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Cold Flow Concepts Compared

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Summary

The aim of the project was to compare two cold flow concepts, SINTEF and NTNU, by general and simple heat and mass balance calculations. These concepts have different cooling process, so the main task has been to calculate the cooling processes. To find out where the cold flow can be appropriate, typical Norwegian deepwater production condition have been surveyed. It was found out that most of the Norwegian oilfields have GOR varying from 125 – 250, with corresponding WC from 50 – 85 %. The reservoir temperature, T_R , is varying from 70 – 150 °C with corresponding reservoir pressure, P_R , 150 – 600 bar. However if the GOR would be larger then 1000, the cold flow technology would not be appropriate. At so large GOR the transportation of the well fluid would be a problem, since the gas production is so large. The WC would not be a problem for the cold flow concepts, since most of water would be separated. As a result the water content that would appear in the cold flow process would not be larger then 20 %

Since the water content would be so small, the hydrate would be formed in controlled condition. The amount of hydrate would never be more than 50 %. This would indicate that the cold flow technology would have an advantage compared to other used technology to prevent hydrate problem. The low percent of hydrate would make it possible to transport these small hydrate particles for long distance with the well stream without any problem. The cold flow concepts would on the other hand be mounted to existing fields or new developed fields, indicating the flexibility of the technology.

However the calculation on the cooling process shows that several parameters plays an important role in the cold flow technology, like OHTC, GOR and WC. The OHTC is a key parameter in designing the pipeline arrangement in SINTEF concept and in heat exchanger arrangement for the NTNU concept. The value that

have been used in the SINTEF concept is 100, but the industry are using values of 10-20 for the pipe exposed to seawater at seabed. As a result it was found out that the pipe arrangement at 4 – 6 km would be enough for OHTC=100 and for OHTC=15 the pipe arrangement have to be more than 10 km. The NTNU concept is using OHTC=250 for the design of the heat exchanger arrangement, but it was found out that this value could be much higher. The diameter of the tube in the heat exchanger arrangement would in this case be so small, that the OHTC value could be up to 1000.

It was drawn a hydrate curve to find out if the temperature would be low and pressure high enough to formate hydrate in the concepts. It was found out that both concept would achieve the low temperature for hydrate formation below 10 °C) and the pressure would not be a problem since the pressure is high enough (150 bar and 375 bar).

The result in the this project shows that cold flow technology have some uncertain parametres like OHTC that requires more researh and the technology is still on the development stage. However, the technology have potensial to challenge the existing methods used to prevent the hydrate formation.

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1 Introduction

The trend of oil and gas industry is currently moving into deeper production and colder water. At these conditions the depth could be up to , 1 – 3 km, and the temperature could be near to freezing, 2 – 4 °C. The flow assurance would be a technical challenge since the well fluid in the flowline, without protection, can form hydrates and wax solids. This would mostly occur at shutdown and restart situations and can afterward result in plugged flow.

The industry are using a lot of methods to prevent hydrate formation, like injection of chemicals, methanol or glycol to the flowline. Another method that is used is heating of the pipeline to keep the temperature in the flowline as high as possible. This method would prevent hydrate formation and wax deposition on the pipe wall. Another frequently used method is depressurization. By reducing the pressure, hydrate formation and wax solids can be prevented. The drawback for all these methods is that they are expensive, difficult and can often result in lost production.

Cold flow is an alternative technology on hydrate prevention in pipelines at deep-water production. This technology aims to eliminate the need for injection of chemicals and heating under normal operating conditions at seabed. However, there are two different concepts based on cold flow technology and they have different ways of cooling. Since the cold flow is an alternative method to hydrate prevention, the best method of cooling should be found out. As a result the NTNU and SINTEF concept will be compared in general and simple heat and mass balance calculations will be carried out. The main task will be the cooling process and try to find out which of these concepts have the easiest and best cooling. Also deepwater production conditions at offshore will be considered. This will indicate at which range of GOR-WC for Norwegian oilfields, the cold flow will be appropriate.

2 Deepwater Production

Deepwater production has been started at offshore Mid-Norway, West of Shetlands, Gulf of Mexico, offshore Brazil and West Africa, and is likely to expand considerably the coming decades. The production occurs with seafloor depths of 1-3 km and temperatures of -2 to 4 °C, so this will run into many technical challenges. At these conditions flow assurance could be a major technical challenge considering oil and gas production. [1]

Figure 1 is showing the pressure of hydrocarbon fluid at various points along the pipeline, which lies at seabed. One may observe as a unit mass of hydrocarbon traverses the pipeline, the pressure drops uniformly due to friction losses. These friction losses is associated with fluid flow, like water, oil and condensate, that occurs with the gas in the pipeline. However, the temperature change is more interesting. [2]

During the transport from the wellhead to surface the temperature and pressure will occur inside the hydrate curve. The hot fluids, with temperature at 40-80 °C, exiting at wellbore would need to be transported to processing facilities located on the seabed, topside or beach. However, the seawater at the seabed would provide an infinite cooling medium for the hot hydrocarbon fluid from the reservoir. If the travel distance for the hot hydrocarbon fluid is short, then the hydrocarbon fluid would maintain some residual heat, high pressure and high temperature, from the hot reservoir hydrocarbon fluid at the pipeline entrance. If the temperature of the fluids can be maintained, flow can be assured to the processing facilities. [1],[2]

However, these conditions will cause the cooled hydrocarbon fluids in the pipeline, if unprotected, to form hydrates (to the left of the L_w -H-V line), particularly during shutdown and restart situations. These solids can build up and result in

plugged flowline, which will require very expensive methods to remove hydrates. These methods are often difficult and lengthy and can lead to lost production. [3]

To overcome these flow assurance obstacles, several methods are been used by the oil industry. Figure 2 is showing the methods like burial/covering, induction heating, injection of inhibitors, direct heating, bundling and insulation. These methods are only used to prevent the hydrate growth in the pipeline at seabed, but there are also thermodynamics way to prevent hydrate formation by

- Remove the water to lower the dewpoint
- Keep the system temperature above the hydrate formation point
- Keep the system pressure below the hydrate formation point, and
- use inhibitors to shift the hydrate equilibrium curve, so the system is in the fluid region

The hydrate equilibrium curve is indicating the thermodynamic point of hydrate formation, or the highest possible temperature at which hydrates exist for a given pressure. The techniques of hydrate prevention and dissociation are determined from the phase diagrams. [2]

The removal of water can be done by separation or by use of molecular sieve. The molecular sieve are crystalline solids which provide the lowest dewpoint commonly obtainable and they are typically used in low temperature process plant. Water condensation from the gas phase is prevented by drying the gas, either with TEG to obtain less water content or with molecular sieves to obtain lower water content. [4]

However, there are two common misconceptions exist concerning the presence of water in forming hydrate in pipeline. The first misconception is that free water

phase is absolutely necessary for the formation of hydrate and the second one that ice is in solid phase in equilibrium with temperature below the hydrate. The water content in the hydrocarbon phase would be so low, that a lot of time is required for the water molecules to accumulate into significant hydrate mass. [4]

To maintain high temperatures during the transport from the reservoir to surface, there are been used several methods like use of thermal insulation, bundling and isolation. These methods are able to keep the system in the hydrate free region.

The thermal insulation and heating of subsea pipelines can be achieved by, for example coating the pipeline, or pipe-in-pipe, or electrical or circulated heating of fluid along the entire pipeline length. [3] However, these methods are considered expensive and will unlikely be used for medium-to-long distances, 5 to 50 km. Insulation and heating are considered more suitable for distances of a few kilometres. Figure 3 is showing the operating area for insulation and heating compared to hydrate curve. If the hot wellbore fluids enter a bare flowline without insulation and heating on the seafloor, then the fluid will cool gradually from the 40-80 °C to the ambient sea temperature of -2 to 4 °C. [1]

An other way to prevent the hydrate formation is by pressure reduction. There are three consiting cases of pressure reduction used in the industry as shown in Figure 4:

- Isothermally, as with infinetly slow pressure reduction. At this case the depressurization represent a upper limit to the expansion. When the pressure is reduced, sensible heat is supplied from the surroundings to both the hydrate interface and vapor phase. The dissociation of the hydrate start since the temperature is constant.
- Isenthalpically, as with rapid pressure reduction without heat transfer. This

method is also known as Joule-Thomson expansion. The pressure reduction would make the gas expand further into the hydrate region. The rapid isenthalpic expansion alone would promote the hydrate formation by cooling the gas.

- Isentropically, as with pressure reduction through an ideal turboexpander without heat transfer.

A common misconception about the hydrate depressurization is that depressurization alone can cause hydrate dissociation. The dissociated hydrate would have more energy in the vapour and liquid than they do in the hydrate, energy required to promote the dissociation must be derived from the surroundings like seawater at seabed or from the hydrate itself. The purpose of the depressurization is to decrease the pressure at the hydrate interface, so that the hydrate equilibrium temperature is below the surroundings causes the heat and hydrate dissociation. [2]

When hydrate growth do occur in pipeline then depressurization is used frequently. Both one side depressurization and two sided depressurization are used. However, one should depressurize a hydrate plug simultaneously from both ends. If only one end of the plug is depressurized, the pressure gradient across the dislodge plug may cause a pipeline hydrate projectile enough momentum to cause damage and safety problems at bends and elbows. It is very important to prevent large pressure difference across the hydrate plug, if possible . [2]

The most used method in oil industry is injection of chemicals like methanol or MEG, DEG and TEG. In Figure 5 one may observe how the inhibitors act compared to the hydrate curve. For chemicals and inhibitors a delivery system at wellhead would be available. The chemicals can be delivered through a small diameter pipeline. This pipeline should have chemicals flow in opposite direction

to the production stream. For chemicals like methanol or glycol can be delivered through fixed tanks, on the seabed or at the ocean surface. The glycols provide more hydrogen bonding opportunity with water through one more hydroxyl group than alcohols, as well as through oxygen atoms in the case of the larger glycols. The glycols generally have higher molecular weights with lower volatility, so they may be recovered and recycled more from the processing equipment. [1], [2]

Two new means of hydrate inhibition are being added to the thermodynamic inhibitor group and are being brought in common practice, the kinetic inhibitors and anti-agglomerants. The required concentration of these inhibitors is very low between 0.5-2 % wt. However, Norway have banned the use of these inhibitors due to high pollution of the environment. [4], [5]

The kinetic inhibitors are low-molecular-weight polymers and small molecules dissolved in a carrier solvent and injected into the water phase in pipelines. These inhibitors bond to the hydrate surface and prevent significant crystal growth for a period longer than the free-water residence time in pipeline. [4]

The anti-agglomerants are dispersants that cause the water phase to suspend as small droplets in the oil or condensate. When the suspended water droplets convert to hydrates, pipeline flows are maintained without blockage. Because this prevention method relies on emulsified water-hydrate, a condensate hydrocarbon is required. [4]

3 Hydrate growth in pipelines

In open literature there is little details about how hydrate growth occurs in real system. The process of hydrate growth can be describe in many different ways, and the following way to describe it comes from SINTEF. [6]

The hydrate start to nucleate close to the hydrocarbon phase on a water droplet in gas, oil, or condensate phases. Growth of hydrate would appear along the surface of the droplet until it is completely covered with a thin hydrate layer. Water in the hydrocarbon phase would then penetrate from the interior of the water droplet to the hydrophilic hydrate surface next to the hydrocarbon phase through microperforations or small cracks in the hydrate film, as illustrated in Figure 6. This would decrease the formation rate as the hydrate layer increases in thickness, depending on the hydrate formation driving force and shear forces on the droplets. After a relatively short time no further conversion of water to hydrate would be observed.

If a water droplet covered by a hydrate film hits e.g. a pipe or reactor wall in a turbulent system, the impact may create larger cracks in the film. The subcooled water inside the droplet will drain through these cracks and spread on the dry hydrophilic hydrate film. Hydrate-forming species close to the pipe wall may convert this water to hydrate quickly, and this can often result in deposition of the hydrate/water droplet on the wall.

In turbulent liquid systems the water phase would often distributed in the hydrocarbon phase as rough, unstable water-in-oil emulsions. As surface tension of the droplets increases due to the hydrate layer, the water droplets agglomerate to larger droplets or water lumps in order to minimize surface area, as shown in Figure 7. In turbulent liquids these water lumps will change form, surface area, and

volume continuously. The thin hydrate layer on the water lump will thereby often be broken, giving new water-hydrocarbon interfaces where more hydrates quickly form. The turbulent forces will also create small hydrate-covered water droplets as illustrated in Figure 8. Due to the hydrophilic properties of the hydrate surface, these droplets will be absorbed in the water lumps giving a slush-like appearance.

Further growth and particle accumulation will make the outer area of the lumps stiffer. When these lumps collide with each other or with e.g. a pipe wall, free water from the lump interior will spread to the outer hydrate surface, acting as "glue" for agglomeration of the lumps to bigger lumps or plugs or to the pipe wall, by converting to hydrates. The hydrate layer covering lumps or plugs increases in thickness until internal pressure gradients due to capillary forces and volume changes breaks it down to smaller hydrate bits as illustrated in Figure 9 and Figure 10. This process continues until the lumps have been broken down to a powder-like appearance, assuming that flowing conditions can be maintained throughout the process. In a realistic industry case, the pipeline will more often than not be plugged before this stage is reached. Figure 11 is showing how hydrate particle and water would react in a system. This would make the hydrate particle very stabil.

However, there is a lot information about that natural gas hydrate contains water and natural gas and appears at high pressure and low temperature. The gas hydrate are dependent on several parametres like the rate of hydrate formation and the depostion, the blocking properties, transport conditions as momentum transfer, heat transfer and mass transfer. If the production stream does not contain any water or associated gas¹ then the natural gas hydrate would not be formed. [1]

¹gas that occurs at a pressure that is above the bubble point pressure of the crude oil

4 Norwegian Oilfield Condition

The production from a field consist always gas, oil and water. Some of the Norwegian fields have water production with oil and gas. As shown in Table 1 some of the fields are in the early lifestage and some are in the latest. Hydrocarbon production without water production may occur in the early life of a well. With time, however, water breakthrough happens and the water content increases thereafter. The timing of water breakthrough and the rate of increase in water content, vary greatly from fields to fields. [1]

Table 1 are showing some of the Norwegian fields that have water production with oil and gas. The production is from a time 2000 to September 2005. By use of these equation we can find the GOR and WC for all the Norwegian oilfields with some gas production [7]

$$GOR = \frac{q_g}{q_o} \quad (4.1)$$

$$WC = \frac{q_w}{q_o + q_w} \quad (4.2)$$

Table 1 is showing that many fields are in their late lifestayle as WC range from 50-85 % and new fields have WC from range of 10-45 %. In the early life of wells the WC may be a few percent, and in the late life the WC may be above 90 percent. The Norwegian field, Troll, is very special because it consist of Troll A that produces gas and Troll B and C that produce oil [8], so the production value shown in Table 1 do not contain the entire production, but separate production from Troll A, B and C. [9],

The GOR ratio vary also from field to field and can be from 50-2800. Be comparing

the GOR initial [10] for the fields one may observe if the fields have increased or decreased GOR in the period from 2000-September 2005.

To find out typical deepwater condition for Norwegian oilfields a graph of WC vs GOR has been made, where the used value for some Norwegian oilfields are shown in Table 1. The oilfields have been selected due to water production. The gas condensate fields have not been studied, because of there was no water production present. The graph of WC vs GOR is illustrated in Figure 12. The graph shows that one have three section, section 1 contains fields that have WC between 60-90 % with GOR from 50-500. Most of these fields in this section are in their late life stage, as can be shown from the high WC. At section 2 the fields have WC between 10-40 % with same GOR as previous section. The last section, section 3, have very low WC, from 10-30 %, with GOR from 1000-1500. For further case of study, WC from each section have been selected with corresponding GOR, as shown in Table 2.

However, the volume used of bulk chemicals to lower the hydrate formation temperature is proportional to the WC. The volume would in the case of large WC be very large. Required volume of specialty chemicals is more complicated and do not need to be proportional, although it increases if the WC increases. The use of specialty chemicals depends also on the distance from wellhead to processing facilities or the time it takes to flow the distance. [1]

Table 1 is illustrating that many oilfields have different reservoir temperature and pressure. To find out typical Norwegian reservoir conditions, a graph have been made as shown in Figure 13. As shown from Table 1 the reservoir temperature vary from 72 °C to 143 °C and the pressure vary from 177 bar to 595 bar. The graph shows that one may observe two cases, case A and case B. For case A the pressure range is from 300 bar to 600 bar and the temperature range from 70 °C to

150 °C. For case B the pressure range from 150 bar to 350 bar with corresponding temperature from 70 °C to 130 °C.

By use of the graph it is possible to find out typical Norwegian deepwater condition. The reservoir temperature and pressure will be used to find out subsea condition for the further case of study. It is assumed that the subsea condition for pressure and temperature is 3/4 of the reservoir temperature and pressure, as illustrated in Table 3. [11]

5 Cold Flow

Cold flow is an alternative technology on hydrate prevention in pipelines at deep-water production. This technology aims to eliminate the need for injection of chemicals and heating under normal operating conditions at seabed. Cold flow is based on slurry transport of hydrate particles and possibly other solids, like wax. However, it will only occur when we have reached steady-state operating conditions. The main goal for this technology is to have a technology solution which allows subsea field development based on long multiphase wellstream transport. The only problem that one may have is at the start-up and shut-in of cold flow technology operations. These operations can be managed by use of chemicals, or pipe insulation and heating. Whatever system will be selected for start-up and shut-in operation, it will add cost and complication to deepwater production facilities. [1],[6]

Both NTNU and SINTEF have done some research work based on cold flow technology. The works are based on separating gas or water as soon as possible from the production stream.

5.1 SINTEF Cold Flow Technology, "Seeding and Growing"

SINTEF's concept is based on making hydrate in a fast and controlled conditions with all the water from the production stream near the well. This should be done as soon as the production stream comes from the well. However, the water content would be not more than 20 % because the free water is not wanted. A free-knockout of water², would be used to reduce the water content from the production stream.

²A vertical or horizontal separator used mainly to remove any free water that can cause problems

This is very important due to avoid having problem with hydrates later. The reduced water would be transported as a stable hydrate slurry and the hydrates should not contain any free water. This will make it possible to avoid any problems caused by deposits on the pipe wall or agglomeration at stop or start of the flow. When the free water from the production stream is converted fast to hydrate, without chemical additives, then one may have used the fact that hydrate surfaces exhibit a high degree of hydrophilic behaviour. [6]

Later the production stream, containing free water droplets, will be mixed with a cooled well stream, containing a large number of existing dry hydrate particles, oil and water. This recycled cooled well stream could be between 50-90 % of the main well stream. During this mixture the water will quickly coat the hydrate particles with a thin water film. If the temperature conditions are right, the water will be converted to hydrates by growing from the existing hydrate surfaces and outwards. This would ensure that no free water encapsulated within the hydrate particles, and therefore no agglomeration or deposition can take place later. [6],[12]

The production stream from a subsea well is lead into the hydrate reaction part, as showned in Figure 14, where most of the free water is knockout as mentioned above. The water have to be driven quickly to total completion such that no more solids will be able to deposit later in the process. This will help preventing further hydrate formation and eliminate the avaiability of free water outside the reaction zone. The hydrate will be seen as powder particles flowing along with the production stream. [6]

When the production stream is lead into the hydrate reaction part of the system, then the dry hydrate particles are mixed in the productuion stream, as can be showned in Figure 15. These particles are transported with cold hydrocarbons from a downstream splitter. Further the water in the production stream will

be converted to hydrate particles well before it reaches the splitter. This would be done by the fact that the bare pipe is exposed to surroundings ambient sea temperature. [6]

However, particles that escape without being recirculated will convert to dry, solid hydrate. The cooling of the bar pipe that occurs due to ambient sea temperature, will bring the system to ambient sea temperature. This will prevent further condensation of water from either liquid or gas hydrocarbone phases through the rest of the pipeline. The main aim for the splitting the production stream is to have some fully converted particles, most preferably the largest, proceed downstream, in equal amount to the content of water in the production stream that enters the system. [6]

At the end of the system, when the temperature arises and the pressure drops, the hydrate particles would not melt to free water. However, these particles can be separated by mechanically separated with a sieve or by gravity in a separator. The gravity would be dependent of the density of the particles. [6]

The cold flow concept by SINTEF can be used to produce cold slurry from a well, or from a chain of wells or from an entire field. If more than one well is included, then the loop may be enlarged so that only one splitter or recirculation loop is needed, as illustrated in Figure 16. However, the percent of recycling fluid would depend on how many wells are producing. The more wells incorporated, the less cold hydrocarbon fluid is needed in the recycling flow. Also the concept is flexiable, since it can be mounted on existing infrastructure by adding an extra pipeline. The concept is primarily developed for operating at a new field. [6]

5.2 NTNU Cold Flow Technology

NTNU have done some research work and found out that liquid with particles does not engage enough pressure drop compared to liquid in turbulence mixing. One may expect that the pressure drop should be large due to hydrate, but the research work show that this is not the case in turbulence mixing. This will make it possible to use the capacity for compressors and pumps without enlarging it. [1]

Figure 17 is showing the field implementation of the NTNU system. The system consist of several main units, WHU, SU, HXU and RU. The concept is dependent on parametres like WC, GOR and other fluid properties to find out how many set of SU, HXU and RU are required. [1]

However, NTNU have found that the fluids need to be cooled before it reaches the pipeline. This cooling can done by a heat exchanger arrangment, consiting of a tube heat exchanger unit and a refrigeration unit. Sea water would not be used as heat sink in this case due to limiting approach temperature. Since natural cooling requires large heat trasnfer sufarcnes, active cooling in small equipment would be preferred. [1], [13]

In this concept the in-situ gas rate is converted to hydrate. The hydrate formation is also dependent on how much water is available. If there is enough water to convert all in-situ associated gas into hydrate. A new paramter, WHR, would in this case be used to illustrate if all the water would be converted to hydrate, or if all the associted gas would be converted to hydrate. If the $WHR < 1$ then there is not enough water present to convert all of the assosciated gas into hydrate. [13]

The production stream will be lead into the wellhead unit from a subsea well. The gas and liquid mixture will be separated in a SU, where the liquid phase will go to a HXU. At the RU the gas and cooled liquid phase would by mixed and hydrate

formation would appear. [1]

At the subsea separator the associated gas is separated at high temperature from the liquid phase and this is done very sufficiently at high temperature. The separator would be based on a two-phase separator instead of three-phase separator and this will simplify the separation of liquid-phase, consisting of water and oil, from the associated gas. The water content would be much higher in a two-phase separator in compared to three-phase separator, so the amount of hydrate formed would be higher. However, the water content would be not more than 15 % in liquid phase after the separation. [13], [11]

The heat exchanger arrangement would consist of a tube heat exchanger unit and a refrigeration unit as mentioned above. The liquid phase would be cooled with seawater, but it will not cool down to the ambient sea temperature. The tube heat exchanger can only cool the liquid to lowest 10 °C. However, with a refrigeration unit one may obtain the ambient sea temperature and should be done with help of a compressor. The cooling of gas is not necessary, since it would require less effort. [13]

At the reactor the cooled liquid with ambient sea temperature is mixed with associated gas. The temperature and the pressure in the reactor should be within the hydrate forming region, high pressure with low temperature. Hydrate formation would occur in turbulence mixing between the cooled liquid and the associated gas in controlled conditions. Using the fact that the pressure drop in turbulence mixing would not be so large as expected due to hydrate formation. The outlet would be hydrate particles with the production fluid. [13]

5.3 The difference and similar between the concepts

- The concepts are based almost on the same principle to avoid hydrate problem in pipelines, but they have different way of approaching the problem. The SINTEF concept use bare steel pipe exposed to the ambient sea temperature and the NTNU concept use a heat exchanger arrangement to cool down the liquid phase, before it would be lead into a reactor.
- For both concept the water content in the production stream have to be reduced. A free water knockout and a three-phase separator would be used to reduce the water content to 15 – 20 % before the production stream enters the process.
- SINTEF are adding dry, hydrate particles to production stream. These particles would "eat" up the water droplet. This would make the particle stabil, so they do not react with the rest of the fluid.
- NTNU concept creates the hydrate from the starting point, by letting the associated gas react with the water content and form small hydrates particles, that will flow further with the liquid phase. The excess of gas will also flow further with the liquid phase.
- Both concepts can handle other coldflow issues, like wax problem
- Larger infrastructure and flexiability. With SINTEF concept a pipe loop and a downhole splitter can be mounted on a existing field and for NTNU a set of SU, HXU and RU can be mounted close to the wellhead. How many set of SU, HXU and RU are required, depend on GOR, WC and other fluid properties.
- Both concepts have primary oilfields with some gas as target. However, gas

and condensate field would also be of interest. Also both concept have as main goal to eliminate the use of chemical injection. This would help the concepts to be more enviromentally friendly.

