R) - (R - h_w) * s q r t (2 * R * h_w - h_w^2);
17
        Alimit_D = (A*(fw)-A_w)/H_limit;
18
19
         Alimit_o = A - A_w - Alimit_D;
20
21
        if H_d >= H_limit
                                      %no settling
             h_w = h_w;
22
             h_{-}d = h_{-}d;
23
             h_{-}o = h_{-}o;
24
                                      %settling
25
         else
26
             h_{o}_{new} = h_{o} + dt * V1;
             A_{o_new} = (R^2) * acos(1 - h_{o_new}/R) - (R - h_{o_new}) * sqrt(2 * R * R)
27
                 h_o_new_{-h_o_new^2};
28
              if A_o_new <= Alimit_o %check if H_d <= H_limit
29
                  h_{-}o = h_{-}o_{-}new;
30
                  h_{-}d = h_{-}d - dt * V1;
31
32
                  h_w = h_w;
              else
33
34
                  syms alp
35
                   alpha = vpasolve(Alimit_o == ((R^2)/2)*(alp-sin(alp
                      )));
                  h_{-o} = R*(1 - \cos(alpha/2));
36
                  h_w = h_w;
37
                  h_{-}d = D - h_{-}w - h_{-}o;
38
39
             end
```

```
40
       end
41
42
   %% COALESCENCE
43
44
       C0 = 1e - 20;
                                 %initial coalescence rate
45
        Cinter = 1.5e7;
                                 %coalescence constant at interface
46
        Cdisp = 0.0012;
                                 %coalescence constant inside
47
           dispersion
48
49
       I_wd = 2 * sqrt(2 * R * h_w - h_w^2); %water-emulsion interface (
           width)
50
        if h_d <= 0.001
51
            h_{-}o = hfinal_{-}o;
52
            h_w = hfinal_w;
53
            h_{-}d = 0;
54
        else
55
56
            if I_wd \ll 0
57
                A_wd = A*C0;
                                      %initial coalescence area (mass)
58
                     flux
            else
59
                 Ddrop = Ddrop*(1+dt*Cdisp*H_d); %Droplet growth
60
                A_wd = I_wd * Cinter * Ddrop^3;
                                                   %coalescence mass
61
                    flux proportional to the interface area
            end
62
63
            A_{-}w = A_{-}w + A_{-}wd;
64
65
            if A_w >= fw * pi * R^2
                                          %check if maximum water
66
               height is reached
                A_{-}w = fw * pi * R^2;
67
```

```
68
             else
             end
69
70
             syms alp
71
             alpha = vpasolve(A_w == ((R^2)/2)*(alp-sin(alp)));
72
             h_w = R*(1 - \cos(alpha/2));
73
             h_{-}d = D - h_{-}o - h_{-}w;
74
75
        end
76
77
        h_w = round(h_w * 1e + 20)/1e + 20;
        h_{-}o = round(h_{-}o*1e+20)/1e+20;
78
        h_d = round(h_d * 1e + 20)/1e + 20;
79
80
81
   end
```

#### **D.1.5** Pressure Gradient model

```
function [ DPDX ] = ThreeLpressure_adp( D, Umix, h_0, h_w, h_d,
1
       H_d, rho_water, rho_oil, visc_water, visc_oil)
2 %This function computes the pressure gradient based on a three
      layer
  %stratified model assuming no slip. The third layer is the
3
      emulsion layer.
4
  %Wetted perimeter of each layer
5
  R = D/2;
6
7
  alpha_w = 2 * a \cos(1 - h_w/R);
8
9
  b_w = R*alpha_w;
10
  alpha_{-}o = 2 * a \cos(1 - h_{-}o/R);
11
12 | b_-o = R * alpha_-o;
```

```
13
14
   b_{-d} = pi * D - (b_{-w} + b_{-o});
15
16
17 % Partial pressure gradients
   eps=0.00001; %surface roughness [m]
18
19
20
   Re_w = rho_water *D*Umix/visc_water;
   THETAwater1_D=(-2.457 * \log (((7/\text{Re}_w)^0.9) + (0.27 * \exp /D)))^16;
21
22 | THETAwater2_D = (37530/\text{Re}_w)^{16};
   23
      ^1.5)))^(1/12)); %Darcy friction factor
24
   DPDX_water = (b_w/(pi*D)) * (Fwater_D*rho_water*((Umix)^2))/(2*D);
      %partial pressure gradient for the oil perimeter
25 DPDX_water=round (DPDX_water *1e+10)/1e+10;
26
   Re_o = rho_oil *D*Umix / visc_oil;
27
   THETAoil1_D=(-2.457 * \log (((7/\text{Re}_0)^0.9) + (0.27 * \exp /D)))^16;
28
   THETAoil2_D = (37530/\text{Re}_0)^{16};
29
   Foil_D = 8 * ((((8/Re_0)^12) + (1/((THETAoil1_D+THETAoil2_D)^1.5)))
30
      ^(1/12)); %Darcy friction factor
   DPDX_oil = (b_o / (pi *D)) * (Foil_D * rho_oil * ((Umix)^2)) / (2*D); \%
31
       partial pressure gradient for the oil perimeter
   DPDX_oil=round(DPDX_oil*1e+10)/1e+10;
32
33
34
   rho_disp = rho_water * H_d + rho_oil * (1 - H_d);
35
   visc_d = visc_oil * (1 + (0.8415 * (H_d) / 0.775) / (1 - 0.8415 * (H_d)))
      (0.775))^{2.5};
36 |\% visc_d = visc_oil * (1 + (1.558 * H_d) / (1.66 - 1.558 * H_d))^2.5;
37 | \text{Re}_d = \text{rho}_d \text{isp} * D * U \text{mix} / \text{visc}_d;
38 |THETAdisp1_D=(-2.457 * \log (((7/\text{Re}_d)^0.9) + (0.27 * \exp /D)))^16;
39 THETAdisp2_D=(37530/\text{Re}_d)^{16};
```

```
Fdisp_D = 8 * ((((8/Re_d)^{12}) + (1/((THETAdisp1_D+THETAdisp2_D)^{1.5}))))
40
      )^(1/12)); %Darcy friction factor
   DPDX_disp = (b_d / (pi * D)) * (Fdisp_D * rho_disp * ((Umix)^2)) / (2 * D); \%
41
      partial pressure gradient for the oil perimeter
   DPDX_disp=round(DPDX_disp*1e+10)/1e+10;
42
43
   %Total pressure gradient
44
   DPDX = DPDX_water+DPDX_oil+DPDX_disp;
45
   DPDX = round (DPDX *1e+5)/1e+5;
46
47
48
   end
```

#### **D.1.6** Sample results of the model



Figure D.1:  $DP_{valve} = 0.35bar$ ,  $U_{mix} = 1m/s$ , WC = 0.2



Figure D.2:  $DP_{valve} = 0.5bar$ ,  $U_{mix} = 1m/s$ , WC = 0.2