6 Calculations

When fluids flow from the reservoir to the surface, pressure and temperature decrease. This affects the gas-liquid equilibrium and the properties of the gas and liquid phases. Although the assumption has been made that the subsea temperature and pressure is $3/4$ of the reservoir temperature and pressure, the a black-oil model would be able to estimate these differences, from a minimum of input data. [14]

One may assume at subsea that the gas may dissolve in the liquid hydrocarbon phase, but no oil will dissolve in the gaseous phase. This implies that the composition of the gaseous phase is assumed the same at all pressure and temperatures. [14]

The black-oil model assumption is reasonable for mixtures of heavy and light components, like many reservoir oils are in North Sea. The assumption gets worse for mixtures containing much of intermediate components (propane, butane), and is directly misleading for mixtures of light and intermediate components typically found in condensate reservoirs. However, in this case one may assume that the oil contains heavy and light components. [14]

As long as liquid and gas are in contact and in thermodynamic equilibrium, the liquid will be gas saturated at the actual pressure and temperature. The saturation pressure for a gas-oil system is the pressure at which the gas solubility equals the producing gas-oil ratio. [14] In this case the producing gas-oil ratio has been found at standard condition, by use of the production data [9] from the North Sea.

At standard condition the production rate for gas, water and oil have been calculated, show in Table 4. One may observe that the mass flow rates and densities of gas, water and oil were first calculated. By use of these equations, the mass flow

rate of gas, water and oil were found at standard condition. [7]

$$q = \frac{m}{\rho} \quad (6.1)$$

$$m_{\text{total}} = m_o + m_g + m_w \quad (6.2)$$

$$GOR = \frac{q_g}{q_o} \quad (6.3)$$

$$WC = \frac{q_w}{q_o + q_w} \quad (6.4)$$

These equation would further be use and combine to find out mass flow rates of gas, water and oil. In this case one may have equal amount of unknown parametres and equations. The expressions of mass flow rates of gas, oil and water shows that mass flow rate is a function of GOR, WC and densities of the component. The mass flow rates would in this case be only dependent on GOR and WC

$$m_g = GOR m_o \frac{\rho_g}{\rho_o} \quad (6.5)$$

$$m_w = \frac{WC m_o \rho_w}{(1 - WC) \rho_o} \quad (6.6)$$

$$m_o = \frac{m_t}{1 + \frac{WC}{1-WC} \frac{\rho_w}{\rho_o} + GOR \frac{\rho_g}{\rho_o}} \quad (6.7)$$

The density of oil, ρ_o , vary from field to field. However, there was assumed to

use an average oil density to simplify the calculation. The average oil density was found by taking the highest oil density and adding the lowest oil density, before taking the average of the sum. [10] This would be an acceptable assumption for oilfields in the North Sea.

The gas composition was assumed to be 92 % methane, 5 % ethane and 3 % ethane [11], after making this assumption the specific gravity of gas, γ_g , could be found by the following equation [7]

$$\gamma_g = \frac{M_g}{M_{\text{air}}} \quad (6.8)$$

where $M_{\text{air}}=28.97$ kg/kJ and M_g is the molecular weight of the gas. The molecular weight for gas composition made it possible to find out the density of gas, ρ_g , by the following equation [14]

$$\rho_g = \gamma_g \rho_{\text{air}} \quad (6.9)$$

where the density of air is at standard condition ($T_{\text{sc}} = 15$ °C, $P_{\text{sc}}=1$ atm).

The water density, ρ_w , is assumed to be 1015 kg/m³. This is been assumed by the fact that fresh water have density 1000 kg/m³ and seawater have density 1030 kg/m³. The produce water from the reservoir would in most case have a density in range of 1000 – 1030 kg/m³ at surface, so the assumption should be acceptable. [7].

Table 4 is showing the calculation of production rate for oil, gas and water at standard condition. The standard condition for the calculation is shown in Table 5. One may observe that the last case is not possible, due to very high production of gas compared to oil and water. In this case the total massrate at 30 kg/s would

be impossible to hold, due to high gas production. This would make it very difficult to transport the liquid phase, oil and water, without any kind of pump. The pressure drop would in this case be very high, so it would be not suitable for further study. As a result new value was selected, as shown in Table 6. These values was selected by use of the Figure 1 and the fact that more WC was needed for further study.

After finding the production rate at surface, the same GOR and WC were assumed to appear at subsea condition. To find out the production rate for gas, oil and water at subsea condition Glasø's correlation have been used. The Glasø's correlation may give better results for North Sea oil than Standings uncalibrated correlation. However, it appears to be less thermodynamically consistent, and is based on a smaller data base. [14]

At subsea condition, shown in Table 7, the gas dissolves in the oil and the mass of the liquid phase increases. This makes the pressure-volume behaviour of liquid below the saturation pressure fundamentally different than from above the saturation pressure. In the calculation the pressures at seabed conditions are assumed to be below the saturation pressure, so both the liquid and gaseous phases would be present at seabed. One may observe effects like expansion of the liquid volume by the dissolved gas. This should be roughly proportional to amount of gas dissolved and increase by increasing molecular size (molar volume) of the gas. As a result of the volume expansion the temperature increase and this will effect the gas solubility, as it reduces. The overall effect of pressure increase at constant temperature, will be increased liquid volume. Temperature increase at constant pressure will result in reduced liquid volume, caused by vaporization. [14]

The formation volume factor for oil and gas at subsea condition should be found, since both the oil and gas are dependent on the pressure and temperature. The

formation volume factor for water should be the same at standard condition and subsea condition.

Before one may find the formation volume factor for oil, B_o , the specific gravity of oil, γ_o , should be found by the following equation [7]

$$\gamma_o = \frac{\rho_o}{\rho_w} \quad (6.10)$$

where $\rho_w = 1000 \text{ kg/m}^3$ is for fresh seawater.

The Glasø's correlation have been used to find the formation volume factor for oil, B_o , at subsea [14]

$$B^* = 5.615 \frac{\gamma_g^{0.526}}{\gamma_o} R_s + 1.74T - 445 \quad (6.11)$$

$$B_o = 1 + 10^{(-6.58 + 2.91(\log B^*) - 0.276(\log B^*)^2)} \quad (6.12)$$

The formation volume factor for the gas, B_g , is by definition the ratio of volume at given temperature and pressure, to volume at standard surface temperature and pressure. By the general gas equation, this is expressed as [14]

$$B_g = \frac{p^o T}{p T^o} \frac{z}{z^o} \quad (6.13)$$

At surface conditions natural hydrocarbon gas behaves close to ideal. Thus, $z = 1$ at surface pressure. At subsea condition pressure, the z-factor (supercompressibility factor) is usually in the order of 0.7 – 0.9. In this case supercompressibility factor, z-factor, is assumed to be 0.8 at subsea condition.[14]

The density of oil, ρ_o , and the density for gas, ρ_g , are both dependent on the pressure and temperature and can be found by following equations [14]

$$\rho_o = \frac{\rho_o^o + \rho_g R_s}{B_o} \quad (6.14)$$

$$\rho_g = \frac{PM_g}{zRT} \quad (6.15)$$

Table 8 is showing the calculated parameters that are important to find the production rate at subsea condition. One may observe that the massrate for gas at seabed condition is much higher then at surface condition. This have to do with the higher pressure and temperature at seabed and that the gas have not been dissolved in the oil. This will also explain why the density of oil is much smaller at subsea then at standard condition. This will affect the production rate of gas compared to oil and water, since it is very large.

With increasing WC and decreasing GOR, the water production rate increases and the production rate of gas decreases. This is due to increasing liquid phase because of the waterbreakthrough and gas been dissolved in oil.

6.1 Calculation on the SINTEF concept

A flow sheet calculation has been made in Excel, to find out how the SINTEF concept on cold flow technology works. Production data for hot fluid (oil/water/gas) streams from subsea wells have been calculated in the previous section and would be used to find out all the necessary parameter in the concept. However, Table 9 are showing all the assumption made to simplify the calculation.

The North Sea cases given in Table 6 would be used to simulate 5 cases, with two

different temperature and pressure, in the concept. The main pipe have assumed $ID = 0.225$ m. However, there have been done calculation in this case to find out if the pipe would be effected by bouyancy. If the pipe would be affected by bouyancy then concrete coating may be required to hold the pipe at seabed. Figure 18 is showing that the pipe used in SINTEF concept would not have any problem concerning the bouyancy effect. The bouyancy effect start first at ID of 0.28 m (11").

The OHTC is a parameter that have been assumed to be 15 [11] and 100 [12]. The OHTC is a function of the component parts of a pipeline including the parent steel and any coatings for insulation or protection. [16] However, the OHTC for bare pipe at seabed, shown in Figure 19, show that the bare pipe have little resistance to heat loss. [15] One may also observe that the OHTC increases when the OD of the decreases. This have to do with large thermal conductivity to steel pipe, $k_{\text{steel}} = 50$ W/mK at seabed condition. However, the thermal conductivity to seawater is very low, $k_{\text{sea}} = 0.65$ W/mK. This mean that seawater have large resistance to heat loss. As the can be observed from Table 19 the OHTC decreases exponentially with increasing OD of the pipe. The OD would for $OHTC = 100$ be 0.65 m, but for SINTEF concept the ID used is 0.225 m for main pipe. [6] In this case concrete coating could have been used to increase the OHTC to the pipe. By light coating of 3 layer polypropylene the OHTC can increase up to 100. However, the primary source from a solid (steel pipeline) to a fluid (seawater) will be convection³ and not conduction⁴. In this case exposed bare pipe at seabed would lose heat to the surroundings by convection. [16],

However, shown in Table 10. The mass flow rates of gas, water and oil are the same as found out at seabed condition. The mass flow rate of hydrate have been

³a process which heat travels through air, water, and other gases and liquids

⁴a process by which heat passes through or along something

calculated in consideration that the hydrate composition contain 15wt% water and 85wt% gas. The mass flow rate of hydrate would increase if the mass flow rate of water increases.

To find out if the system have excess gas or water, the mass fractions of gas, water and oil were found by the following equation [11]

$$x_{fr, i} = \frac{m, i}{m_t} \quad (6.16)$$

The calculated mass fractions in Table 10 shows that the system have excess of gas and with the excess of gas it would be very difficult to form hydrate with pre assumed hydrate composition. The gas would in this case "eat up" the water and hydrate formation would not occur.

However, the heat required to raise the temperature for the unit mass flow rate must be found out. In this case the specific heat capacity for water is assumed to be 4.18 kJ/kgK. This is higher then the specific heat capacity for gas, $C_{p,g} = 2.141$ kJ/kgK, and the assumed specific heat capacity for hydrate, $C_{p,h} = 2.7$ kJ/kgK. As a result, the water plays a more important role then gas, oil and hydrate in temperature regulation.

The specific heat capacity for oil, $C_{p,o}$, should be found by use of following equation [17]

$$C_{p,a} = 2.96 - 1.34\gamma_o + T(0.00620 - 0.00234\gamma_o) \quad (6.17)$$

As one may observe from the equation that the specific heat capacity for oil, $C_{p,o}$, is dependent at which temperature the oil occurs at and the specific gravity of oil, γ_o . [17]

The production stream from the well would not only consist of oil, but also water and gas. Since the fluid temperature would change a long a pipeline, the fluid's specific heat would play an important role. Oil, water and gas have different values for specific heat capacity. Therefor a mixed specific heat capacity must be found by following equation [11]

$$C_{p,\text{mix}} = x_g C_{p,g} + x_o C_{p,o} + x_w C_{p,w} + x_h C_{p,h} \quad (6.18)$$

As can be observe from the equation, the specific heat capacity for hydrate, $C_{p,h}$, have been included. This have been done due to hydrate formation occurs instantaneously. However, as mention earlier the specific heat capacity for hydrate, $C_{p,h} = 2.7 \text{ kJ/kgK}$, is very close to the specific heat capacity for gas, $C_{p,g} = 2.141 \text{ kJ/kgK}$. This can be explained from the gas composition (92 % methane, 5 % ethane and 3 % propane), where the content of methane is very large.

The hydrate formation reaction is highly exothermal, so the increasing temperature for hydrate was found by the following equation. [18] However, the heat capacity of hydrate was assumed to be 410 kJ/kg [13]

$$\Delta T = \frac{\Delta H}{m_t C_{p,\text{mix}}} \quad (6.19)$$

The enthalpy for hydrate, ΔH_h , would be dependent on the mass flow rate of the hydrate. It would be large if the mass flow rate of hydrate would be large and vice versa. However, the increasing temperature due to hydrate formation, ΔT_h , would increase if the enthalpy for hydrate, ΔH_h , would increase. This can be observe from Table 10

Since the bare pipe is exposed to ambient sea temperature, the temperature at the

downhole splitter should be evaluated, so the given equation was used to find the temperature at the end of the main pipe [18]

$$T_2 = T + (T_1 - T) \exp\left(\frac{-U\pi dL}{mC_p}\right) \quad (6.20)$$

Where T_2 should be the outlet temperature, T would be the ambient sea temperature and T_1 would be the sum of the inlet temperature to the main pipe and the hydrate formation temperature, ΔT_h . In this case it was assumed that the hydrate was made instantaneously. [11]. However, length from 2 – 20 km was only studied in this case, because the whole loop arrangement should be not more than 20 km. [12], [11].

Table 11 is showing the temperature is decreasing as the length to the downhole splitter increases. One may observe that the outlet temperature decreases instantaneously after few km of length when the OHTC is 100 instead of 15. The outlet temperature would be equal to ambient sea temperature after only 4 – 6 km, as can be shown in Figure 20 and Figure 21. These figures are showing that the outlet temperature decreases exponential with the length of the pipe. However, one may notice the big difference in temperature decreasing with OHTC=15 and OHTC=100. For the OHTC=100 the heat loss to the surroundings is much higher and appears instantaneously after only few km. [15]

At the downhole splitter it was assumed that the splitter splitted 50% of the cold hydrocarbon fluid. The largest dry hydrate particles with oil and water was recycled back to starting point of the hydrate reactor system. However, this assumed percent of recycling fluid made it possible to assume that the recycling pipe had an area of 1/2 the area of the main pipe. [11] If the recycling fluid had been larger, then a larger area of recycling pipe would have been required. The recycling fluid

for SINTEF concept is suppose to be 50 – 90% of the main fluid. [12]

Table 12 is showing the recycling fluid consist of water, oil and hydrate. In this case the gas would not be recycled and this was made as an assumption to avoid more hydrate formation in the recycling pipe. In this part of the process the pressure would be to low to transport all the recycling fluid, so a subsea pump is required to "help" the recycling fluid with the transport. However, there have not be done any calculation on a susbsea pump in this project, but it is assumed that it provide enough pressure to the recycling fluid to make it possible to mix with the production fluid at starting point of the reactor. The pressure drop over the subsea pump would be assumed to be 2 bar. [11]

At the starting point the inlet temperature to the exposed pipe would be of 50 % from the wellhead and 50 % of the recycling temperature. This will reduce the inlet temperature to the exposed pipe to be 29.5 °C (55 °C) and 52 °C (100 °C). Table 13 is showing that the mass flow rate of water oil and hydrate have increased and this would effect the total mass flow rate, as it increases also. This would further effect the mass fractions, the entalphy, the specific heat capacity for the mixing fluid and the increasing hydrate formation temperature.

Table 14 is showing that the increased total massrate have not so large effect on the outlet temperature, as shown in Figure 22 and Figure 23. The exponential graph for decreasing outlet temperature would be lowered a little bit. However, it have been assumed that the recycling pipe was empty in the beginning of the calculation and a second recycling would give a better result compared to the main process. This assumption would not been possible in a realistic system, because the recycling loop would never been empty. [12]

Table 15 is showing the same process as previous, increasing total massrate affect- ing the massfractions, the entalphy, the specific heat capacity for the mixed fluid

and the increasing hydrate formation temperature. This would once again not have so large effect on the outlet temperature, but as shown in Table 16, Figure 22 and Figure 23 the second recycling graph is more closed to the main process graph than the first recycling graph was. This would be realistic, because the temperature would only be affected by a few degree by recycling.

6.2 Calculation on the NTNU concept

For the NTNU concept the mass flow rate, production rates and densities of oil, water and gas would be the same at wellhead as for SINTEF concept. Other assumption made to simplify the calculation is shown in Table 17.

However, a new parameter, WHR, have been used in the calculation. This parameter is used in the calculation to illustrate whether all of the water will be converted to hydrate, or whether all of the in-situ associated gas will be converted to hydrate. If the $WHR > 1$ then there is not enough water to convert all of the associated gas into hydrate. The WHR for this case is calculated to be 0.85, so the system have not enough water to convert all the associated gas to hydrate.

A subsea separator have been used to separate the liquid phase and gas phase. The assumption was made that the water would be separated due to higher density and have been included in the liquid phase after the separation calculation have been made. This assumption made it possible to make calculation on only a two-phase separator instead of three-phase separator. However, a three-phase separator would be used in a realistic system and the water content would not be more than 15 %. [11]

The gas phase was calculated by the following equation [18]

$$q_g = A_g k_s \left(\frac{L}{6}\right)^{0.58} \sqrt{\frac{\rho_l - \rho_g}{\rho_g}} \quad (6.21)$$

where the separation constant, $k_s = 0.137\text{m/s}$ for NORSOK. [18]

$$F = \left(\frac{L}{6}\right)^{0.58} \quad (6.22)$$

where the length factor, $F = 1$, from NORSOK.[18]

The design of a subsea separator was not determined by calculation and was assumed to be a tank-type horizontal separator with length of 6 m and diameter of 2 m. [13].

To determine the liquid phase from the separator, the velocity for the droplet was found by the following equation and the time for the droplet to fall to liquid phase [18]

$$v_b = \frac{3}{2} d^2 g \frac{(\rho_l - \rho_g)}{18\mu} \quad (6.23)$$

where the d is the assumed diameter for a droplet at $200\mu\text{m}$ [18]. The viscosity, $\mu = 0.3$ cP, was assumed. However the time before the droplet was found by equation [18]

$$t_D = \frac{d}{2v_b} \quad (6.24)$$

The residence time should be around 120 s. However, shown in Table 18 it would be from a range of 23 – 32 s for the predefined cases.

The liquid phase is found by the following equation [18]

$$q_1 = A_1 \frac{L}{t_D} \quad (6.25)$$

The area of liquid phase is assumed to be the same as for the gas phase. [18]. This assumption could be made by the fact that two-phase homogenous flow is assumed to appear in the pipe. As shown in Table 18, the liquid phase would be a little higher than the gas phase, due to increasing WC. This has to do with the water content in production fluid that also increases, when WC increases.

The primary goal of the calculation is to describe the cooling done by heat exchanger unit in cold flow concept of NTNU. The main challenge being to cool the produced stream cost effectively to allow the same pipeline inlet temperature at the surrounding ambient sea temperature. The cooling should be made in two stages, cooling in a tube heat exchanger and further cooling in a refrigeration plant. [13]

The heat exchanger is assumed to be designed based on the ambient sea temperature, with production rate calculated for typical Norwegian oilfields. However, the length of the pipeline between the fields has not been taken into consideration when the calculation was made and is assumed to have less effect on the calculation. The length should be very small and could be neglected. [13]

The liquid phase from the subsea separator has been cooled by a tube heat exchanger, as illustrated in Figure 24, but a simple tube heat exchanger could not achieve low enough temperature. The tube heat exchanger would in this case only cool the liquid phase from 100 °C or 55 °C to 10 °C, so a refrigeration unit is needed to cool further the liquid phase from 10 °C to ambient sea temperature. However, the cooling of the gas phase has not been studied in this project, since it would require less energy. [13]

Table 19 is showing the calculated area for heat exchanger. The cooling demand,

Q , have been calculated by following equation [13]

$$Q = m_o C_{p,o} \Delta T + m_w C_{p,w} \Delta T \quad (6.26)$$

The cooling demand would in this case not be so large and will vary from 0.08 MW to 4.27 MW. This can be explained from the low water production from the fields. The cooling demand would increase if the water production increases.

The area of the heat exchanger have been calculated by use of following equation [18]

$$A = \frac{Q}{U \Delta T_{LMTD}} \quad (6.27)$$

where the U is assumed to be 250 for the tube with $ID = 0.0254$ m [13]. One may observe from the equation that the area of the heat exchanger increases, if the value of U decreases. The LMTD function is given by [18]

$$\Delta T_{LMTD} = \frac{T_1 - T_2}{\ln \frac{T_1 - T}{T_2 - T}} \quad (6.28)$$

T_1 would in this case be 100 °C or 55 °C, T_2 would be the wanted low outlet temperatur 10 °C and T would be the ambient seawater temperature.

One may observe that the area for the heat exchanger vary from $14.90m^2$ to $526.36m^2$. This have to do with the fact that, the wellhead have in this project two predefine temperature, 55 °C and 100 °C. Therefore the ΔT would be different and so the area of the heat exchanger would be different. However, the water production would have an important role in designing the heat exchanger area. If the water production is very high then the required heat exchanger area increases

and if the water production is low, as in this case, the heat exchanger area would be small. However, it is assumed free convection outside the tube and this would increase the OTHC value. [13]

The required total length of the tubes that will make the tube heat exchanger was calculated by the following equation [18]

$$L = \frac{A}{\pi d} \quad (6.29)$$

where the diameter, d_{tube} , of the tubes was assumed to be 0.0254 m. However, the space between the tubes have not been calculated in this project, but was assumed to be the same as the diameter of the tube, 0.0254 m. The length of a pipe was assumed to be 70 m. [13]

The refrigeration plant would consist of four main components which would be connected by tubes for circulation of the refrigeration working fluid, as illustrated in Figure 25. In the evaporator, the cooling of liquid phase occurs by evaporating the refrigerant fluid. The refrigerant vapour from the evaporator would be compressed to higher pressure with corresponding higher saturation temperature. However, the heat exchanger with the surrounding sea water in the condenser, would condense the refrigerant vapour. The pressure of the refrigerant liquid would be reduced in the expansion valve before it is fed into the evaporator for cooling the liquid phase. [13]

Table 20 is showing the cooling demand from 10 °C to 4 °C and is very low. The cooling demand varies from 0.00998 MW to 0.283 MW. The compressor would in this case be assumed to need 1/5 of the cooling demand. The electric power for the compressor would vary from 0.002 MW to 0.0566 MW.

At the reactor the associated gas and the cooled liquid phase would be mixed by

turbulent. The reactor would be of a static mixer.[11]. However, the temperature and pressure must be within the hydrate forming region. This mean that the inlet temperature should be under 12 °C and pressure would be above 40.70 bar, as illustrated in Table 21 and Figure 26 for the predefined cases in the project.

Table 21 is showing the calculation done to find out if the temperature and the pressure is within the hydrate formating region. The procedure for the calculation that have been made is the same as for the SINTEF concept. However, one may observe that the increasing hydrate formation temperature is not so high, but there would not be a problem in formating hydrate since the pressure is high enough (150 bar, 375 bar).

7 Discussion

The field implementation of the SINTEF's cold flow concept is very flexible. One may produce from a single well, or from a chain of wells or a possible from an entire field. If more than one well is included, then the loop may be enlarged so that only one splitter or recirculation point is needed. This means that it would be possible to mount the concept to an existing system at subsea and only add an extra pipeline loop. However, the concept has been primarily developed for new field development.

The field implementation of the NTNU concept is dependent on the how many fields are producing. If there is more than one well, then the production from all the wells would be joint. The production stream would after the joint enter the SU. However if several fields are producing then several sets of SU, HXU and RU are required and depend on GOR, WC and other fluid properties. The hydrate formation would in this case be done by "force" and not by the environment. The hydrate formation would appear in smaller area than the pipe length arrangement for the SINTEF concept. However, the area would on the other side be filled with arrangement of SU, HXU and RU.

Both concepts have no problem with varying WC and GOR and the location of the concept could be everywhere geologically possible. There will always be WC present in production from a subsea well, but water content in the concept would not be so large. Both concepts have free water knockout before the production stream enters the cold flow concept. Therefore the water content would be not more than 20% in the concepts. The vary of hydrate forming particles would either be a problem since either the gas would be eliminated or the water, but it should be below then 50%

Since hydrate formation is an exothermic reaction, it can create a problem for the SINTEF concept. The temperature increasment due to hydrate formation will creat heat that should be transported to surroundings. The solution for the SINTEF concept is a 2 – 10 km pipeline that cools the solution down to ambient sea temperature, but is regarded as an engineering challenge.

The concept is based on heat transfer from a pipeline to surrounding seawater. This would make the concept very dependent on the OTHC value. The concept would use OTHC=100, but the industry is operating with OTHC=15 – 20 for bare pipe at seabed exposed to seawater.

The question arises where the hydrate formation in the pipe would appear. Since the pipe is exposed to the surrounding ambient sea temperature, the wall of the pipe would be the coldest place in the pipe. The hydrate formation would often prefer the coldest place in the system to formate and in this case, it would be the wall of the pipe. Since the hydrate formation appears at the wall of the pipe, then the thermal conductivity would play an important role. The thermal conductivity for seawater is , $k_{\text{sea}} = 0.65 \text{ W/mK}$. This make the seawater a bad heat transfer and have a large resistance to heat transport. However, the steel pipe is a much better heat transfer with a thermal conductivity of, $k_{\text{pipe}} = 50 \text{ W/mK}$ at the ambient sea temperature and the thermal conductivity for solid gas hydrate would be, $k_{\text{sea}} = 0.5 \text{ W/mK}$. As a result the formatted hydrate at wall pipe would not transfer enough heat to steel pipe and this would make it almost impossible for the steel pipe to transport the heat to the surroundings. Since the heat would not be transported to the surroundings, a hydrate growth would appear. This would make the diameter for the fluid to flow smaller and the velocity would increase. The hydrath growth at the wall would cause friction increasement and this would result in larger pressure drop.As a result the required length of pipe

arrangement would increase. This would make it difficult to transport the fluid, since the pressure drop would be large and a pipe arrangement between 2 – 10 km would be not possible to maintain.

Since hydrate and steel are hydrophilic (they like water), one may have to change the surface properties of the pipewall. This can be done by application of coating or chemical injection. By coating one may reduce the roughness of the pipe and the pipe would be acting like a hydrophobic (opposite to like water). However, in clod flow technology the use of hydrophobic surfaces both in process units and in the pipeline would be a big advantage.

For the NTNU concept, a heat exchanger arrangement, consisting of a tube heat exchanger unit and a refrigeration unit, would cool the liquid phase to ambient sea temperature. In this case the tube heatexchanger would be dependent on OTHC. If the OTHC value is large, then a larger area is required for the heatexchanger arrangement. In this project a tube with diameter of 0.0254 m have been used and one may observe from Table 19 the OTHC value would be higher then 1000. This would make the tube a good heat transfer medium. However, the question also arises if the refrigeration unit is required. The calculation have showed that the pressure is so large that it would be not a problem to be within the hydrate formation curve without an refrigeration unit.

In this project a two-phase separator was used in the NTNU-concept, but it would be more appropriate to use a three-phase separator. The water content of the production fluid would play an very important role in designing the SU, HXU and RU. For the design of the RU one may start with the information where, $WHR=1$. This mean that tha amount of water is equally the amount of hydrate in the system. If there is a three-phase separator, the water content would be not more done 15%. This would affect the size of the SU, HXU and RU to be a smaller.

As shown from the calculation the required area for the tube heatexchanger is not so large. Therefore the NTNU cocept would not enlarge the capacity of the equipment an existing field.

For the SINTEF concept there would be challenge to create a felxiable system that can deal with different fluid and conditions. The amount of hydrates up to 30% will not necessarily give measurable changes in the viscosity of the fluid, but different cocnditons would demand flexiability in the operating condition. The fluid would be very difficult to transport at ambient sea temperature, since the oil would be barely moveable. The difference in viscosity would create limitations on the transport distcance. This would be as result in large pressuredrop over long distances. However, the operating condition would be dependent on the WC and the amount of hydrate forming components, like associtaed gas and free water from the production stream.

However, both concepts are developed on the base on the oilfields with certain amount of gas production. If the gas production would be very high, then the amount of the hydrate formated would be much higher then the amount of water that is being produced. All the water would then be "eaten up" of the dry hydrate particle. The transportation of the fluid would be difficult and one may gain agglomeration of hydrates. As long as the the amount of dry hydrate particles and water from the production is equal, no problem should appear in the SINTEF concept. The NTNU concept would on the other hand not have problem with different GOR and WC values.

Both SINTEF and NTNU have oilfield as its main target, but they solves the problem of wax formation. That would make it possible to use the concepts in gas and condensate field. In this project only oilfield and hydrate formation have been studied.

8 Conclusions

- Cold flow is a future technology for preventing hydrate and other depositions like wax problem. The technology concerns trouble free flow of oil and gas from deepwater wellheads to processing facilities and is environmentally friendly because of reduction of use of chemicals.
- Two concept on cold flow, NTNU and SINTEF, have different ways of cooling. These cooling methods are dependent on GOR-WC window and deepwater production condition to find out if cold flow is appropriate.
- Typical Norwegian deepwater condition for oilfields have been found, where cold flow technology would be appropriate. The WC is from a range 50 – 85 % with corresponding GOR from 125 to 500, the reservoir temperature, T_R , range from 70 °C to 150 °C with corresponding reservoir pressure, P_R , from 150 – 600 bar.
- OHTC is a very sensitive parameter for the SINTEF concept and NTNU concept, both are dependent on this parameter regarding the pipeline arrangement and heat exchanger surface. SINTEF are operating with OHTC=100 for the pipeline arrangement, but the industry are operating with OHTC=15-20 for pipe at seabed. NTNU are using OTHC=250, but for pipe with small diameter the OHTC could be up to 1000. This indicates that OHTC is a key parameter in cold flow technology and requires more research.

Nomenclature

Latin letters

T - temperature [$^{\circ}\text{C}$]

P - pressure [Pa]

m - massrate [kg/s]

M - molar weight [kg/mol]

R - gas constant [kJ/kmolK]

GOR - gas oil ratio [Sm^3/Sm^3]

Rs - gas oil ratio [Sm^3/Sm^3]

q - production rate [m^3/s]

Bo - formation volume factor oil [m^3/Sm^3]

Bg - formation volume factor gas [m^3/Sm^3]

Cp - specific heat capacity [kJ/kgK]

ΔH - enthalpy [kJ/kg]

U - overall heat transfer coefficient [$\text{W}/\text{m}^2\text{K}$]

A - area [m^2]

g - force of gravity [m/s^2]

v_b - velocity for the droplet to fall [m/s]

t - residence time [s]

Q - energy power [kJ/s]

k - thermal conductivity [W/mK]

Greek letters

ρ - density [kg/m³]

ΔT - temperature

γ - specific gravity

μ - viscosity [Pas]

Subscripts and superscripts

R reservoir

sc standard condition

o oil

l liquid

g gas

w water

h hydrate

t total

d diameter

z supercompressibility factor

$x_{fr,i}$ massfraction

F_s factor of the length in a horizontal separator

k_s separation constant for liquid and gas phase in a separator

L length

com compressor

Abbreviations

GOR gas-oil-ratio

MEG methane-ethylene glycol

DEG di-ethylene glycol

TEG tri-ethylene glycol

WC watercut

wt weight percent

WHU wellhead unit

SU separator unit

HXU heat exchanger unit

RFU refrigeration unit

RU reactor unit

OHTC overall heat transfer coefficient

WHR water-hydrate-ratio

LMTD logarithmic mean temperature difference

ID inner diameter

OD outer diameter

km kilometer

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Tables

| Oilfields | PR | TR | GOR ini | GOR | | GOR ave | WC ave | WC ave[%] |
|----------------|-------------|-------------|-------------|----------|----------|----------|--------|-----------|
| | [bar] | [C] | | Max | Min | | | |
| BALDER | 177 | 77 | 53 | 68,604 | 52,607 | 57,867 | 0,311 | 31,109 |
| BRAGE | 244,215 | 98,87 | 60,93 | 145,219 | 105,301 | 120,515 | 0,766 | 76,596 |
| DRAUGEN | 165 | 71 | 52 | 57,802 | 55,905 | 56,793 | 0,195 | 19,541 |
| EKOFISK | 490,497 | 130,131 | 273 | 198,853 | 182,526 | 190,413 | 0,256 | 25,637 |
| ELDFISK | 472,476 | 126 | 471,479,458 | 694,486 | 340,275 | 534,301 | 0,182 | 18,201 |
| EMBLA | - | - | - | 662,691 | 449,529 | 528,062 | 0,017 | 1,656 |
| FRAM | - | - | - | 368,815 | 144,430 | 243,017 | 0,022 | 2,174 |
| FRØY | - | - | - | 1579,522 | 1231,814 | 1405,668 | 0,108 | 10,828 |
| GLITNE | - | - | - | 54,494 | 50,145 | 52,489 | 0,363 | 36,307 |
| GRANE | 176 | 77 | - | 31,197 | 14,660 | 25,015 | 0,263 | 26,329 |
| GULLFAKS | 310,319,320 | 72,80 | 94,116,171 | 805,062 | 235,800 | 524,167 | 0,716 | 71,615 |
| GULLFAKS SØR | 450,470,510 | 125,129 | 200,200,180 | 633,620 | 366,127 | 489,799 | 0,065 | 6,477 |
| GYDA | 595 | 154 | 327 | 412,570 | 167,957 | 246,238 | 0,589 | 58,912 |
| HEIDRUN | 252,251 | 85 | 117,79,60 | 249,757 | 193,875 | 218,261 | 0,234 | 23,382 |
| HOD | - | - | - | 238,607 | 131,285 | 183,732 | 0,158 | 15,792 |
| JOTUN | 200 | 82 | - | 72,832 | 44,166 | 52,609 | 0,639 | 63,931 |
| NJORD | - | - | - | 1852,571 | 693,339 | 1399,468 | 0,044 | 4,413 |
| NORNE | - | - | - | 273,109 | 197,176 | 224,373 | 0,169 | 16,851 |
| OSEBERG | 288,281 | 125,100 | 145 | 1328,594 | 677,321 | 1008,915 | 0,178 | 17,758 |
| OSEBERG SØR | 288 | 125 | 145 | 349,986 | 201,096 | 292,078 | 0,087 | 8,705 |
| OSEBERG ØST | 288 | 125 | 145 | 163,030 | 84,627 | 116,933 | 0,375 | 37,495 |
| SNORRE | 380,383 | 90,93 | 133,105 | 187,438 | 151,874 | 166,624 | 0,364 | 36,389 |
| STATFJORD | 450,383,404 | 115,92,99 | 190,155 | 808,118 | 542,412 | 664,124 | 0,808 | 80,759 |
| STATFJORD NORD | 450,398 | 115,98 | 93,66 | 79,547 | 75,239 | 76,277 | 0,510 | 50,957 |
| STATFJORD ØST | 450 | 115 | 93 | 141,999 | 141,580 | 141,715 | 0,550 | 55,015 |
| SYGNA | - | 110 | - | 62,801 | 60,298 | 61,620 | 0,306 | 30,614 |
| TAMBAR | - | - | - | 235,794 | 230,548 | 232,923 | 0,005 | 0,470 |
| TOR | - | - | - | 192,239 | 146,455 | 171,130 | 0,554 | 55,433 |
| TORDIS | - | - | - | 116,468 | 107,402 | 112,832 | 0,291 | 29,063 |
| ULA | 491 | 143 | 164 | 222,563 | 93,732 | 151,096 | 0,758 | 75,805 |
| VALHALL | 455 | 90 | - | 270,760 | 238,169 | 254,284 | 0,077 | 7,705 |
| VARG | - | - | - | 406,507 | 194,052 | 254,769 | 0,349 | 34,935 |
| VESLEFRIKK | 321,346,355 | 122,128,133 | 125,140,320 | 401,644 | 315,143 | 359,137 | 0,697 | 69,733 |
| VISUND | 450 | 115 | - | 1910,399 | 447,047 | 1122,609 | 0,283 | 28,323 |
| YME | - | - | - | 55,473 | 44,916 | 50,195 | 0,511 | 51,058 |
| ÅSGARD | - | - | - | 5340,535 | 730,832 | 2790,793 | 0,041 | 4,110 |
| TROLL | 158 | 68 | 62 | 1978,094 | 1177,762 | 1430,240 | 0,506 | 50,572 |

Table 1: Data for some Norwegian oilfields

| Case | GOR | WC |
|------|------|------|
| 1 | 250 | 0.2 |
| 2 | 250 | 0.7 |
| 3 | 1250 | 0.15 |

Table 2: GOR and WC

| Tres | Pres | T | P |
|------|------|-----|-----|
| 97 | 260 | 55 | 150 |
| 175 | 650 | 100 | 375 |

Table 3: Temperature and pressure at reservoir- and subsea condition

| GOR [m ³ /Sm ³] | WC [-] | m _g [kg/s] | m _w [kg/s] | m _o [kg/s] | m _t [kg/s] |
|---|-----------|--------------------------|--------------------------|--------------------------|--------------------------|
| 250 | 0,20 | 4,48 | 6,11 | 19,41 | 30 |
| 250 | 0,70 | 1,66 | 21,15 | 7,19 | 30 |
| 1250 | 0,15 | 14,57 | 2,81 | 12,62 | 30 |

| q _g [m ³ /s] | q _w [m ³ /s] | q _o [m ³ /s] | q _g [m ³ /d] | q _w [m ³ /d] | q _o [m ³ /d] |
|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 6,02 | 6,02E-03 | 2,41E-02 | 5,20E+05 | 520,38 | 2081,52 |
| 2,23 | 2,08E-02 | 8,93E-03 | 1,93E+05 | 1800,09 | 771,47 |
| 19,59 | 2,77E-03 | 1,57E-02 | 1,69E+06 | 238,91 | 1353,82 |

Table 4: Data at standard condition

| Standard condition | | |
|--------------------|---------|-------------------|
| T_{sc} | 15 | °C |
| P_{sc} | 1.10325 | bar |
| m_t | 30 | kg/s |
| $\rho_{w,fresh}$ | 1000 | kg/m ³ |
| M_{air} | 28.97 | kg/kmol |
| R | 8314 | kg/kmolK |
| z_{sc} | 1 | |

Table 5: Standard condition assumptions

| Case | T | P | GOR | WC |
|------|-----|-----|-----|-----|
| 1 | 55 | 150 | 250 | 0.2 |
| 2 | 55 | 150 | 250 | 0.7 |
| 3 | 100 | 375 | 125 | 0.3 |
| 4 | 100 | 375 | 125 | 0.8 |
| 5 | 100 | 375 | 50 | 0.9 |

Table 6: GOR and WC from Norwegian Oilfields

| Subsea condition | | |
|------------------|-----|------------|
| T_1 | 55 | °C |
| P_1 | 150 | <i>bar</i> |
| T_2 | 100 | °C |
| P_2 | 375 | <i>bar</i> |
| z | 0.8 | |

Table 7: Subsea condition assumptions

| Rs [Sm³/Sm³] | WC [-] | B* [-] | Bo [m³/Sm³] | Bg [m³/Sm³] | | |
|---|-------------------------|-------------------------|--|--|--|--|
| 250,00 | 0,20 | 1429,81 | 1,71 | 0,00815 | | |
| 250,00 | 0,70 | 1429,81 | 1,71 | 0,00815 | | |
| 125,00 | 0,30 | 856,20 | 1,38 | 0,00280 | | |
| 125,00 | 0,80 | 467,91 | 1,17 | 0,00280 | | |
| 50,00 | 0,90 | 468,27 | 1,17 | 0,00280 | | |

| p_o kg/m³ | p_g kg/m³ | p_w kg/m³ | m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_t [kg/s] |
|---|---|---|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 595,33 | 139,37 | 1015 | 29,29 | 0,21 | 0,50 | 30 |
| 595,33 | 139,37 | 1015 | 27,65 | 1,88 | 0,47 | 30 |
| 681,51 | 306,40 | 1015 | 29,17 | 0,33 | 0,50 | 30 |
| 782,55 | 306,40 | 1015 | 26,63 | 2,82 | 0,54 | 30 |
| 727,09 | 306,40 | 1015 | 18,25 | 10,88 | 0,87 | 30 |

| q_g [m³/s] | q_w [m³/s] | q_o [m³/s] | q_g [m³/d] | q_w [m³/d] | q_o [m³/d] |
|--|--|--|--|--|--|
| 2,10E-01 | 2,10E-04 | 8,41E-04 | 18155,70 | 18,16 | 72,62 |
| 1,98E-01 | 1,85E-03 | 7,94E-04 | 17140,21 | 159,98 | 68,56 |
| 9,52E-02 | 3,26E-04 | 7,61E-04 | 8223,98 | 28,20 | 65,79 |
| 8,69E-02 | 2,78E-03 | 6,95E-04 | 7509,90 | 240,32 | 60,08 |
| 5,96E-02 | 1,07E-02 | 1,19E-03 | 5146,47 | 926,37 | 102,93 |

Table 8: Data at subsea condition

| SINTEF assumptions | | |
|--------------------|--------|--------------------|
| ρ_w | 1015 | kg/m ³ |
| M_g | 17.59 | kg/kmol |
| γ_g | 0.607 | |
| ρ_g | 0.7440 | kg/m ³ |
| ρ_o | 805.5 | kg/m ³ |
| $C_{p,w}$ | 4.18 | kJ/kgK |
| $C_{p,g}$ | 2.141 | kJ/kgK |
| T_{sea} | 4 | °C |
| U | 15 | W/m ² K |
| U^* | 100 | W/m ² K |
| d_{main} | 0.225 | m |
| ΔH_h | 410 | kJ/kg |
| $C_{p,h}$ | 2.7 | kJ/kgK |
| wt_{gas} | 15 | % |
| wt_{water} | 85 | % |
| $d_{recycle}$ | 0.159 | m |
| $m_{recycle}$ | 50 | % |

Table 9: Assumption for SINTEF calculation

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | x fr g | x fr w | x fr o | x fr hydrate |
|-----------------|-----------------|-----------------|-----------------|-----------|-----------|-----------|-----------------|
| 29.29 | 0.21 | 0.50 | 0.25 | 0,9762 | 0,0071 | 0,0167 | 0,0084 |
| 27,65 | 1,88 | 0,47 | 2,21 | 0,9216 | 0,0626 | 0,0157 | 0,0737 |
| 29,17 | 0,33 | 0,50 | 0,39 | 0,9722 | 0,0110 | 0,0168 | 0,0130 |
| 26,63 | 2,82 | 0,54 | 3,32 | 0,8878 | 0,0941 | 0,0181 | 0,1107 |
| 18,25 | 10,88 | 0,87 | 12,80 | 0,6084 | 0,3628 | 0,0289 | 0,4288 |

| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] |
|------------------------|-----------|---------------------|
| 102,880 | 2,178 | 1,575 |
| 906,505 | 2,467 | 12,247 |
| 159,776 | 2,201 | 2,419 |
| 1361,763 | 2,635 | 17,227 |
| 5249,277 | 4,038 | 43,334 |

Table 10: Data for mainpipe

| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
|-----------|----------------|----------------|----------------|----------------|----------------|
| 0 | 56,57 | 67,25 | 102,42 | 117,23 | 143,33 |
| 2 | 42,00 | 51,49 | 75,39 | 90,59 | 120,96 |
| 4 | 31,47 | 39,66 | 55,78 | 70,21 | 102,18 |
| 6 | 23,86 | 30,78 | 41,56 | 54,63 | 86,41 |
| 8 | 18,35 | 24,11 | 31,25 | 42,72 | 73,18 |
| 10 | 14,37 | 19,10 | 23,76 | 33,61 | 62,07 |
| 12 | 11,50 | 15,34 | 18,34 | 26,64 | 52,74 |
| 14 | 9,42 | 12,51 | 14,40 | 21,31 | 44,91 |
| 16 | 7,92 | 10,39 | 11,54 | 17,24 | 38,34 |
| 18 | 6,83 | 8,80 | 9,47 | 14,12 | 32,83 |
| 20 | 6,05 | 7,60 | 7,97 | 11,74 | 28,20 |

| L* [km] | Tout1.1* [C] | Tout1.2* [C] | Tout1.3* [C] | Tout1.4* [C] | Tout1.5* [C] |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0 | 56,57 | 67,25 | 102,42 | 117,23 | 143,33 |
| 2 | 10,04 | 13,37 | 15,57 | 22,93 | 47,37 |
| 4 | 4,69 | 5,39 | 5,36 | 7,17 | 17,50 |
| 6 | 4,08 | 4,21 | 4,16 | 4,53 | 8,20 |
| 8 | 4,01 | 4,03 | 4,02 | 4,09 | 5,31 |
| 10 | 4,00 | 4,00 | 4,00 | 4,01 | 4,41 |
| 12 | 4,00 | 4,00 | 4,00 | 4,00 | 4,13 |
| 14 | 4,00 | 4,00 | 4,00 | 4,00 | 4,04 |
| 16 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 18 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

Table 11: Outlet temperature mainpipe

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | WHR [-] | | |
|---------------|---------------|---------------|---------------|------------|--|--|
| 29,29 | 0,21 | 0,50 | 0,25 | 0,85 | | |
| 27,65 | 1,88 | 0,47 | 2,21 | 0,85 | | |
| 29,17 | 0,33 | 0,50 | 0,39 | 0,85 | | |
| 26,63 | 2,82 | 0,54 | 3,32 | 0,85 | | |
| 18,25 | 10,88 | 0,87 | 12,80 | 0,85 | | |

Recycling fluid 0,50

| m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | x_fr w | x_fr o | x_fr h |
|---------------|---------------|---------------|---------------|-----------|-----------|-----------|
| 0,1066 | 0,2502 | 0,1255 | 0,4823 | 0,2211 | 0,5188 | 0,2601 |
| 0,9397 | 0,2382 | 1,1055 | 2,2814 | 0,4119 | 0,1035 | 0,4846 |
| 0,1656 | 0,2519 | 0,1948 | 0,6123 | 0,2705 | 0,4113 | 0,3182 |
| 1,4116 | 0,2721 | 1,6607 | 3,3443 | 0,4221 | 0,0814 | 0,4966 |
| 5,4413 | 0,4331 | 6,4016 | 12,2760 | 0,4432 | 0,0353 | 0,5215 |

Table 12: First recycling data

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | x_fr g | x_fr w | x_fr o | x_fr h |
|---------------|---------------|---------------|---------------|---------------|-----------|-----------|-----------|-----------|
| 29,29 | 0,3199 | 0,75 | 0,38 | 30,73 | 0,9529 | 0,0104 | 0,0244 | 0,0122 |
| 27,65 | 2,8190 | 0,71 | 3,32 | 34,49 | 0,8016 | 0,0817 | 0,0205 | 0,0962 |
| 29,17 | 0,4969 | 0,76 | 0,58 | 31,00 | 0,9407 | 0,0160 | 0,0244 | 0,0189 |
| 26,63 | 4,2348 | 0,82 | 4,98 | 36,67 | 0,7264 | 0,1155 | 0,0223 | 0,1359 |
| 18,25 | 16,3240 | 1,30 | 19,20 | 55,08 | 0,3314 | 0,2964 | 0,0236 | 0,3487 |

| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] | WHR [-] |
|------------------------|-----------|---------------------|------------|
| 154,32 | 2,166 | 2,318 | 0,850 |
| 1359,76 | 2,359 | 16,714 | 0,850 |
| 239,66 | 2,183 | 3,541 | 0,850 |
| 2042,64 | 2,452 | 22,723 | 0,850 |
| 7873,92 | 2,939 | 48,635 | 0,850 |

Table 13: Data after first recycling

| m_t | | 30,733 | | kg/s | |
|-----------|----------------|----------------|----------------|----------------|----------------|
| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
| 0,00 | 31,82 | 46,21 | 55,54 | 74,72 | 100,84 |
| 2,00 | 24,23 | 35,51 | 41,58 | 57,37 | 80,42 |
| 4,00 | 18,71 | 27,52 | 31,39 | 44,28 | 64,43 |
| 6,00 | 14,70 | 21,55 | 23,97 | 34,40 | 51,79 |
| 8,00 | 11,78 | 17,10 | 18,56 | 26,94 | 41,79 |
| 10,00 | 9,66 | 13,78 | 14,61 | 21,32 | 33,88 |
| 12,00 | 8,11 | 11,30 | 11,74 | 17,07 | 27,63 |
| 14,00 | 6,99 | 9,45 | 9,64 | 13,86 | 22,69 |
| 16,00 | 6,18 | 8,07 | 8,11 | 11,44 | 18,78 |
| 18,00 | 5,58 | 7,03 | 7,00 | 9,62 | 15,68 |
| 20,00 | 5,15 | 6,26 | 6,19 | 8,24 | 13,24 |

| m_t | | 30,733 | | kg/s | |
|-------|----------|----------|----------|----------|----------|
| L* | Tout1.1* | Tout1.2* | Tout1.3* | Tout1.4* | Tout1.5* |
| [km] | [C] | [C] | [C] | [C] | [C] |
| 0,00 | 31,82 | 46,21 | 55,54 | 74,72 | 100,84 |
| 2,00 | 7,33 | 10,00 | 10,27 | 14,83 | 24,21 |
| 4,00 | 4,40 | 4,85 | 4,76 | 5,66 | 8,23 |
| 6,00 | 4,05 | 4,12 | 4,09 | 4,25 | 4,88 |
| 8,00 | 4,01 | 4,02 | 4,01 | 4,04 | 4,18 |
| 10,00 | 4,00 | 4,00 | 4,00 | 4,01 | 4,04 |
| 12,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 14,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 16,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 18,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

Table 14: Outlet temperature main pipe after first recycling

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | WHR [-] | | | |
|---------------|---------------|---------------|---------------|---------------|------------|--|--|--|
| 29,29 | 0,32 | 0,75 | 0,38 | 30,73 | 0,85 | | | |
| 27,66 | 2,82 | 0,71 | 3,32 | 34,49 | 0,85 | | | |
| 29,17 | 0,50 | 0,76 | 0,58 | 31,00 | 0,85 | | | |
| 26,63 | 4,23 | 0,82 | 4,98 | 36,67 | 0,85 | | | |
| 18,25 | 16,32 | 1,30 | 19,20 | 55,08 | 0,85 | | | |

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | x fr g | x fr w | x fr o | x fr h |
|---------------|---------------|---------------|---------------|---------------|-----------|-----------|-----------|-----------|
| 29,29 | 0,48 | 1,13 | 0,56 | 31,46 | 0,93 | 0,02 | 0,04 | 0,02 |
| 27,66 | 4,23 | 1,06 | 4,97 | 37,91 | 0,73 | 0,11 | 0,03 | 0,13 |
| 29,17 | 0,75 | 1,13 | 0,88 | 31,92 | 0,91 | 0,02 | 0,04 | 0,03 |
| 26,63 | 6,35 | 1,22 | 7,47 | 41,68 | 0,64 | 0,15 | 0,03 | 0,18 |
| 18,25 | 24,49 | 1,95 | 28,81 | 73,49 | 0,25 | 0,33 | 0,03 | 0,39 |

| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] |
|------------------------|-----------|---------------------|
| 231,48 | 2,18 | 3,38 |
| 2039,64 | 2,44 | 22,07 |
| 359,50 | 2,20 | 5,11 |
| 3063,97 | 2,55 | 28,82 |
| 11810,87 | 3,04 | 52,89 |

Table 15: Second recycling data

| m_t | | 31,46 kg/s | | | |
|-----------|----------------|----------------|----------------|----------------|----------------|
| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
| 0,00 | 32,88 | 51,57 | 57,11 | 80,82 | 104,89 |
| 2,00 | 25,19 | 40,07 | 43,11 | 62,98 | 84,82 |
| 4,00 | 19,55 | 31,36 | 32,80 | 49,28 | 68,74 |
| 6,00 | 15,41 | 24,75 | 25,21 | 38,76 | 55,85 |
| 8,00 | 12,37 | 19,74 | 19,62 | 30,69 | 45,54 |
| 10,00 | 10,14 | 15,94 | 15,50 | 24,49 | 37,27 |
| 12,00 | 8,51 | 13,05 | 12,47 | 19,73 | 30,65 |
| 14,00 | 7,31 | 10,87 | 10,23 | 16,08 | 25,35 |
| 16,00 | 6,43 | 9,21 | 8,59 | 13,27 | 21,10 |
| 18,00 | 5,78 | 7,95 | 7,38 | 11,12 | 17,70 |
| 20,00 | 5,31 | 7,00 | 6,49 | 9,47 | 14,97 |

| m_t | | 31,46 kg/s | | | |
|-------|----------|------------|----------|----------|----------|
| L* | Tout1.1* | Tout1.2* | Tout1.3* | Tout1.4* | Tout1.5* |
| [km] | [C] | [C] | [C] | [C] | [C] |
| 0,00 | 32,88 | 51,57 | 57,11 | 80,82 | 104,89 |
| 2,00 | 7,67 | 11,53 | 10,90 | 17,19 | 26,99 |
| 4,00 | 4,47 | 5,19 | 4,90 | 6,27 | 9,24 |
| 6,00 | 4,06 | 4,19 | 4,12 | 4,39 | 5,19 |
| 8,00 | 4,01 | 4,03 | 4,02 | 4,07 | 4,27 |
| 10,00 | 4,00 | 4,00 | 4,00 | 4,01 | 4,06 |
| 12,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 14,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 16,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 18,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

Table 16: Outlet temperature main pipe after second recycling

| NTNU assumptions | | |
|------------------------|--------|--------------------|
| $L_{\text{separator}}$ | 6 | m |
| $d_{\text{separator}}$ | 2 | m |
| g | 9.81 | m/s ² |
| d_{droplet} | 200 | μm |
| k_s | 0.137 | NORSOK |
| F_s | 0.225 | NORSOK |
| U_{HXU} | 250 | W/m ² K |
| d_{tube} | 0.0254 | m |
| $T_{\text{out,HXU}}$ | 10 | °C |
| $T_{\text{in,RFU}}$ | 10 | °C |
| $T_{\text{out,RFU}}$ | 4 | °C |

Table 17: Assumption made for the calculation of NTNU

| Gas phase | | | | | Liquid phase | | Liquid phase | |
|---------------|---------------|-------------|--------------|----------|--------------|-------------|---------------|---------------|
| q_g [m3/s] | q_g [m3/d] | A_g [m2] | v_b [m/s] | t [s] | q_l m3/s | q_l m3/d | q_l,t m3/s | q_l,t m3/d |
| 0,39 | 33630,57 | 1,571 | 0,050 | 20,121 | 0,47 | 40470,35 | 0,46862 | 40488,50 |
| 0,39 | 33630,57 | 1,571 | 0,050 | 20,121 | 0,47 | 40470,35 | 0,47026 | 40630,32 |
| 0,23 | 20016,50 | 1,571 | 0,039 | 25,835 | 0,36 | 31519,09 | 0,36513 | 31547,29 |
| 0,27 | 23177,97 | 1,571 | 0,052 | 19,268 | 0,49 | 42261,80 | 0,49192 | 42502,12 |
| 0,25 | 21786,52 | 1,571 | 0,046 | 21,808 | 0,43 | 37339,89 | 0,44290 | 38266,25 |

Table 18: Horizontal separator calculation

| m_w [kg/s] | m_o [kg/s] | delta_t [C] | q [kJ/s] | q [MW] | A [m2] |
|---------------|---------------|----------------|-------------|-----------|-----------|
| 0,21 | 0,50 | 45 | 87,81 | 0,09 | 16,70 |
| 1,88 | 0,47 | 45 | 398,53 | 0,40 | 75,81 |
| 0,33 | 0,50 | 90 | 229,44 | 0,23 | 28,27 |
| 2,82 | 0,54 | 90 | 1175,31 | 1,18 | 144,83 |
| 10,88 | 0,87 | 90 | 4274,30 | 4,27 | 526,71 |

| Total length [m] | Total pipe [-] |
|---------------------|-------------------|
| 209,34 | 2,99 |
| 950,06 | 13,57 |
| 354,31 | 5,06 |
| 1814,98 | 25,93 |
| 6600,62 | 94,29 |

Table 19: The tube heatexchanger calculation

| mass_rate water [kg/s] | mass_rate oil [kg/s] | delta_t [C] | q [kJ/s] | q [MW] | Pcom [kJ/s] | Pcom [MW] |
|---------------------------|-------------------------|----------------|-------------|-----------|----------------|--------------|
| 0,21 | 0,40 | 6 | 9,98 | 9,98E-03 | 2,00 | 2,00E-03 |
| 1,89 | 0,38 | 6 | 51,64 | 5,16E-02 | 10,33 | 1,03E-02 |
| 0,33 | 0,45 | 6 | 13,48 | 1,35E-02 | 2,70 | 2,70E-03 |
| 2,83 | 0,48 | 6 | 76,53 | 7,65E-02 | 15,31 | 1,53E-02 |
| 10,90 | 0,82 | 6 | 282,84 | 2,83E-01 | 56,57 | 5,66E-02 |

Table 20: The refrigeration calculation

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | x fr g | x fr w | x fr o | x fr hydrate |
|------------------------|---------------|---------------------|-------------------|-----------|-----------|-----------|-----------------|
| 29,29 | 0,21 | 0,50 | 0,25 | 0,978 | 0,007 | 0,017 | 0,008 |
| 27,65 | 1,88 | 0,47 | 2,21 | 0,922 | 0,083 | 0,016 | 0,074 |
| 29,17 | 0,33 | 0,50 | 0,39 | 0,972 | 0,011 | 0,017 | 0,013 |
| 26,63 | 2,82 | 0,54 | 3,32 | 0,888 | 0,094 | 0,018 | 0,111 |
| 18,25 | 10,88 | 0,87 | 12,80 | 0,608 | 0,363 | 0,029 | 0,427 |
| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] | Pressure [kPa] | WHR | | | |
| 102,88 | 2,18 | 1,57 | 15000,00 | 0,85 | | | |
| 906,50 | 2,47 | 12,25 | 15000,00 | 0,85 | | | |
| 159,78 | 2,20 | 2,42 | 37500,00 | 0,85 | | | |
| 1361,76 | 2,83 | 17,23 | 37500,00 | 0,85 | | | |
| 5249,28 | 4,04 | 43,33 | 37500,00 | 0,85 | | | |

Table 21: The reactor calculation

Figures

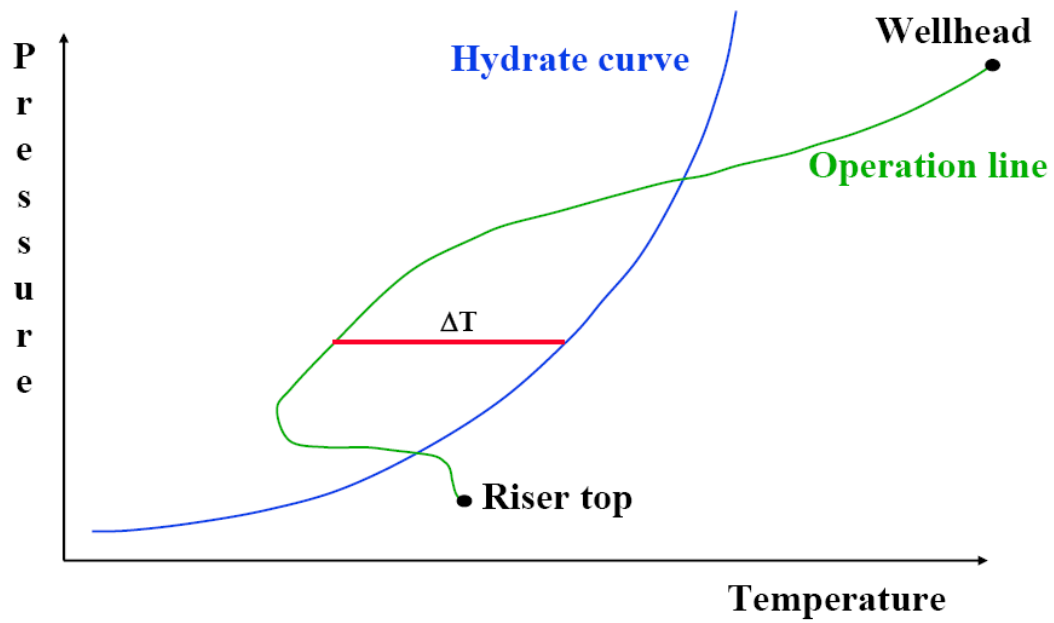


Figure 1: Pressure-temperature course during transport. Source:[5]

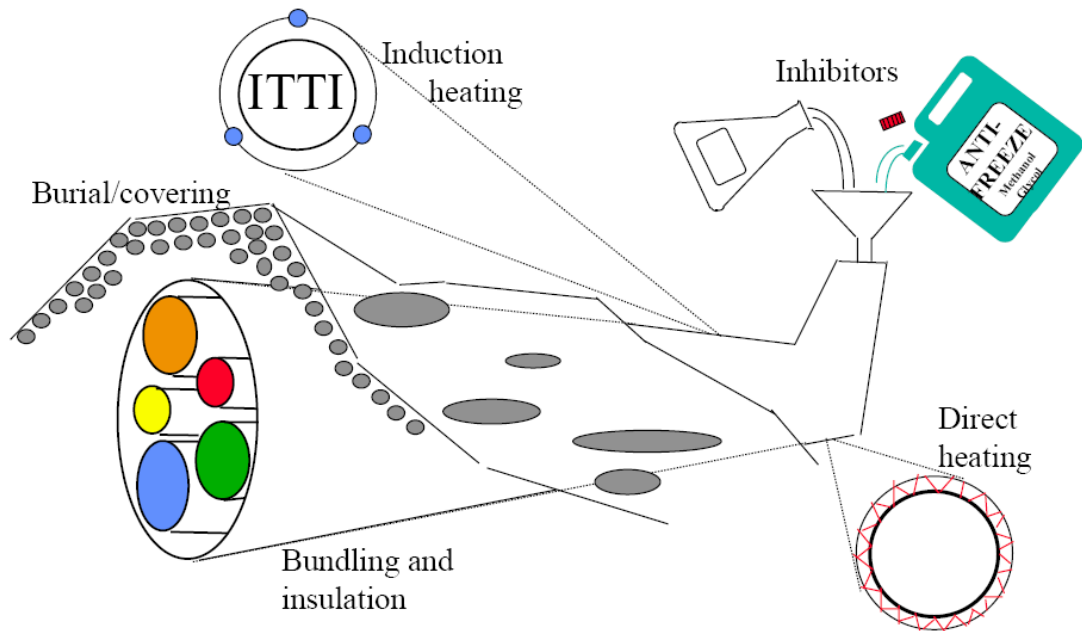


Figure 2: Flowlines. Source: [5]

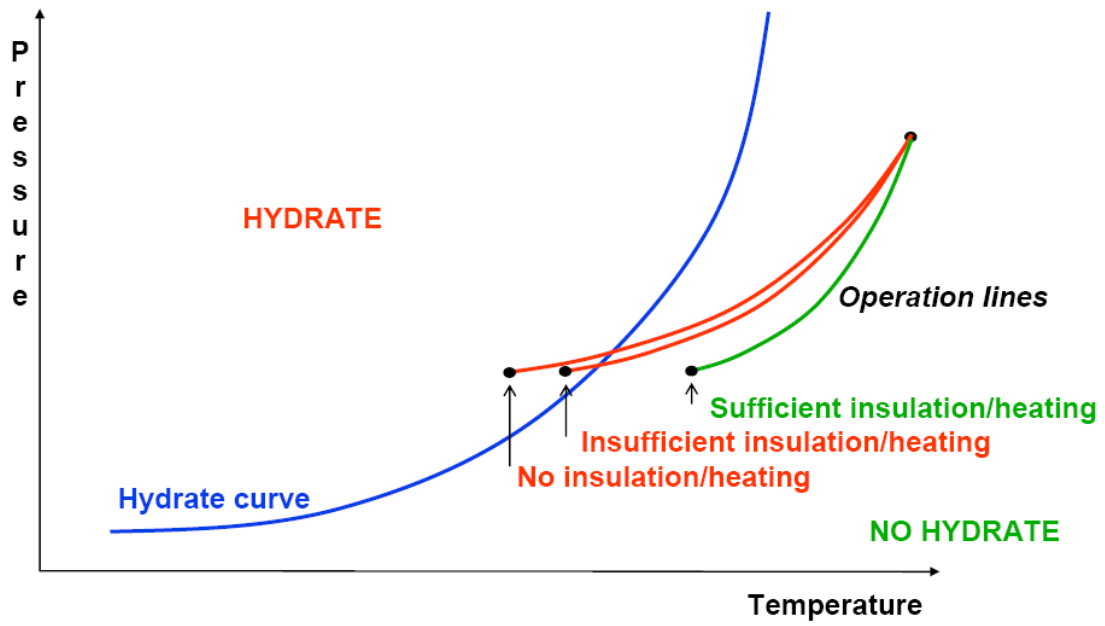


Figure 3: Heating and insulation. Source: [5]

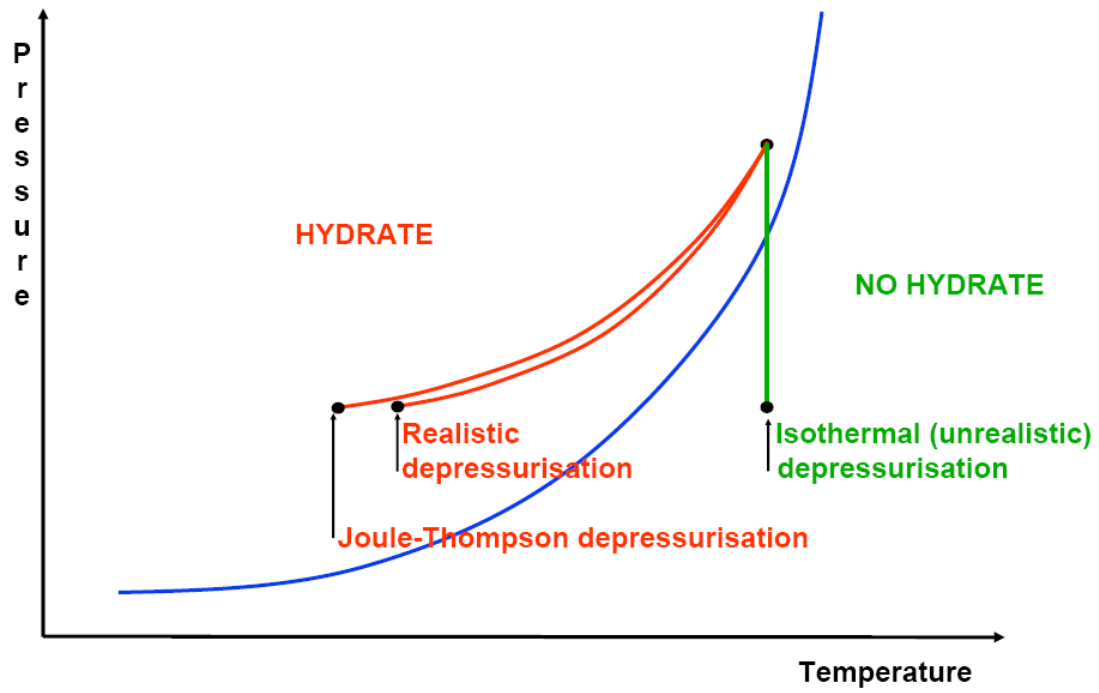


Figure 4: Depressurization. Source: [5]

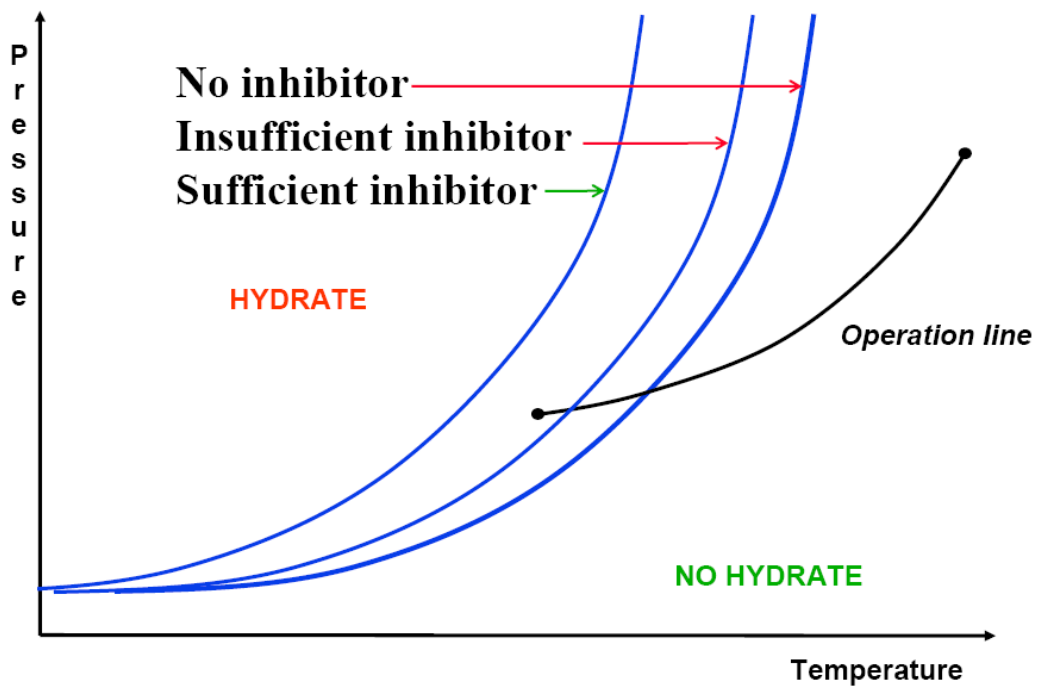


Figure 5: Inhibitor injection. Source: [5]

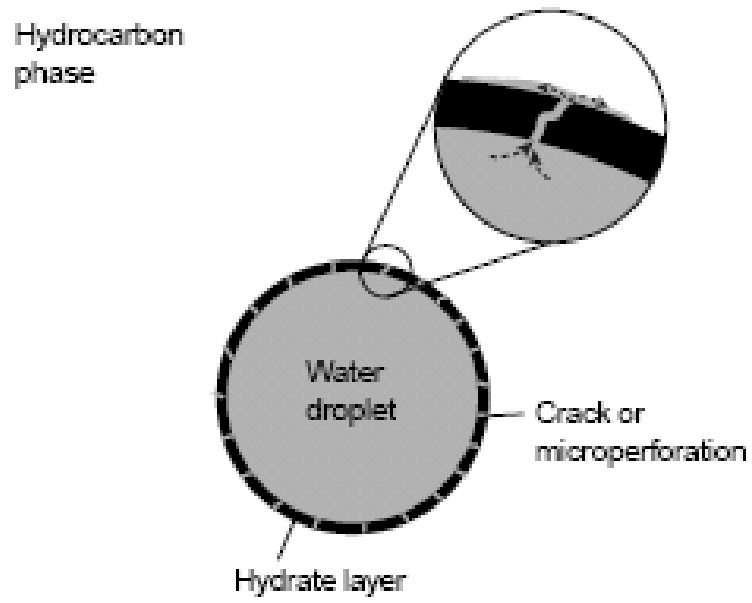


Figure 6: Growth of hydrate layer on a droplet surrounded by hydrocarbons.
Source: [6]

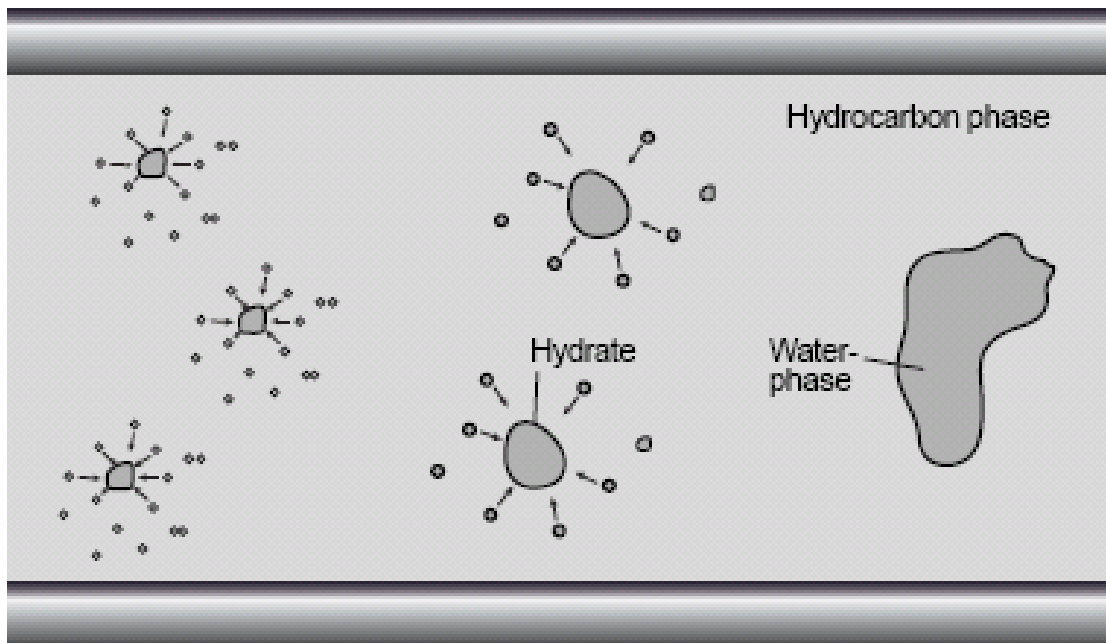


Figure 7: Agglomeration of water droplets after hydrate initiation. Source: [6]

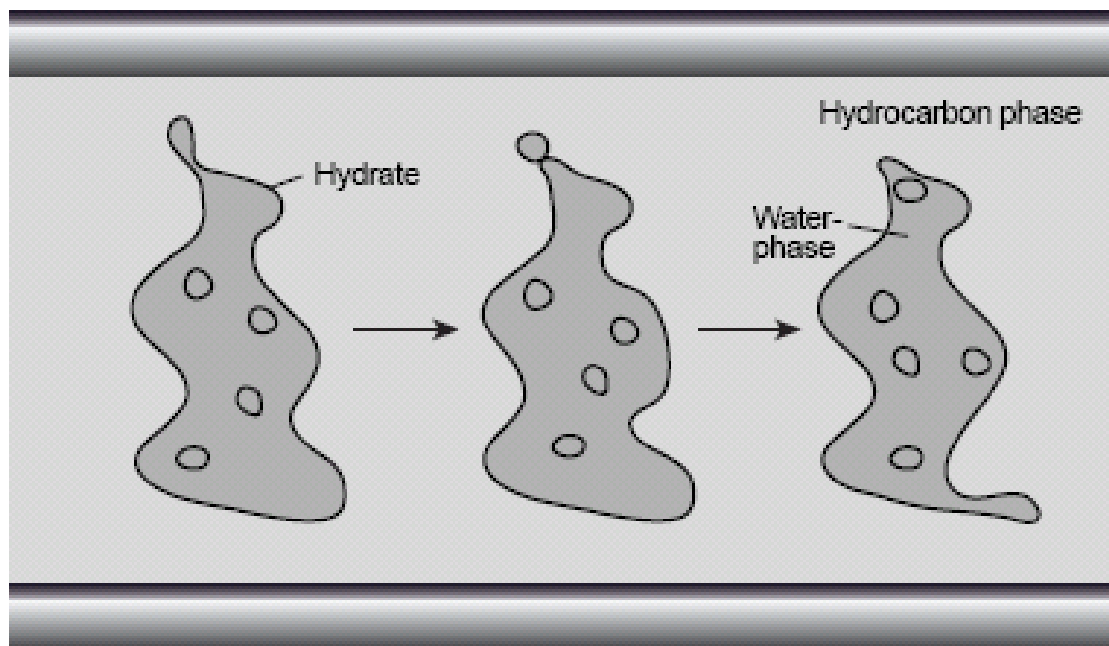


Figure 8: Hydrate covered water droplet inside larger water lumps. The start of slush like flow behaviour. Source: [6]

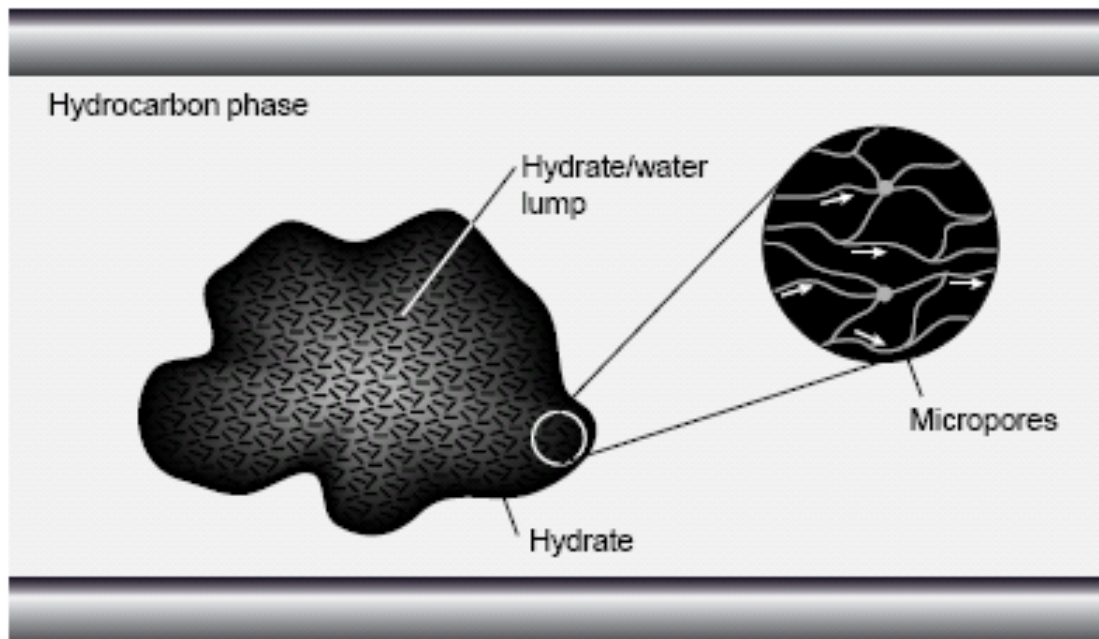


Figure 9: Ongoing conversion of water to hydrate by water transport to surface of large lumps. Source: [6]

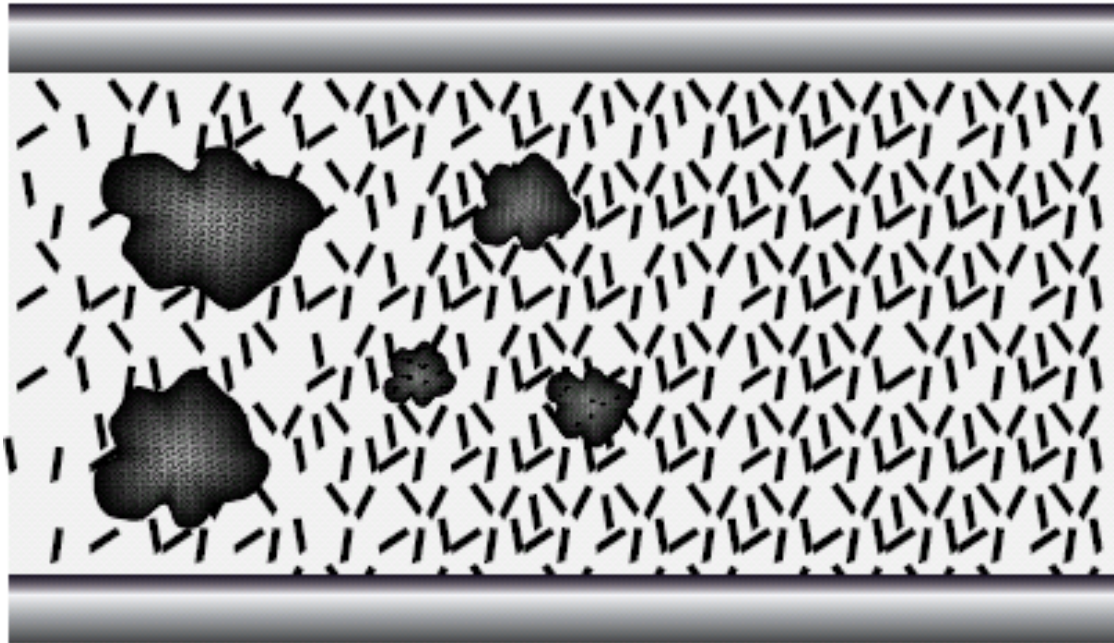


Figure 10: Break-up of large hydrate lumps. Source: [6]

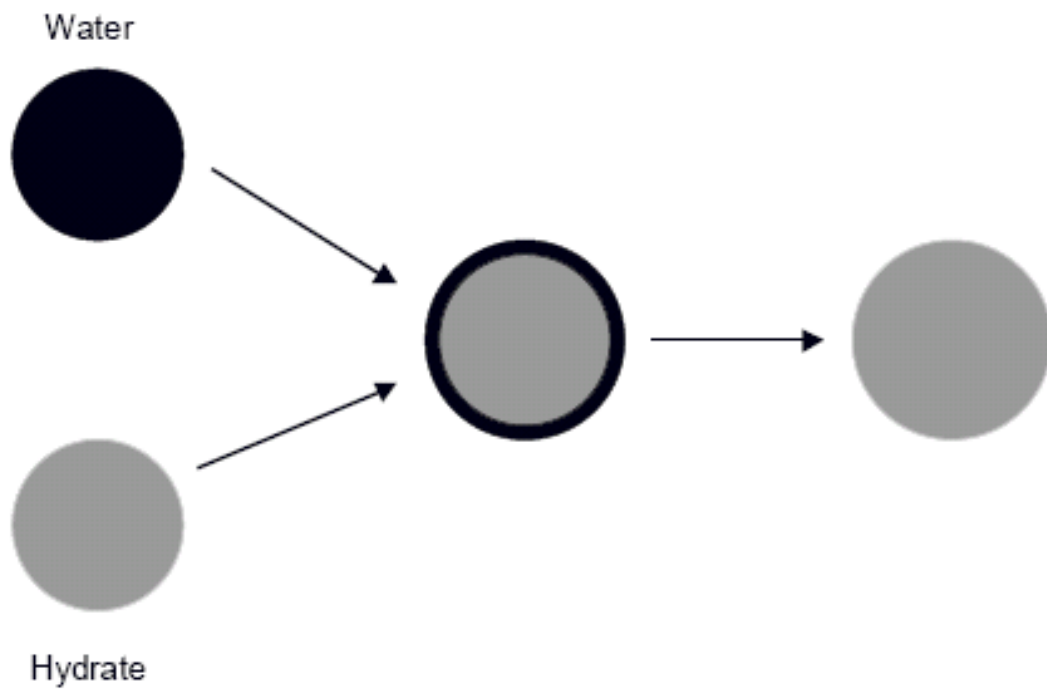


Figure 11: A water droplet a dry hydrate particle. After wetting, the water layer is converted to hydrates from the existing hydrate surface and outwards. Source: [6]

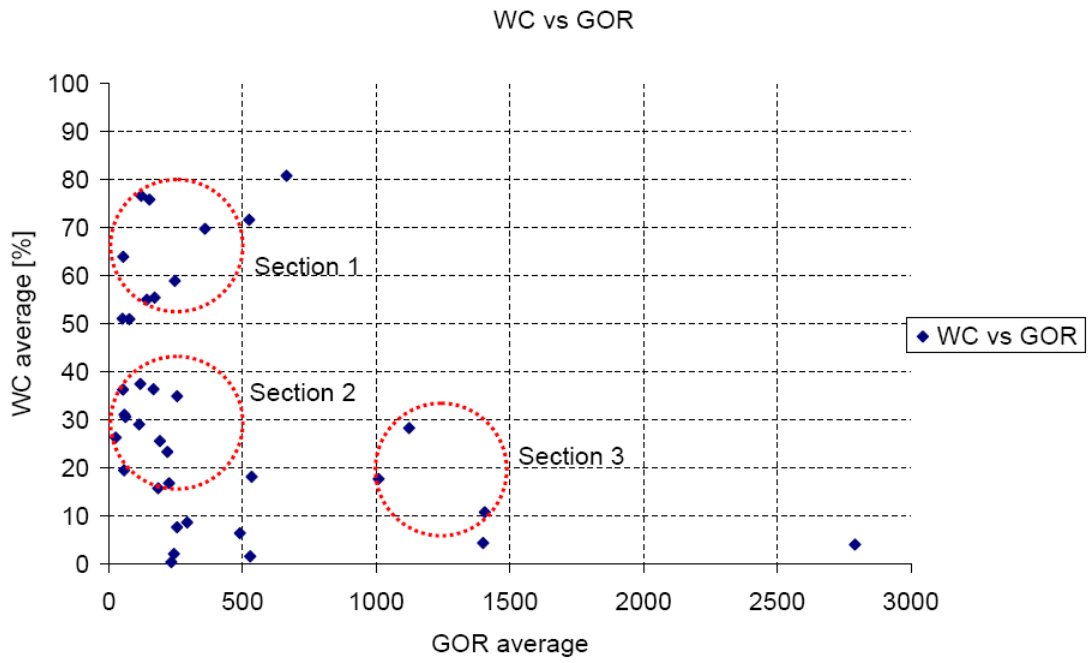


Figure 12: WC vs GOR

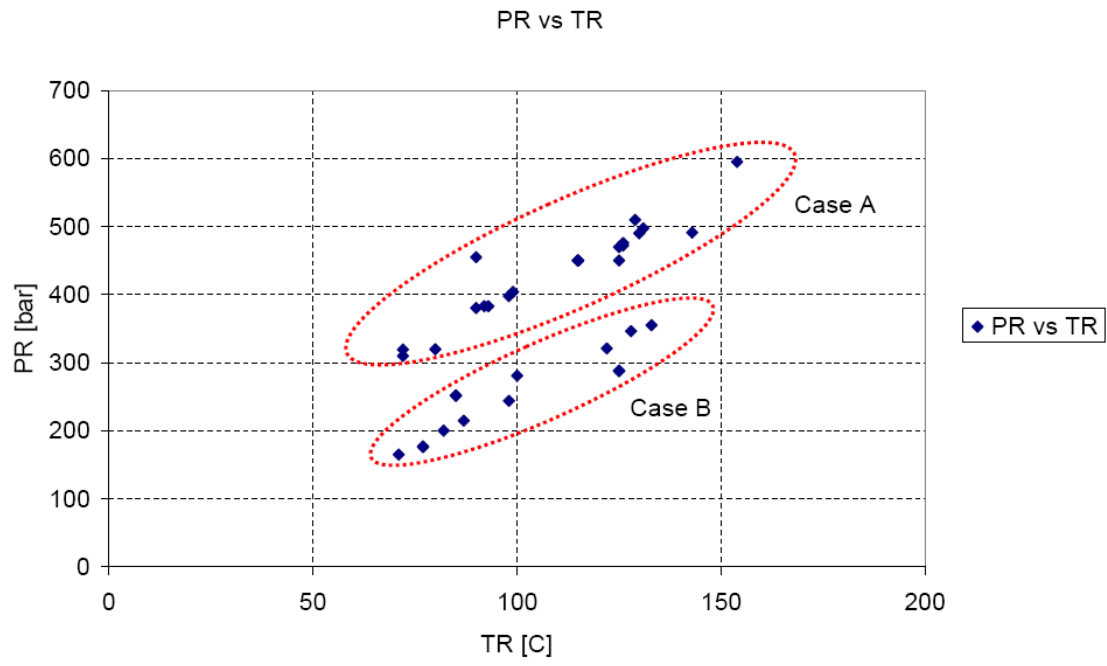


Figure 13: PR vs TR

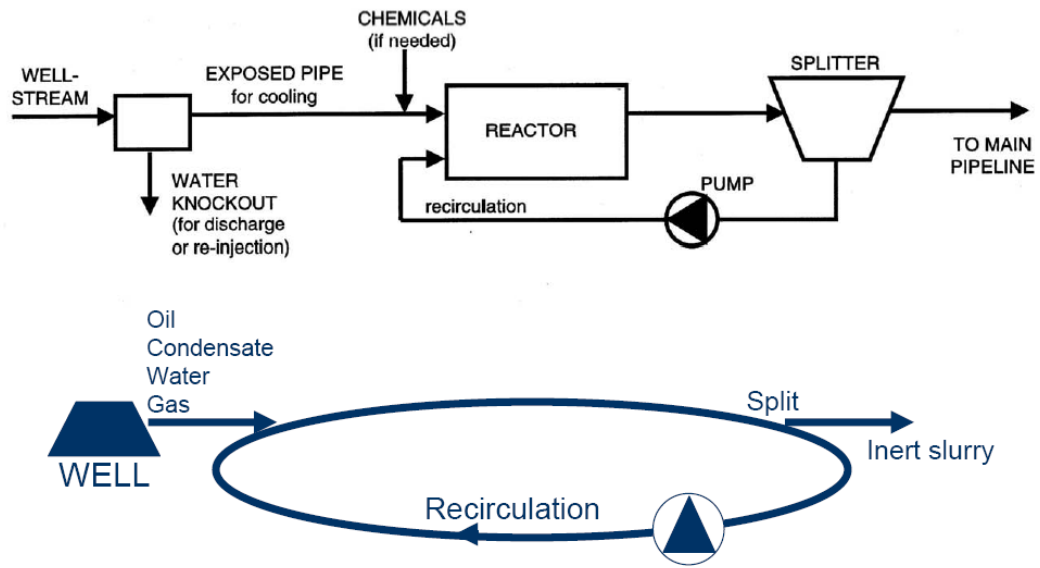


Figure 14: A schematic description of the hydrate reactor, SINTEF. Source: [6]

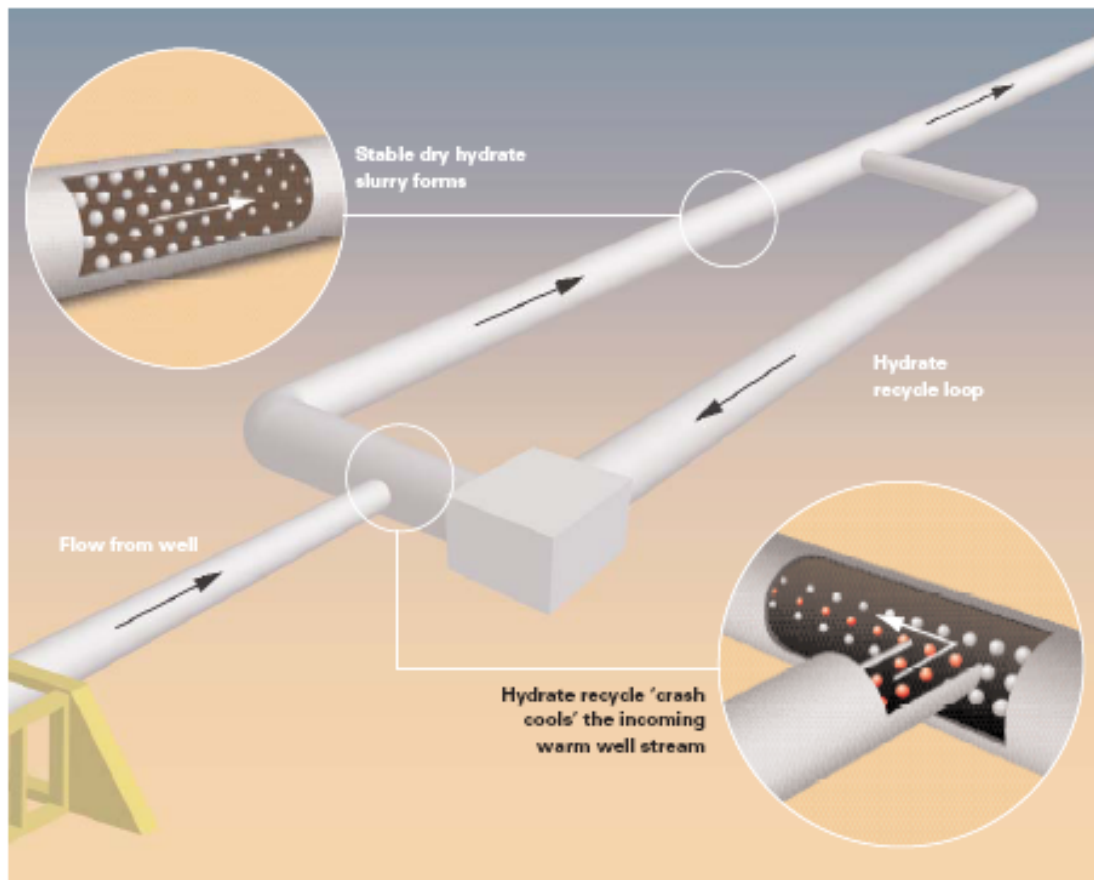


Figure 15: A schematic description of the mixing in the SINTEF concept. Source: [3]

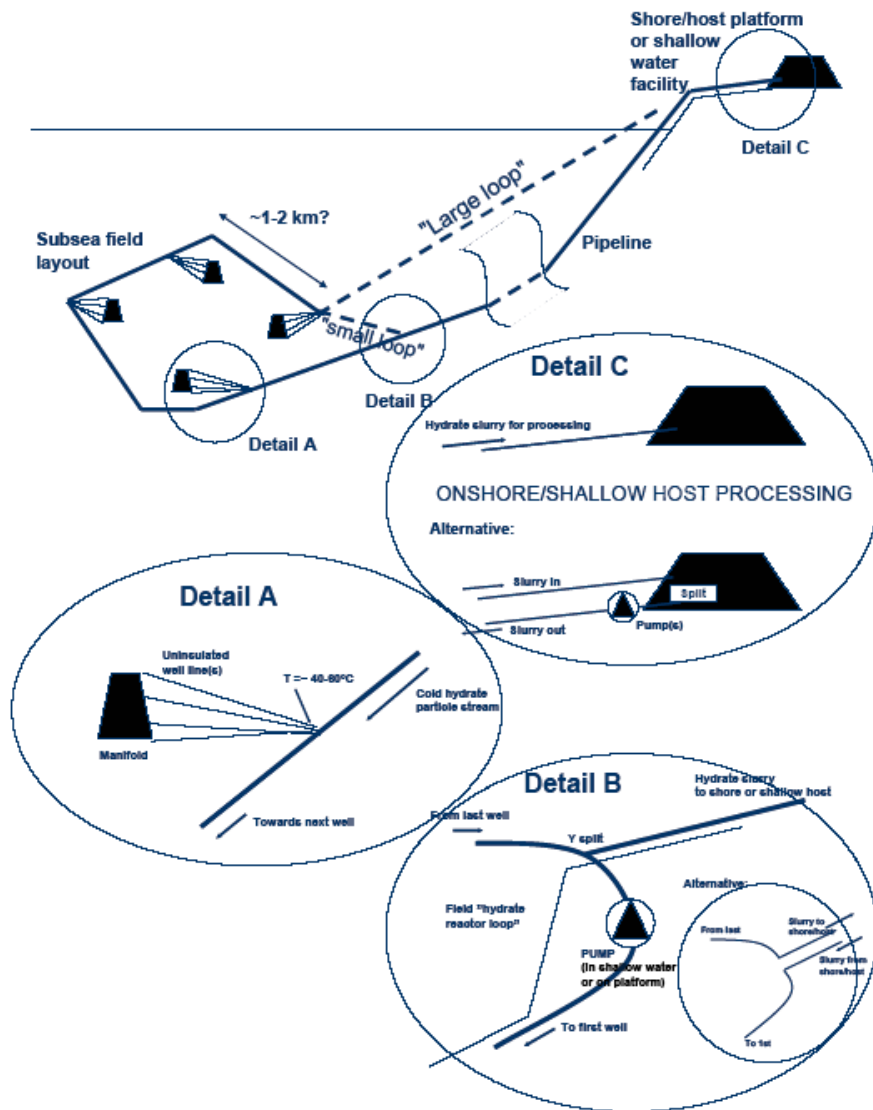


Figure 16: Field implementation of the SINTEF concept. Source: [6]

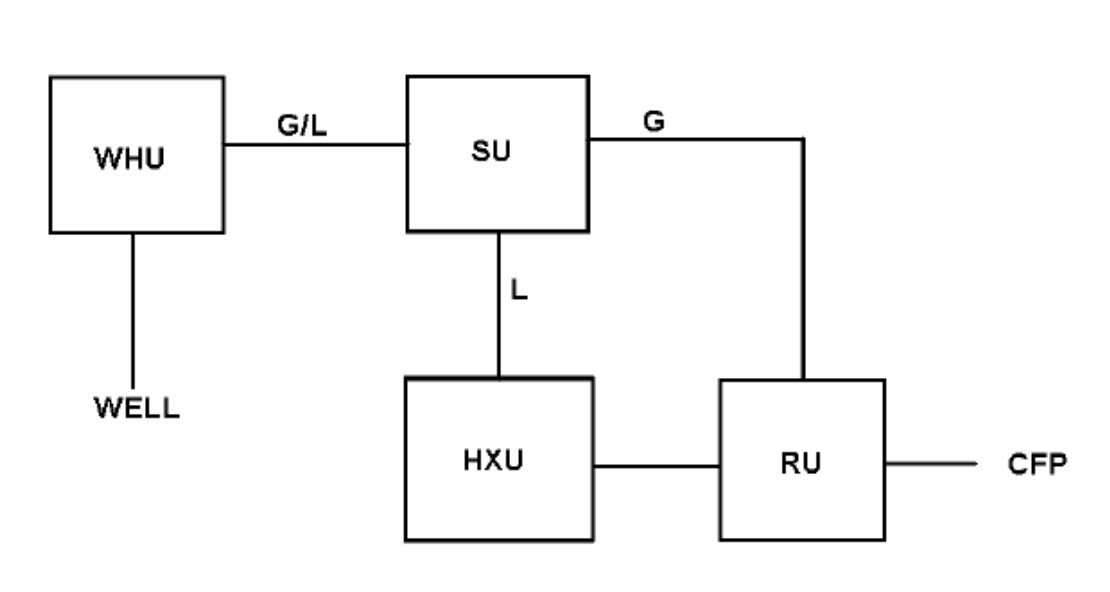


Figure 17: A schematic description on the field implementation of NTNU concept.
Source: [1]

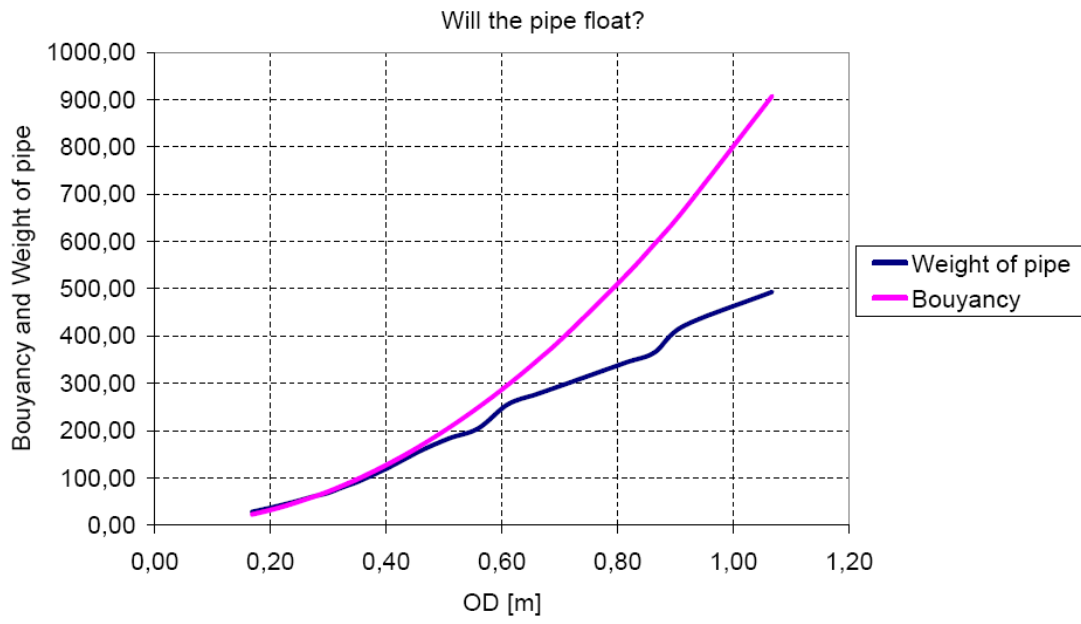


Figure 18: Will the pipe float?

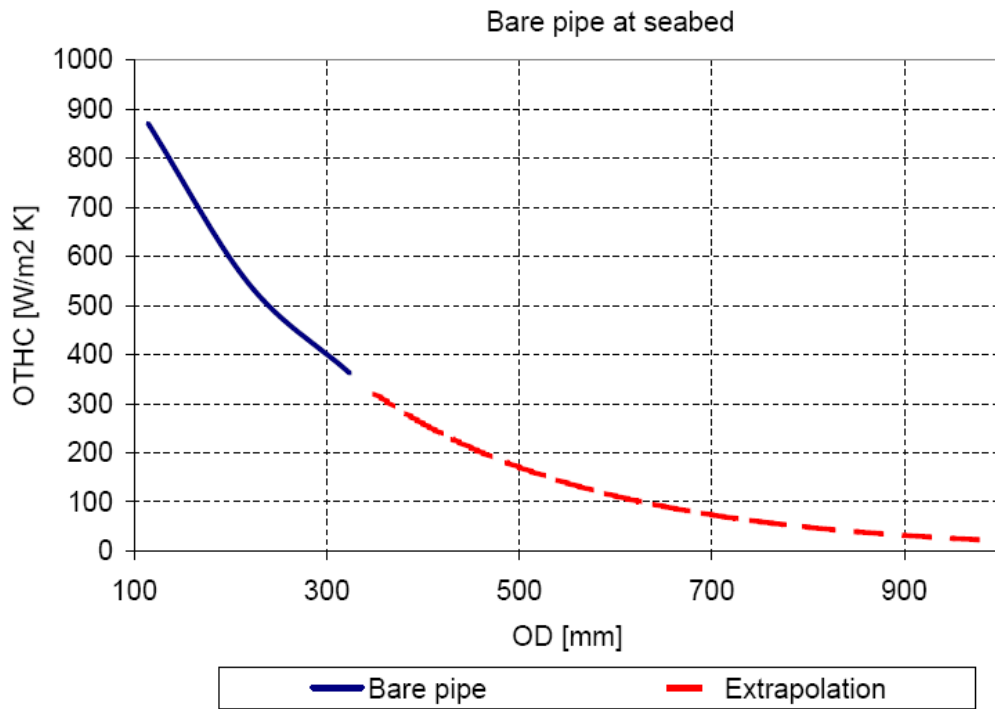
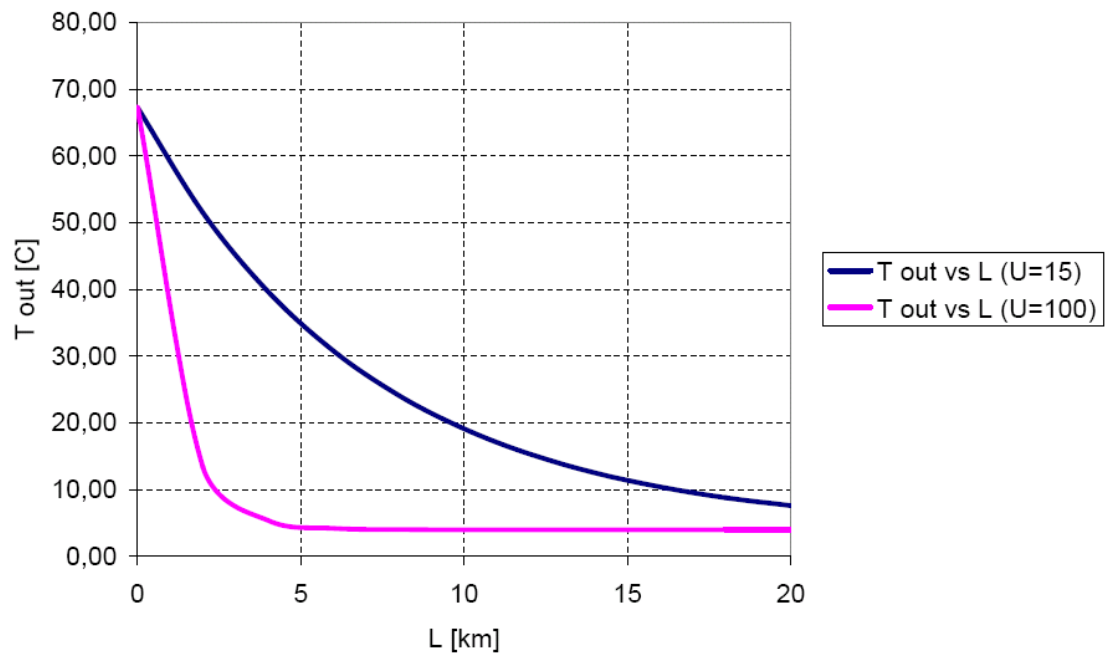
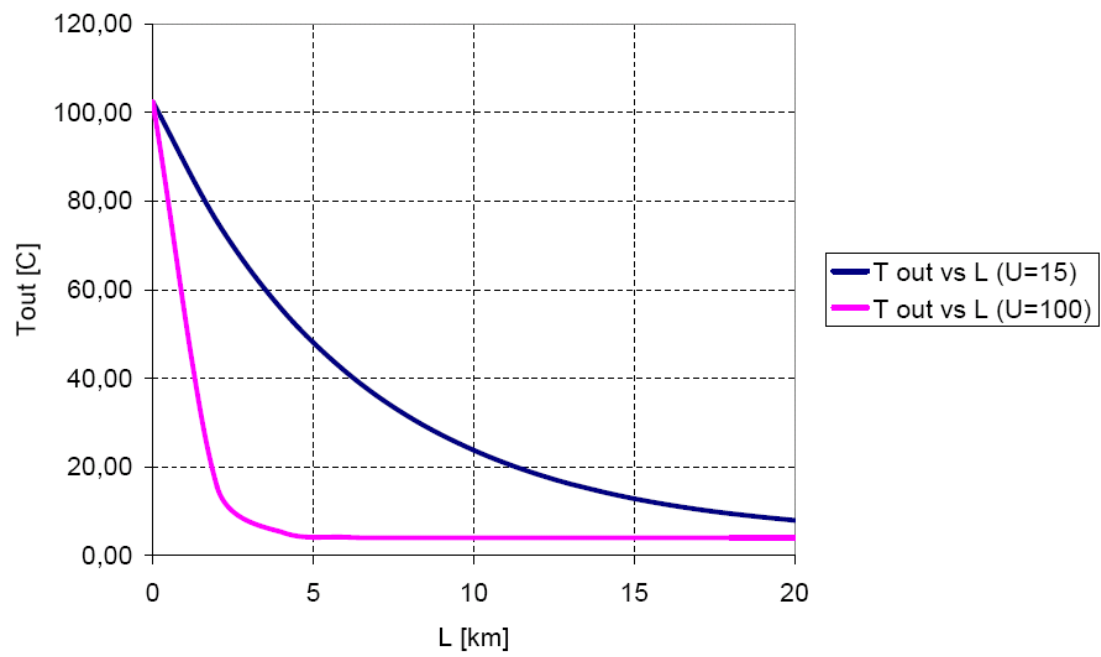
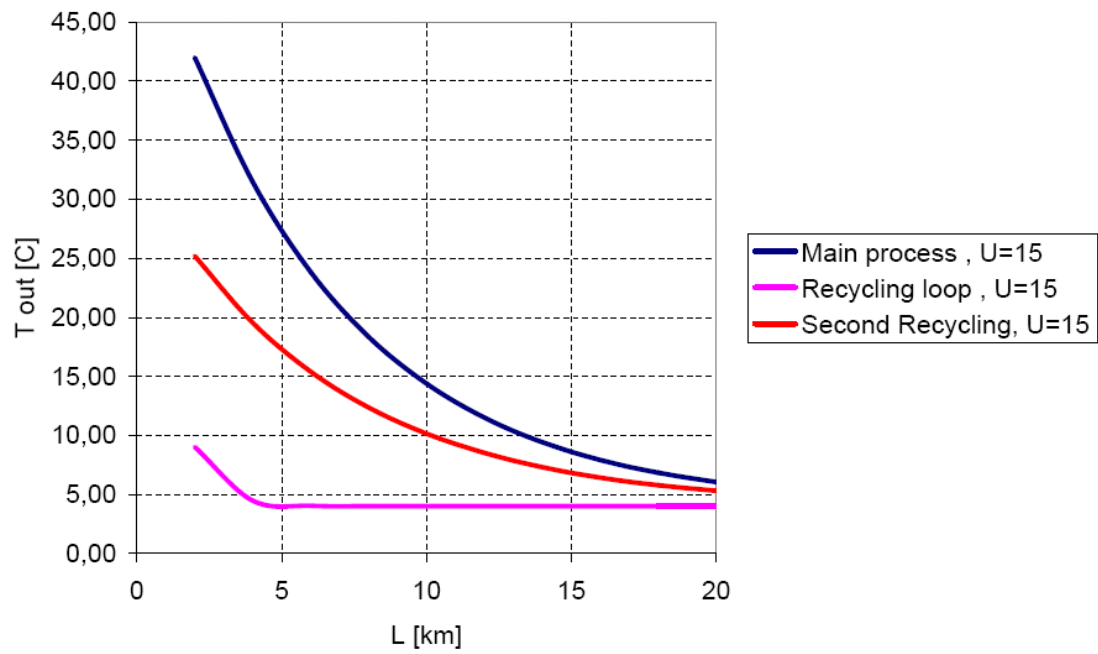
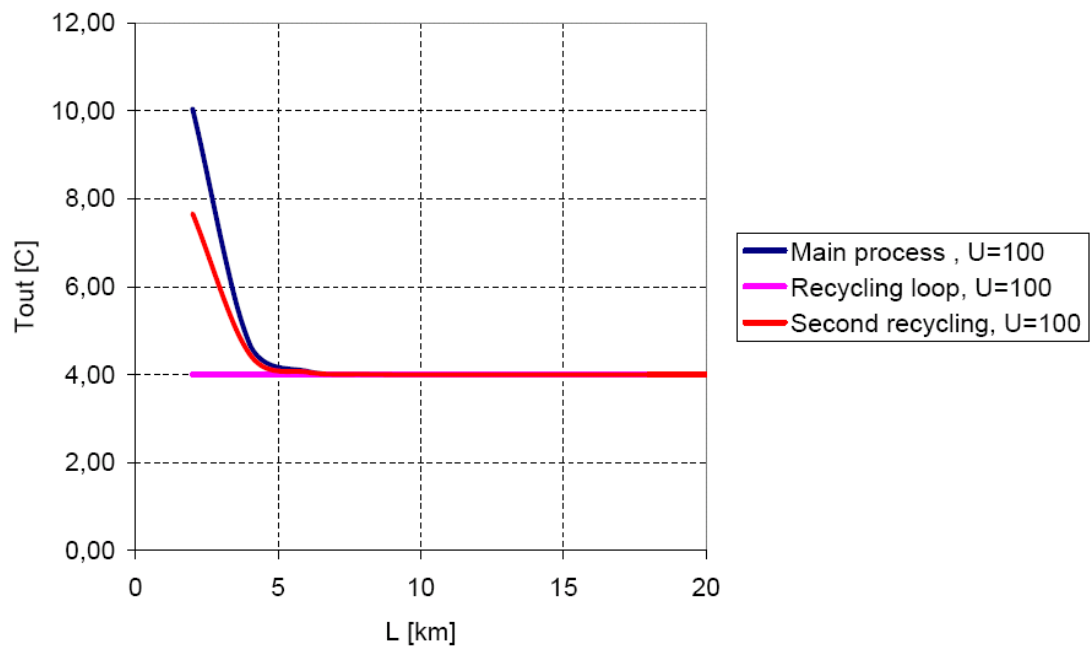


Figure 19: OTHC for bare pipe at seabed

Figure 20: $T_{out}(55\text{ C})$ vs L

Figure 21: $T_{out}(100\text{ C})$ vs L

Figure 22: Main vs Recycling for $U=15$

Figure 23: Main vs Recycling for $U=100$

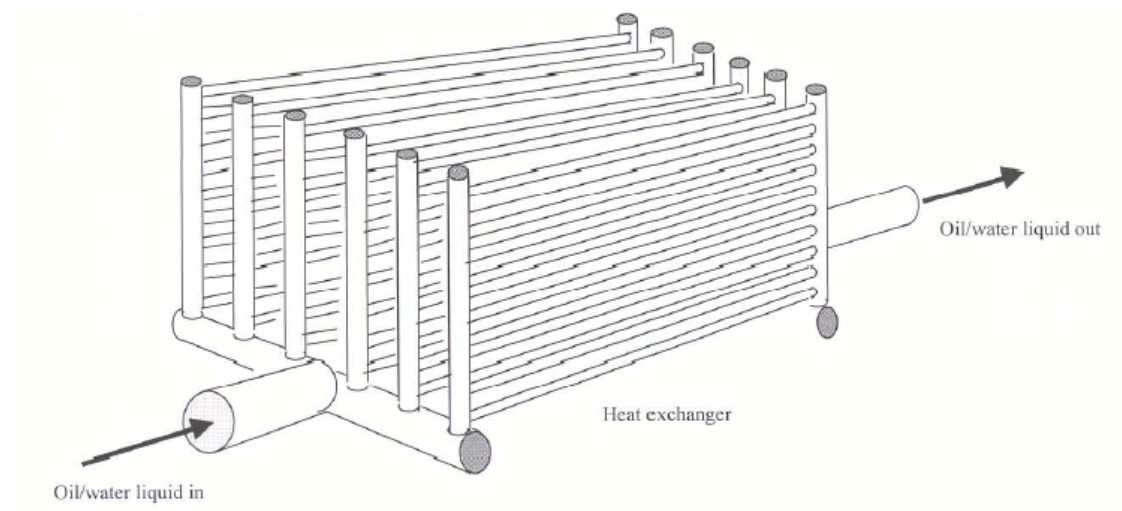


Figure 24: The tube heatexchanger unit in NTNU concept. Source: [13]

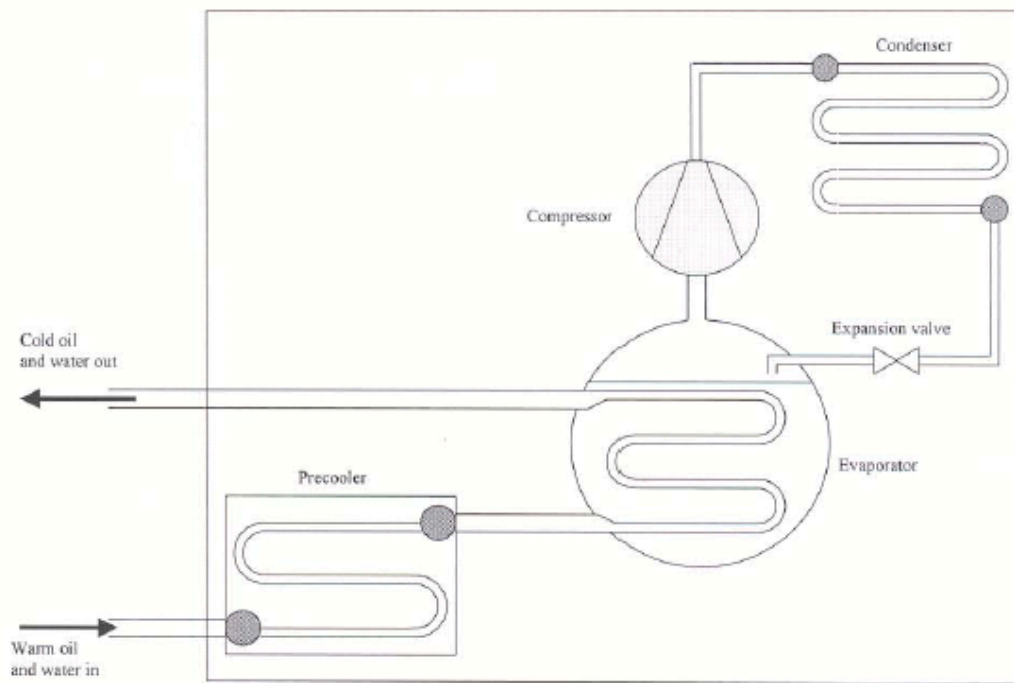


Figure 25: The refrigeration unit in NTNU concept. Source: [13]

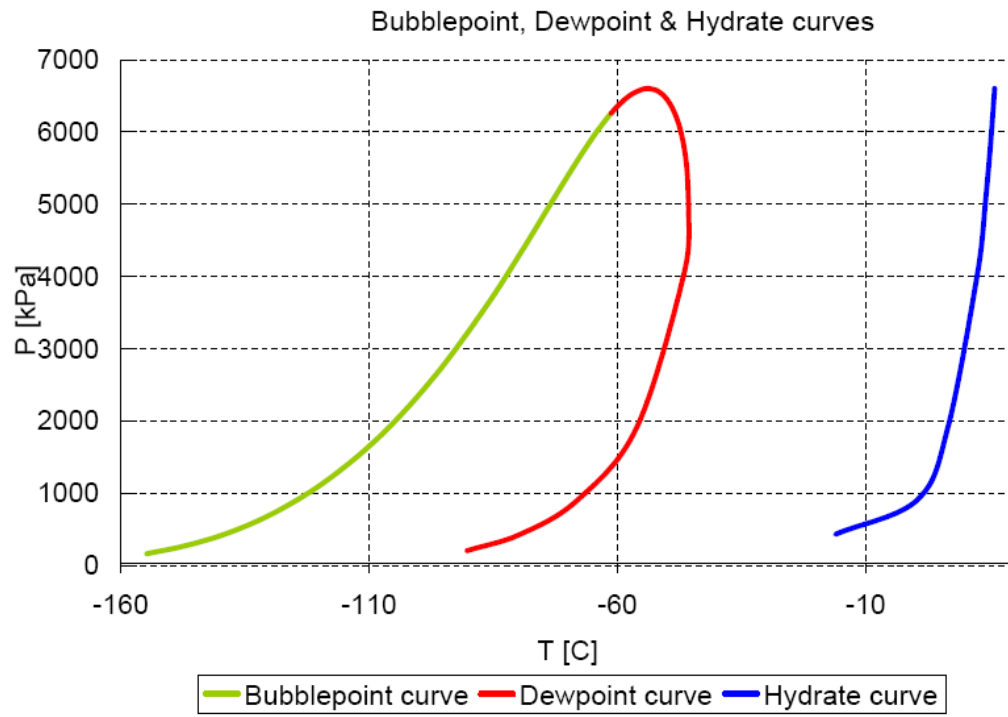


Figure 26: Bubble, Dewpoint and Hydrate Curves

A Calculation in Excel

The calculation on the two concepts have been done in Excel. The main calculation have been on the cooling process of the concepts.

SINTEF calculation

Data:

| Standard conditions | | | Assumption: | |
|----------------------|------------------------|-------------|--|--------------------------|
| T _{sc} | 15 C | 288,15 K | The gas composition is 92% methane, 5% ethane and 3% propane | |
| P _{sc} | 101325 Pa | 1,01325 bar | M _g | 17,59 kg/mol |
| m _t | 30 kg/s | | Y _g | 0,807 |
| ρ _{fresh w} | 1000 kg/m ³ | | ρ _g | 0,7440 kg/m ³ |
| R | 8314 kJ/kmolK | | ρ _w | 1015 kg/m ³ |
| M _{air} | 28,97 kg/kmol | | ρ _o | 805,6 kg/m ³ |
| z _{sc} | 1 | | | |

| GOR [m ³ /Sm ³] | WC [-] | Calculation of y _o y _o |
|---|-----------|---|
| 250 | 0,20 | 0,806 |
| 250 | 0,70 | |
| 1250 | 0,15 | |

Calculation of massrate and production rate at standard condition

| GOR [m ³ /Sm ³] | WC [-] | m _g [kg/s] | m _w [kg/s] | m _o [kg/s] | m _t [kg/s] |
|---|-----------|--------------------------|--------------------------|--------------------------|--------------------------|
| 250 | 0,20 | 4,48 | 6,11 | 19,41 | 30 |
| 250 | 0,70 | 1,66 | 21,15 | 7,19 | 30 |
| 1250 | 0,15 | 14,57 | 2,81 | 12,62 | 30 |

| q _g [m ³ /s] | q _w [m ³ /s] | q _o [m ³ /s] | q _g [m ³ /d] | q _w [m ³ /d] | q _o [m ³ /d] |
|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 6,02 | 6,02E-03 | 2,41E-02 | 5,20E+05 | 520,38 | 2081,52 |
| 2,23 | 2,08E-02 | 8,93E-03 | 1,93E+05 | 1800,09 | 771,47 |
| 19,59 | 2,77E-03 | 1,57E-02 | 1,69E+06 | 238,91 | 1353,82 |

Data:

| Subsea conditions | | |
|-------------------|------------------------|-------------|
| Tsc | 15 C | 288,15 K |
| Psc | 101325 Pa | 1,01325 bar |
| T1 | 55 C | 328,15 K |
| T2 | 100 C | 373,15 K |
| P1 | 1,50E+07 Pa | 150 bar |
| P2 | 3,75E+07 Pa | 375 bar |
| m | 30 kg/s | |
| $\rho_{fresh\ w}$ | 1000 kg/m ³ | |
| R | 8314 kg/kmol | |
| M _{air} | 28,97 kg/mol | |
| z | 0,8 | |

Assumption:

| | |
|----------------|-------|
| V _g | 0,7 |
| V _o | 0,806 |

| Rs [Sm ³ /Sm ³] | WC [-] | B* [-] | Bo [m ³ /Sm ³] | Bg [m ³ /Sm ³] |
|---|-----------|-----------|--|--|
| 250,00 | 0,20 | 1429,81 | 1,71 | 0,00615 |
| 250,00 | 0,70 | 1429,81 | 1,71 | 0,00615 |
| 125,00 | 0,30 | 856,20 | 1,38 | 0,00280 |
| 125,00 | 0,80 | 467,91 | 1,17 | 0,00280 |
| 50,00 | 0,90 | 468,27 | 1,17 | 0,00280 |

| ρ_o kg/m ³ | ρ_g kg/m ³ | ρ_w kg/m ³ | m _g [kg/s] | m _w [kg/s] | m _o [kg/s] | m _t [kg/s] |
|-------------------------------|-------------------------------|-------------------------------|--------------------------|--------------------------|--------------------------|--------------------------|
| 595,33 | 139,37 | 1015 | 29,29 | 0,21 | 0,50 | 30 |
| 595,33 | 139,37 | 1015 | 27,65 | 1,88 | 0,47 | 30 |
| 661,51 | 306,40 | 1015 | 29,17 | 0,33 | 0,50 | 30 |
| 782,55 | 306,40 | 1015 | 26,63 | 2,82 | 0,54 | 30 |
| 727,09 | 306,40 | 1015 | 18,25 | 10,88 | 0,87 | 30 |

| q _g [m ³ /s] | q _w [m ³ /s] | q _o [m ³ /s] | q _g [m ³ /d] | q _w [m ³ /d] | q _o [m ³ /d] |
|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|---------------------------------------|
| 2,10E-01 | 2,10E-04 | 8,41E-04 | 18155,70 | 18,16 | 72,82 |
| 1,98E-01 | 1,85E-03 | 7,94E-04 | 17140,21 | 159,98 | 68,56 |
| 9,52E-02 | 3,26E-04 | 7,61E-04 | 8223,98 | 28,20 | 65,79 |
| 8,69E-02 | 2,78E-03 | 6,95E-04 | 7509,90 | 240,32 | 60,08 |
| 5,96E-02 | 1,07E-02 | 1,19E-03 | 5148,47 | 928,37 | 102,93 |

Data

| | | |
|----------------------------|------------------------|--|
| Cp_w | 4,18 kJ/kg K | |
| Cp_g | 2,141 kJ/kg K | Assuming that the gas composition is 92% methane, 5% ethane and 3% propane |
| Y_o | 0,806 | |
| T1 | 55 C | 328,15 K |
| T2 | 100 C | 373,15 K |
| Tsea | 4 C | 277,15 K |
| m | 30 kg/s | |
| U | 15 W/m ² K | Assuming that the pipe is not digged down in the seabed, but it lays on the seabed |
| U* | 100 W/m ² K | |
| d | 0,225 m | The diameter that SINTEF used in their simulation |
| Hydrate | 410 kJ/kg | |
| Cp_h | 2,7 kJ/kg K | This value can be from 2,075-3,21, so I assume 2,7 should be acceptable |
| Cp_o_1 | 2,118 kJ/kg K | |
| Cp_o_2 | 2,312 kJ/kg K | |
| Hydrate composition | | |
| wt g | 15 % | |
| wt w | 85 % | |

Mass of hydrate

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | x fr g | x fr w | x fr o | x fr h |
|---------------|---------------|---------------|---------------|-----------|-----------|-----------|-----------|
| 29,29 | 0,21 | 0,50 | 0,25 | 0,9762 | 0,0071 | 0,0167 | 0,0084 |
| 27,65 | 1,88 | 0,47 | 2,21 | 0,9216 | 0,0626 | 0,0167 | 0,0737 |
| 29,17 | 0,33 | 0,50 | 0,39 | 0,9722 | 0,0110 | 0,0168 | 0,0130 |
| 26,63 | 2,62 | 0,54 | 3,32 | 0,8878 | 0,0941 | 0,0181 | 0,1107 |
| 18,25 | 10,88 | 0,87 | 12,80 | 0,6084 | 0,3628 | 0,0289 | 0,4268 |

| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] | x fr gas [%] | xfr water [%] |
|----------------|-----------|-------------|-----------------|------------------|
| 102,880 | 2,178 | 1,575 | 97,62 | 0,71 |
| 908,505 | 2,467 | 12,247 | 92,16 | 6,28 |
| 159,776 | 2,201 | 2,419 | 97,22 | 1,10 |
| 1381,763 | 2,635 | 17,227 | 88,78 | 9,41 |
| 5249,277 | 4,038 | 43,334 | 60,84 | 36,28 |
| | | | 15 | 85 |

| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
|-----------|----------------|----------------|----------------|----------------|----------------|
| 0 | 56,57 | 67,25 | 102,42 | 117,23 | 143,33 |
| 2 | 42,00 | 51,49 | 75,39 | 90,59 | 120,96 |
| 4 | 31,47 | 39,66 | 55,78 | 70,21 | 102,18 |
| 6 | 23,88 | 30,78 | 41,58 | 54,63 | 86,41 |
| 8 | 18,35 | 24,11 | 31,25 | 42,72 | 73,18 |
| 10 | 14,37 | 19,10 | 23,78 | 33,61 | 62,07 |
| 12 | 11,50 | 15,34 | 18,34 | 26,64 | 52,74 |
| 14 | 9,42 | 12,51 | 14,40 | 21,31 | 44,91 |
| 16 | 7,92 | 10,39 | 11,54 | 17,24 | 38,34 |
| 18 | 6,83 | 8,80 | 9,47 | 14,12 | 32,83 |
| 20 | 6,05 | 7,60 | 7,97 | 11,74 | 28,20 |

| L* [km] | Tout1.1* [C] | Tout1.2* [C] | Tout1.3* [C] | Tout1.4* [C] | Tout1.5* [C] |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 0 | 56,57 | 67,25 | 102,42 | 117,23 | 143,33 |
| 2 | 10,04 | 13,37 | 15,57 | 22,93 | 47,37 |
| 4 | 4,69 | 5,39 | 5,36 | 7,17 | 17,50 |
| 6 | 4,08 | 4,21 | 4,16 | 4,53 | 8,20 |
| 8 | 4,01 | 4,03 | 4,02 | 4,09 | 5,31 |
| 10 | 4,00 | 4,00 | 4,00 | 4,01 | 4,41 |
| 12 | 4,00 | 4,00 | 4,00 | 4,00 | 4,13 |
| 14 | 4,00 | 4,00 | 4,00 | 4,00 | 4,04 |
| 16 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 18 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

Recycle

Assumption:

The splitter split 50-50, as some dry hydrate particles with gas travel further and "cold" fluid hydrocarbones (water, oil and hydrate) are recycle back to the reactor

The area of recyclepipe is half the area of the major pipeline

The temperatur in to the recycled pipe should be the temperatur out from the major pipeline

The recycle fluid contains no gas, so we do not have any hydrate growth in the recycling pipe

Just looking at 2-20 km for the recycling length

Data:

Cp_w 4,18 kJ/kg K
 Cp_g 2,141 kJ/kg K
 Cp_h 2,7 kJ/kg K This value can be from 2,075-3,21, so I assume 2,7 should be acceptable

d,major pipe 0,225 m
 Area major pipe 0,040 m2
 Area recycled pipe 0,020 m2
 d,recycled pipe 0,159 m
 U 15 W/m2 K
 U* 100 W/m2 K

Hydrate composition

wt g 15 %
 wt w 85 %

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | WHR [-] |
|---------------|---------------|---------------|---------------|------------|
| 29,29 | 0,21 | 0,50 | 0,25 | 0,85 |
| 27,65 | 1,88 | 0,47 | 2,21 | 0,85 |
| 29,17 | 0,33 | 0,50 | 0,39 | 0,85 |
| 28,63 | 2,82 | 0,54 | 3,32 | 0,85 |
| 18,25 | 10,88 | 0,87 | 12,80 | 0,85 |

Recycling fluid 0,50

| m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | x_fr w | x_fr o | x_fr h |
|---------------|---------------|---------------|---------------|-----------|-----------|-----------|
| 0,1066 | 0,2502 | 0,1255 | 0,4823 | 0,2211 | 0,5188 | 0,2601 |
| 0,9397 | 0,2362 | 1,1056 | 2,2814 | 0,4119 | 0,1036 | 0,4846 |
| 0,1656 | 0,2519 | 0,1948 | 0,6123 | 0,2705 | 0,4113 | 0,3182 |
| 1,4116 | 0,2721 | 1,6807 | 3,3443 | 0,4221 | 0,0814 | 0,4966 |
| 5,4413 | 0,4331 | 6,4016 | 12,2760 | 0,4432 | 0,0353 | 0,5215 |

Cp_w 4,18 kJ/kg K
 Cp_h 2,7 kJ/kg K
 d,recycled pipe 0,159 m
 U 15 W/m² K
 Y_o 0,806
 Tsea 4 C

| L [km] | Tin [C] | Cp_o [kJ/kg K] | m_t = 0,4326 kg/s | |
|-----------|------------|-------------------|---------------------|-------------|
| | | | Cp mix [kJ/kg K] | Tout [C] |
| 2 | 42,00 | 2,08 | 2,70 | 4,00 |
| 4 | 31,47 | 2,02 | 2,87 | 4,00 |
| 6 | 23,86 | 1,98 | 2,86 | 4,00 |
| 8 | 18,35 | 1,96 | 2,84 | 4,00 |
| 10 | 14,37 | 1,94 | 2,83 | 4,00 |
| 12 | 11,50 | 1,93 | 2,83 | 4,00 |
| 14 | 9,42 | 1,92 | 2,82 | 4,00 |
| 16 | 7,92 | 1,91 | 2,82 | 4,00 |
| 18 | 6,83 | 1,91 | 2,82 | 4,00 |
| 20 | 6,05 | 1,91 | 2,82 | 4,00 |

| m_t = 2,2403 kg/s | | m_t = 0,5846 kg/s | | m_t = 3,3201 kg/s | | m_t = 12,2721 kg/s | |
|---------------------|-------------|---------------------|-------------|---------------------|-------------|---------------------|-------------|
| Cp mix [kJ/kg K] | Tout [C] | Cp mix [kJ/kg K] | Tout [C] | Cp mix [kJ/kg K] | Tout [C] | Cp mix [kJ/kg K] | Tout [C] |
| 3,24 | 9,01 | 2,84 | 4,01 | 3,27 | 13,86 | 3,33 | 30,34 |
| 3,24 | 4,47 | 2,82 | 4,00 | 3,27 | 5,77 | 3,33 | 17,20 |
| 3,24 | 4,04 | 2,81 | 4,00 | 3,27 | 4,32 | 3,33 | 10,81 |
| 3,23 | 4,00 | 2,80 | 4,00 | 3,26 | 4,06 | 3,33 | 7,31 |
| 3,23 | 4,00 | 2,79 | 4,00 | 3,26 | 4,01 | 3,33 | 5,66 |
| 3,23 | 4,00 | 2,78 | 4,00 | 3,26 | 4,00 | 3,33 | 4,83 |
| 3,23 | 4,00 | 2,78 | 4,00 | 3,26 | 4,00 | 3,33 | 4,42 |
| 3,23 | 4,00 | 2,78 | 4,00 | 3,26 | 4,00 | 3,33 | 4,21 |
| 3,23 | 4,00 | 2,78 | 4,00 | 3,26 | 4,00 | 3,33 | 4,10 |
| 3,23 | 4,00 | 2,77 | 4,00 | 3,26 | 4,00 | 3,33 | 4,05 |

Assumption

After the recycling the temperature in process contain 50 % of the recycling temperature and 50% of the wellhead temperature
 The massrate of oil, water and hydrate would increase by 50 % after recycling

Data

| | | |
|---------|---------------|----------|
| Cp_w | 4,18 kJ/kg K | |
| Cp_g | 2,141 kJ/kg K | |
| Y_o | 0,8055 | |
| Tw1 | 55 C | 328,15 K |
| Tw2 | 100 C | 373,15 K |
| Tsea | 4 C | 277,15 K |
| Tin 1 | 29,5 C | 302,65 K |
| Tin 2 | 52 C | 325,15 K |
| U | 15 W/m2 K | |
| U* | 100 W/m2 K | |
| d | 0,225 m | |
| Hydrate | 410 kJ/kg | |
| Cp_h | 2,7 kJ/kg K | |
| Cp_o_1 | 2,008 kJ/kg K | |
| Cp_o_2 | 2,105 kJ/kg K | |

Hydrate composition

| | |
|------|------|
| wt g | 0,15 |
| wt w | 0,85 |

Mass of hydrate

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | x fr g | x fr w | x fr o | x fr h |
|---------------|---------------|---------------|---------------|---------------|-----------|-----------|-----------|-----------|
| 29,29 | 0,3199 | 0,75 | 0,38 | 30,73 | 0,9529 | 0,0104 | 0,0244 | 0,0122 |
| 27,65 | 2,8190 | 0,71 | 3,32 | 34,49 | 0,8016 | 0,0817 | 0,0205 | 0,0962 |
| 29,17 | 0,4969 | 0,76 | 0,58 | 31,00 | 0,9407 | 0,0160 | 0,0244 | 0,0189 |
| 26,63 | 4,2348 | 0,82 | 4,98 | 36,67 | 0,7264 | 0,1155 | 0,0223 | 0,1359 |
| 18,25 | 16,3240 | 1,30 | 19,20 | 55,08 | 0,3314 | 0,2964 | 0,0236 | 0,3487 |

| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] | WHR [-] |
|----------------|-----------|-------------|------------|
| 154,32 | 2,166 | 2,318 | 0,850 |
| 1359,76 | 2,359 | 16,714 | 0,850 |
| 239,66 | 2,183 | 3,541 | 0,850 |
| 2042,64 | 2,452 | 22,723 | 0,850 |
| 7873,92 | 2,939 | 48,835 | 0,850 |

| m_t | | 30,733 | | kg/s | |
|-----------|----------------|----------------|----------------|----------------|----------------|
| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
| 0,00 | 31,82 | 46,21 | 55,54 | 74,72 | 100,64 |
| 2,00 | 24,23 | 35,51 | 41,58 | 57,37 | 80,42 |
| 4,00 | 18,71 | 27,52 | 31,39 | 44,28 | 64,43 |
| 6,00 | 14,70 | 21,55 | 23,97 | 34,40 | 51,79 |
| 8,00 | 11,78 | 17,10 | 18,56 | 26,94 | 41,79 |
| 10,00 | 9,66 | 13,78 | 14,61 | 21,32 | 33,88 |
| 12,00 | 8,11 | 11,30 | 11,74 | 17,07 | 27,63 |
| 14,00 | 6,99 | 9,45 | 9,64 | 13,86 | 22,69 |
| 16,00 | 6,18 | 8,07 | 8,11 | 11,44 | 18,78 |
| 18,00 | 5,58 | 7,03 | 7,00 | 9,62 | 15,68 |
| 20,00 | 5,15 | 6,28 | 6,19 | 8,24 | 13,24 |

| m_t | | 30,733 | | kg/s | |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| L* [km] | Tout1.1* [C] | Tout1.2* [C] | Tout1.3* [C] | Tout1.4* [C] | Tout1.5* [C] |
| 0,00 | 31,82 | 46,21 | 55,54 | 74,72 | 100,64 |
| 2,00 | 7,33 | 10,00 | 10,27 | 14,83 | 24,21 |
| 4,00 | 4,40 | 4,85 | 4,76 | 5,66 | 8,23 |
| 6,00 | 4,05 | 4,12 | 4,09 | 4,25 | 4,88 |
| 8,00 | 4,01 | 4,02 | 4,01 | 4,04 | 4,18 |
| 10,00 | 4,00 | 4,00 | 4,00 | 4,01 | 4,04 |
| 12,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 14,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 16,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 18,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

| m_t | | 36,67 | | kg/s | |
|-----------|----------------|----------------|----------------|----------------|----------------|
| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
| 0,00 | 31,82 | 46,21 | 55,54 | 74,72 | 100,64 |
| 2,00 | 25,30 | 37,03 | 43,55 | 59,86 | 83,37 |
| 4,00 | 20,31 | 29,85 | 34,34 | 48,12 | 69,20 |
| 6,00 | 16,49 | 24,23 | 27,28 | 38,85 | 57,55 |
| 8,00 | 13,56 | 19,83 | 21,86 | 31,53 | 47,99 |
| 10,00 | 11,32 | 16,39 | 17,71 | 25,74 | 40,13 |
| 12,00 | 9,60 | 13,69 | 14,52 | 21,17 | 33,68 |
| 14,00 | 8,29 | 11,59 | 12,07 | 17,56 | 28,38 |
| 16,00 | 7,29 | 9,94 | 10,19 | 14,71 | 24,02 |
| 18,00 | 6,52 | 8,65 | 8,75 | 12,46 | 20,45 |
| 20,00 | 5,93 | 7,64 | 7,65 | 10,68 | 17,51 |

| m_t | | 36,67 | | kg/s | |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| L* [km] | Tout1.1* [C] | Tout1.2* [C] | Tout1.3* [C] | Tout1.4* [C] | Tout1.5* [C] |
| 0,00 | 31,82 | 46,21 | 55,54 | 74,72 | 100,64 |
| 2,00 | 8,69 | 12,23 | 8,97 | 14,01 | 30,03 |
| 4,00 | 4,79 | 5,81 | 4,85 | 6,08 | 11,01 |
| 6,00 | 4,13 | 4,31 | 4,15 | 4,43 | 5,89 |
| 8,00 | 4,02 | 4,06 | 4,02 | 4,09 | 4,51 |
| 10,00 | 4,00 | 4,01 | 4,00 | 4,02 | 4,14 |
| 12,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,04 |
| 14,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 16,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 18,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

Recycling second time 0,50

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | WHR [-] | | | |
|---------------|---------------|---------------|---------------|---------------|------------|--|--|--|
| 29,29 | 0,32 | 0,75 | 0,38 | 30,73 | 0,85 | | | |
| 27,65 | 2,82 | 0,71 | 3,32 | 34,49 | 0,85 | | | |
| 29,17 | 0,50 | 0,76 | 0,58 | 31,00 | 0,85 | | | |
| 26,63 | 4,23 | 0,82 | 4,98 | 36,67 | 0,85 | | | |
| 18,25 | 16,32 | 1,30 | 19,20 | 55,08 | 0,85 | | | |

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | m_t [kg/s] | x fr g | x fr w | x fr o | x fr h |
|---------------|---------------|---------------|---------------|---------------|-----------|-----------|-----------|-----------|
| 29,29 | 0,48 | 1,13 | 0,56 | 31,46 | 0,93 | 0,02 | 0,04 | 0,02 |
| 27,65 | 4,23 | 1,08 | 4,97 | 37,91 | 0,73 | 0,11 | 0,03 | 0,13 |
| 29,17 | 0,75 | 1,13 | 0,88 | 31,92 | 0,91 | 0,02 | 0,04 | 0,03 |
| 26,63 | 6,35 | 1,22 | 7,47 | 41,68 | 0,64 | 0,15 | 0,03 | 0,18 |
| 18,25 | 24,49 | 1,95 | 28,81 | 73,49 | 0,25 | 0,33 | 0,03 | 0,39 |

| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] |
|----------------|-----------|-------------|
| 231,48 | 2,18 | 3,38 |
| 2039,64 | 2,44 | 22,07 |
| 359,50 | 2,20 | 5,11 |
| 3083,97 | 2,55 | 28,82 |
| 11810,87 | 3,04 | 52,89 |

| m_t | | 31,46 | | kg/s | |
|-----------|----------------|----------------|----------------|----------------|----------------|
| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
| 0,00 | 32,88 | 51,57 | 57,11 | 80,82 | 104,89 |
| 2,00 | 25,19 | 40,07 | 43,11 | 62,98 | 84,82 |
| 4,00 | 19,55 | 31,36 | 32,80 | 49,28 | 68,74 |
| 6,00 | 15,41 | 24,75 | 25,21 | 38,76 | 55,85 |
| 8,00 | 12,37 | 19,74 | 19,62 | 30,69 | 45,54 |
| 10,00 | 10,14 | 15,94 | 15,50 | 24,49 | 37,27 |
| 12,00 | 8,51 | 13,05 | 12,47 | 19,73 | 30,65 |
| 14,00 | 7,31 | 10,87 | 10,23 | 16,08 | 25,35 |
| 16,00 | 6,43 | 9,21 | 8,59 | 13,27 | 21,10 |
| 18,00 | 5,78 | 7,95 | 7,38 | 11,12 | 17,70 |
| 20,00 | 5,31 | 7,00 | 6,49 | 9,47 | 14,97 |

| m_t | | 31,46 | | kg/s | |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| L* [km] | Tout1.1* [C] | Tout1.2* [C] | Tout1.3* [C] | Tout1.4* [C] | Tout1.5* [C] |
| 0,00 | 32,88 | 51,57 | 57,11 | 80,82 | 104,89 |
| 2,00 | 7,67 | 11,53 | 10,90 | 17,19 | 26,99 |
| 4,00 | 4,47 | 5,19 | 4,90 | 6,27 | 9,24 |
| 6,00 | 4,06 | 4,19 | 4,12 | 4,39 | 5,19 |
| 8,00 | 4,01 | 4,03 | 4,02 | 4,07 | 4,27 |
| 10,00 | 4,00 | 4,00 | 4,00 | 4,01 | 4,06 |
| 12,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 14,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 16,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 18,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

| m_t | | 41,68 | | kg/s | |
|-----------|----------------|----------------|----------------|----------------|----------------|
| L [km] | Tout1.1 [C] | Tout1.2 [C] | Tout1.3 [C] | Tout1.4 [C] | Tout1.5 [C] |
| 0,00 | 32,88 | 51,57 | 57,11 | 80,82 | 104,89 |
| 2,00 | 26,86 | 42,61 | 46,16 | 66,93 | 89,34 |
| 4,00 | 22,10 | 35,34 | 37,46 | 55,55 | 76,18 |
| 6,00 | 18,33 | 29,43 | 30,56 | 46,23 | 65,05 |
| 8,00 | 15,34 | 24,64 | 25,08 | 38,59 | 55,64 |
| 10,00 | 12,98 | 20,76 | 20,74 | 32,34 | 47,68 |
| 12,00 | 11,11 | 17,60 | 17,28 | 27,21 | 40,95 |
| 14,00 | 9,63 | 15,04 | 14,54 | 23,02 | 35,25 |
| 16,00 | 8,45 | 12,96 | 12,37 | 19,58 | 30,43 |
| 18,00 | 7,53 | 11,27 | 10,64 | 16,76 | 26,36 |
| 20,00 | 6,79 | 9,90 | 9,27 | 14,45 | 22,91 |

| m_t | | 41,68 | | kg/s | |
|------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| L* [km] | Tout1.1* [C] | Tout1.2* [C] | Tout1.3* [C] | Tout1.4* [C] | Tout1.5* [C] |
| 0,00 | 32,88 | 51,57 | 57,11 | 80,82 | 104,89 |
| 2,00 | 10,08 | 15,83 | 15,39 | 24,32 | 37,04 |
| 4,00 | 5,28 | 6,94 | 6,44 | 9,38 | 14,82 |
| 6,00 | 4,27 | 4,73 | 4,52 | 6,42 | 7,54 |
| 8,00 | 4,06 | 4,18 | 4,11 | 4,38 | 5,16 |
| 10,00 | 4,01 | 4,05 | 4,02 | 4,10 | 4,38 |
| 12,00 | 4,00 | 4,01 | 4,01 | 4,03 | 4,12 |
| 14,00 | 4,00 | 4,00 | 4,00 | 4,01 | 4,04 |
| 16,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,01 |
| 18,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |
| 20,00 | 4,00 | 4,00 | 4,00 | 4,00 | 4,00 |

NTNU calculation

Horizontal separator calculations

Data

| | | |
|-----|-----------------------|----------|
| L | 6 m | |
| d | 2 m | |
| T1 | 55 C | 328,15 K |
| P1 | 1,50E+07 Pa | 150 bar |
| T2 | 100 C | 373,15 K |
| P2 | 3,75E+07 Pa | 375 bar |
| g | 9,81 m/s ² | |
| d_b | 2,00E-04 m | |
| μ | 3,00E-04 Pas | |
| k_s | 0,137 NORSOK | |
| F_s | 1 NORSOK | |

Assumptions:

The separator is at seabed and the liquid phase (oil and water) would be separated from the associated gas
 Two-phase separation occurs and the water would be separated due to higher density. Only two-phase separator with oil and associated gas
 The minimum droplet size would be 200μm
 The separator is at seabed, so the subsea condition would be used in the calculation
 The length of the separator is 6 m and the diameter is 2 m. Horizontal separator

| Rs [Sm ³ /Sm ³] | WC [-] | B* [-] | Bo [m ³ /Sm ³] | Bg [m ³ /Sm ³] |
|---|-----------|-----------|--|--|
| 250,00 | 0,20 | 1429,81 | 1,71 | 0,00815 |
| 250,00 | 0,70 | 1429,81 | 1,71 | 0,00815 |
| 125,00 | 0,30 | 866,20 | 1,38 | 0,00280 |
| 125,00 | 0,80 | 467,91 | 1,17 | 0,00280 |
| 50,00 | 0,90 | 466,27 | 1,17 | 0,00280 |

| p_o kg/m3 | p_g kg/m3 | p_w kg/m3 | m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_t [kg/s] |
|--------------|--------------|--------------|---------------|---------------|---------------|---------------|
| 595,33 | 139,37 | 1015,00 | 29,29 | 0,21 | 0,50 | 30,00 |
| 595,33 | 139,37 | 1015,00 | 27,65 | 1,88 | 0,47 | 30,00 |
| 661,51 | 308,40 | 1015,00 | 29,17 | 0,33 | 0,50 | 30,00 |
| 782,55 | 308,40 | 1015,00 | 26,63 | 2,82 | 0,54 | 30,00 |
| 727,09 | 308,40 | 1015,00 | 18,25 | 10,88 | 0,87 | 30,00 |

| q_g [m3/s] | q_w [m3/s] | q_o [m3/s] | q_g [m3/d] | q_w [m3/d] | q_o [m3/d] |
|---------------|---------------|---------------|---------------|---------------|---------------|
| 0,21014 | 0,00021 | 0,00084 | 18155,70 | 18,16 | 72,82 |
| 0,19838 | 0,00185 | 0,00079 | 17140,21 | 159,98 | 68,56 |
| 0,09518 | 0,00033 | 0,00076 | 8223,98 | 28,20 | 65,79 |
| 0,08692 | 0,00278 | 0,00070 | 7509,90 | 240,32 | 60,08 |
| 0,05957 | 0,01072 | 0,00119 | 5146,47 | 926,37 | 102,93 |

| Gas phase | | | | Liquid phase | | Liquid phase | | |
|---------------|---------------|-------------|--------------|--------------|-------------|--------------|---------------|---------------|
| q_g [m3/s] | q_g [m3/d] | A_g [m2] | v_b [m/s] | t [s] | q_l m3/s | q_l m3/d | q_l,t m3/s | q_l,t m3/d |
| 0,39 | 33630,57 | 1,571 | 0,050 | 20,121 | 0,47 | 40470,35 | 0,46862 | 40488,50 |
| 0,39 | 33630,57 | 1,571 | 0,050 | 20,121 | 0,47 | 40470,35 | 0,47026 | 40630,32 |
| 0,23 | 20016,50 | 1,571 | 0,039 | 25,835 | 0,36 | 31519,09 | 0,36513 | 31547,29 |
| 0,27 | 23177,97 | 1,571 | 0,052 | 19,268 | 0,49 | 42261,80 | 0,49192 | 42502,12 |
| 0,25 | 21786,52 | 1,571 | 0,046 | 21,808 | 0,43 | 37339,89 | 0,44290 | 38266,25 |

The Tube Heat Exchanger & The Refrigeration unit

Assumptions:

The tube heat exchanger unit is 1" tubes 4m*4m*20m in size, and can only "cool" to 10 C
 The refrigeration unit is 4m*4m*6m in size and is needed to cool the fluid from 10 C to 4 C

Data:

| | | |
|------|------------|----------|
| Tsea | 4 C | 277,15 K |
| Tin1 | 55 C | 328,15 K |
| Tin2 | 100 C | 373,15 K |
| U* | 100 W/m2 K | |
| U | 15 W/m2 K | |
| V_o | 0,8056 | |

The Tube Heat Exchanger Unit

| | | |
|---------------|---------------|----------|
| Cp_o 1 | 2,118 kJ/kg K | |
| Cp_o 2 | 2,312 kJ/kg K | |
| Cp_w | 4,18 kJ/kg K | |
| U HX | 250 W/m2 K | |
| d, tube | 2,54 cm | 0,0254 m |
| length tubing | 70 m | |
| Tout_HX | 10 C | 283,15 K |
| Δ_t_lmtd 1 | 21,02738727 K | |
| Δ_t_lmtd 2 | 32,46063942 K | |

Assumptions

Due to different kind of values for U exchanger, I assume that we can use 250 W/m2 K
 I assume that each tube has a length of 70m

| m_w [kg/s] | m_o [kg/s] | Δ_T [C] | q [kJ/s] | q [MW] | A [m2] |
|---------------|---------------|------------|-------------|-----------|-----------|
| 0,21 | 0,50 | 45 | 87,81 | 0,09 | 16,70 |
| 1,88 | 0,47 | 45 | 398,53 | 0,40 | 75,81 |
| 0,33 | 0,50 | 90 | 229,44 | 0,23 | 28,27 |
| 2,82 | 0,54 | 90 | 1175,31 | 1,18 | 144,83 |
| 10,88 | 0,87 | 90 | 4274,30 | 4,27 | 526,71 |

| Total length [m] | Total pipe [-] |
|---------------------|-------------------|
| 209,34 | 2,99 |
| 950,06 | 13,57 |
| 354,31 | 5,06 |
| 1814,98 | 25,93 |
| 6800,82 | 94,29 |

The Refrigeration Unit

Tin_RF 10 C 283,15 K
 Tout_RF 4 C 277,15 K
 Y_o 0,808

 Cp_o 1,9237813 kJ/kg K
 Cp_w 4,18 kJ/kg K

Assumptions

The compressor motor need 1/5 of the electric power from the cooling demand
 The out temperature from the refrigeration unit is 4 C

| m_w [kg/s] | m_o [kg/s] | Δ_T [C] | q [kJ/s] | q [MW] | Poom [kJ/s] | Poom [MW] |
|---------------|---------------|------------|-------------|-----------|----------------|--------------|
| 0,21 | 0,40 | 6 | 9,98 | 9,98E-03 | 2,00 | 2,00E-03 |
| 1,89 | 0,38 | 6 | 51,64 | 5,16E-02 | 10,33 | 1,03E-02 |
| 0,33 | 0,45 | 6 | 13,48 | 1,35E-02 | 2,70 | 2,70E-03 |
| 2,83 | 0,48 | 6 | 78,53 | 7,85E-02 | 15,31 | 1,53E-02 |
| 10,90 | 0,82 | 6 | 282,84 | 2,83E-01 | 58,57 | 5,86E-02 |

Reactor

Data:

m_t 30,00 kg/s
 Cp_w 4,18 kJ/kg K
 Cp_g 2,237 kJ/kg K
 Cp_o 1,924 kJ/kg K

Hydrate 410,00 kJ/kg
 Cp_h 2,70 kJ/kg K

Hydrate composition
 wt gas 0,15
 wt water 0,85

Mass of hydrate

| m_g [kg/s] | m_w [kg/s] | m_o [kg/s] | m_h [kg/s] | x fr g | x fr w | x fr o | x fr h |
|----------------|---------------|---------------|-------------------|-----------|-----------|------------|-----------|
| 29,29 | 0,21 | 0,50 | 0,25 | 0,976 | 0,007 | 0,017 | 0,008 |
| 27,65 | 1,88 | 0,47 | 2,21 | 0,922 | 0,083 | 0,016 | 0,074 |
| 29,17 | 0,33 | 0,50 | 0,39 | 0,972 | 0,011 | 0,017 | 0,013 |
| 26,63 | 2,82 | 0,54 | 3,32 | 0,888 | 0,094 | 0,018 | 0,111 |
| 18,25 | 10,88 | 0,87 | 12,80 | 0,608 | 0,363 | 0,029 | 0,427 |
| ΔH_h [kJ/s] | Cp mix | ΔT_h [C] | Pressure [kPa] | | | WHR [-] | |
| 102,88 | 2,18 | 1,57 | 15000,00 | | | 0,85 | |
| 908,50 | 2,47 | 12,25 | 15000,00 | | | 0,85 | |
| 159,78 | 2,20 | 2,42 | 37500,00 | | | 0,85 | |
| 1361,76 | 2,83 | 17,23 | 37500,00 | | | 0,85 | |
| 5249,28 | 4,04 | 43,33 | 37500,00 | | | 0,85 | |

| Bubblepoint curve | | | Dewpoint curve | | | Hydrate curve | | |
|-------------------|----------------|-----------------|----------------|----------------|-----------------|----------------|----------------|-----------------|
| Pressure [kPa] | Pressure [MPa] | Temperature [C] | Pressure [kPa] | Pressure [MPa] | Temperature [C] | Pressure [kPa] | Pressure [MPa] | Temperature [C] |
| 159,80 | 0,1598 | -154,70 | 202,70 | 0,2027 | -90,25 | 429,00 | 0,4290 | -16,12 |
| 278,40 | 0,2784 | -146,60 | 429,00 | 0,4290 | -79,58 | 908,20 | 0,9082 | 0,39 |
| 467,30 | 0,4673 | -137,60 | 908,20 | 0,9082 | -67,95 | 1923,00 | 1,9230 | 6,57 |
| 767,40 | 0,7674 | -128,00 | 1923,00 | 1,9230 | -58,01 | 4070,00 | 4,0700 | 12,54 |
| 1215,00 | 1,2150 | -117,70 | 4070,00 | 4,0700 | -48,49 | 4910,00 | 4,9100 | 13,92 |
| 1842,00 | 1,8420 | -107,00 | 4910,00 | 4,9100 | -45,66 | 4961,00 | 4,9610 | 13,99 |
| 2652,00 | 2,6520 | -98,39 | 4961,00 | 4,9610 | -45,66 | 5538,00 | 5,5380 | 14,76 |
| 3804,00 | 3,8040 | -88,25 | 5538,00 | 5,5380 | -46,08 | 5993,00 | 5,9930 | 15,28 |
| 4331,00 | 4,3310 | -79,43 | 5993,00 | 5,9930 | -47,17 | 6280,00 | 6,2800 | 15,60 |
| 5037,00 | 5,0370 | -73,18 | 6280,00 | 6,2800 | -48,61 | 6464,00 | 6,4640 | 15,79 |
| 5471,00 | 5,4710 | -69,28 | 6464,00 | 6,4640 | -50,20 | 6564,00 | 6,5640 | 15,89 |
| 5736,00 | 5,7360 | -66,82 | 6564,00 | 6,5640 | -51,94 | 6599,00 | 6,5990 | 15,92 |
| 5975,00 | 5,9750 | -64,43 | 6599,00 | 6,5990 | -53,48 | 6588,00 | 6,5880 | 15,91 |
| 6191,00 | 6,1910 | -62,09 | 6600,00 | 6,6000 | -53,84 | | | |
| 6252,00 | 6,2520 | -61,35 | 6588,00 | 6,5880 | -55,09 | | | |
| | | | 6507,00 | 6,5070 | -57,46 | | | |
| | | | 6370,00 | 6,3700 | -59,78 | | | |
| | | | 6252,00 | 6,2520 | -61,35 | | | |

Will the pipes float in the SINTEF concept?

ρ_w 1015 kg/m3
 ρ_steel 7850 kg/m3
 ρ_air 1,25 kg/m3

| Pipe nr | Thickness ["] | ID ["] | OD ["] | ID [m] | OD [m] | Volume @ 1m [m3] | Weight of pipe [kg/m] | Bouyancy |
|---------|---------------|--------|--------|--------|--------|------------------|-----------------------|----------|
| 1 | 0,280 | 6,065 | 6,625 | 0,154 | 0,168 | 0,004 | 26,290 | 22,573 |
| 2 | 0,300 | 7,025 | 7,625 | 0,178 | 0,194 | 0,004 | 34,995 | 29,902 |
| 3 | 0,322 | 7,981 | 8,625 | 0,203 | 0,219 | 0,005 | 42,578 | 38,260 |
| 4 | 0,342 | 8,941 | 9,625 | 0,227 | 0,244 | 0,006 | 50,563 | 47,646 |
| 5 | 0,365 | 10,020 | 10,750 | 0,255 | 0,273 | 0,008 | 60,373 | 59,435 |
| 6 | 0,375 | 11,000 | 11,750 | 0,279 | 0,298 | 0,009 | 67,945 | 71,007 |
| 7 | 0,406 | 11,938 | 12,750 | 0,303 | 0,324 | 0,010 | 79,829 | 83,607 |
| 8 | 0,437 | 13,126 | 14,000 | 0,333 | 0,356 | 0,012 | 94,412 | 100,804 |
| 9 | 0,500 | 15,000 | 16,000 | 0,381 | 0,406 | 0,016 | 123,450 | 131,663 |
| 10 | 0,562 | 16,876 | 18,000 | 0,429 | 0,457 | 0,020 | 156,107 | 166,636 |
| 11 | 0,593 | 18,814 | 20,000 | 0,478 | 0,508 | 0,023 | 183,329 | 205,723 |
| 12 | 0,600 | 20,800 | 22,000 | 0,528 | 0,559 | 0,026 | 204,566 | 248,925 |
| 13 | 0,687 | 22,626 | 24,000 | 0,575 | 0,610 | 0,032 | 255,149 | 296,241 |
| 14 | 0,687 | 24,626 | 26,000 | 0,626 | 0,660 | 0,035 | 277,070 | 347,672 |
| 15 | 0,687 | 26,626 | 28,000 | 0,676 | 0,711 | 0,038 | 298,996 | 403,218 |
| 16 | 0,688 | 30,624 | 32,000 | 0,778 | 0,813 | 0,044 | 343,351 | 526,651 |
| 17 | 0,688 | 32,624 | 34,000 | 0,829 | 0,864 | 0,046 | 365,324 | 594,540 |
| 18 | 0,750 | 34,500 | 36,000 | 0,876 | 0,914 | 0,054 | 421,391 | 666,543 |
| 19 | 0,750 | 40,500 | 42,000 | 1,029 | 1,067 | 0,063 | 493,274 | 907,239 |

| Flowline, OD [mm] | Bare pipe | Coated pipe | Buried pipe | Buried & Coated | PIP |
|-------------------|-------------|-------------|-------------|-----------------|------|
| 114,3 | 871 | 4,65 | 4,56 | 2,52 | 1,56 |
| 219,1 | 544 | 4,04 | 2,87 | 1,81 | 1,44 |
| 323,9 | 362 | 3,81 | 2,22 | 1,5 | 1,02 |
| 350 | 319,8493424 | | | | |
| 400 | 259,2648381 | | | | |
| 450 | 210,1559933 | | | | |
| 500 | 170,3491373 | | | | |
| 550 | 138,082327 | | | | |
| 600 | 111,9273589 | | | | |
| 650 | 90,72655386 | | | | |
| 700 | 73,54151525 | | | | |
| 750 | 59,61159368 | | | | |
| 800 | 48,32021872 | | | | |
| 850 | 39,16760805 | | | | |
| 900 | 31,74864604 | | | | |
| 950 | 25,73495231 | | | | |
| 1000 | 20,86034691 | | | | |

Extrapolated values by use of exponential regression

$$OHTC = 1391,1e^{(-0,0042 \cdot (OD))}$$