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Displacement of liquid in pipe flow: Two-dimensional simulations

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Fortrengning av væske i rørstrøm: 2D dynamisk simulering

Liquid flushing in pipe flow: 2D dynamic simulations

Bakgrunn

Det er flere tilfeller der det er ønskelig å simulere mulighetene for å fortrenge en væsk eller gassfase i et rør med en annen. Etter en ukontrollert nedstengning av en rørledning kan det akkumuleres vann i et lavpunkt, f.eks. i en U-kobling mellom brønnhode og rørledning. Spørsmålet er da om en oljestrøm kan fortrenge vannet, eller om vann blir liggende igjen i røret. Utblåsning av en væskeoppsamling i en rørkomponent kan også være en aktuell problemstilling når gass skal førs til fakling. Likeledes kan det være aktuelt å fjerne luft i et rør ved innstrømning av vann fra ene enden, f.eks. ved oppstart av en ny rørledning.

Det er tidligere utført transiente strømningsforsøk der en oljestrøm pumpes inn i et vannfylt rør, samt forsøk der vann strømmer inn i et rør fylt med luft. Oppgaven går ut på å vurdere simuleringsverktøy for slike dynamiske tofase strømningsforhold. Det er tilfeller der en-dimensjonale modeller ikke er tilstrekkelige. SINTEF utvikler en 2D dynamisk flerfasemodell for rørgeometri. Denne modellen kan være mer hensikstmessig for en del strømningstilfeller. SINTEF vil stille modellen til rådighet og FRAMO vil gjøre en del forsøksdata tilgjengelig for en MSc studie.

Mål

Det skal utføres sammenligninger mellom beregninger og tilgjengelige forsøksdata på fortrengning av gass eller væske i rørgeometrier.

Oppgaven bearbeides ut fra følgende punkter:

1. Kort oversikt over aktuelle problemstillinger, tilgjengelige forsøksdata og tidligere arbeid
2. Kort beskrivelse av modellen i strømningssimulatoren.
3. Dynamiske simuleringer av utvalgte problemstillinger
4. Om mulig, rapportering i form av en publikasjon

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Besvarelsen redigeres mest mulig som en forskningsrapport med et sammendrag både på norsk og engelsk, konklusjon, litteraturliste, innholdsfortegnelse etc. Ved utarbeidelsen av teksten skal kandidaten legge vekt på å gjøre teksten oversiktlig og velskrevet. Med henblikk på lesning av besvarelsen er det viktig at de nødvendige henvisninger for korresponderende steder i tekst, tabeller og figurer anføres på begge steder. Ved bedømmelsen legges det stor vekt på at resultatene er grundig bearbeidet, at de oppstilles tabellarisk og/eller grafisk på en oversiktlig måte, og at de er diskutert utførlig.

Alle benyttede kilder, også muntlige opplysninger, skal oppgis på fullstendig måte. For tidsskrifter og bøker oppgis forfatter, tittel, årgang, sidetall og eventuelt figurnummer.

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NTNU, Institutt for energi- og prosessteknikk, 16. januar 2012

Olav Bolland
Instituttleder

Ole Jorgen Nydal
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Ekstern veileder: Alireza Ashrafian, SINTEF Materialer og Kjemi

Preface

This thesis concludes my Master of Science studies at Norwegian University of Science and Technology (NTNU), at the Department of Energy and Process Engineering.

For most of the time I have been working at SINTEF at the Department of Materials and Chemistry with the development team of the transient multiphase simulator LedaFlow. The work has been concentrated around the use of LedaFlow. During work on the master thesis, a variety of practical and theoretical problems have been encountered. With guidance and help from Jean Christophe Barbier, Sjur Mo and my supervisor at SINTEF, Alireza Ashrafian, I have been able to overcome the challenges I have met along the way. I would like to credit them for their encouragement, support, knowledge and time. It has been a privilege and an invaluable experience for me to work together with them at SINTEF.

As well as numerical simulation work at SINTEF I spent some time at Framo Engineering AS in Bergen, doing laboratory experiments. In collaboration with Framo Engineering AS I conducted displacement tests in one of their facilities in Bergen. I would like to thank Framo Engineering employees and give an extra big thank you to Vivian Lyngvær, Anna Borgund and Erik Sjurseth for their help, cooperation and guidance during the testing period. It has been challenging and fun to work with you.

Finally I would like to thank my supervisor at NTNU Ole Jørgen Nydal for formulating a project which enriched my one-dimensional and multi-dimensional simulation skills, and gave me the opportunity to do both experimental and simulation work.

Abstract

In the oil and gas industries it is crucial to handle flow assurance in a good manner in order to ensure a safe and economical operation. In subsea areas there are challenging conditions, with high pressure and low temperature. In addition the fact that the systems are located subsea makes it more difficult to have control of it. Displacement and slugging[1] are subjects that have been studied in this thesis. Two aspects of displacement have been considered:

- Displacement of hydrocarbons in order to avoid hydrate formation, and
- Displacement of hydrocarbons in order to avoid oil dischange to the sea during subsea intervention[2].

Two cases have been considered in this thesis, one displacement case conducted in collaboration with Framo Engineering, and a blow-through test that had already been conducted at the Norwegian University of Science and Technology (NTNU). The focus of this work has concerned simulations of these tests in LedaFlow 1D and LedaFlow Q3D and comparing the results with each other and with the experiments. In addition the work on this thesis also concerned conducting full scale displacement tests with Framo Engineering.

By simulating and analyzing displacement in different simulator tools, it is possible to predict the displacement and find out how to displace in a best manner, with which type of displacement medium and with which mass flow rate. In the same manner it is possible to predict slug flow, slug behavior and size. Only small variations in pipeline elevation can cause changes in slug characteristics. Therefore it is advantageous to use a simulator to predict slug flow in each pipeline.

Regarding the displacement tests, the trend with simulating in LedaFlow 1D was that it predicted lower displacement rates compared to what was the case in the experiments. When simulating the tests in LedaFlow Q3D with tuned parameters it led to high displacement levels that were very similar to the experimental displacement levels.

Concerning the blow-through test simulations in both LedaFlow Q3D and with LedaFlow 1D resulted in more liquid swept out of the system than what was the case in the experiment. The inlet pressures in LedaFlow 1D and LedaFlow Q3D had about the same progress as in the experiments. The main difference was that LedaFlow 1D reached a higher peak and that the inlet pressure from the experiments decreased slower.

[1] Periodically gas and liquid flow
[2] Subsea intervention: Removal of a subsea system in order to fix it or to change it.

Abstract in Norwegian

I olje-og gassindustrien er det avgjørende å håndtere Flow Assurance på en god måte for å sikre en sikker og økonomisk drift. I undervannssystemer er det vanskelige forhold, med høyt trykk og lav temperatur. Det at systemene er plassert undervanns gjør det vanskeligere å ha kontroll over det. Fortrengning og slugging[3] er temaer som har blitt studert i dette arbeidet. To aspekter ved fortrengning har vært i fokus:

- Fortrengning av hydrokarboner for å unngå hydratdannelse, og
- Fortrengning av hydrokarboner for å unngå olje-utslipp til sjø under undervanns-intervensjon[4] av systemer

To tilfeller har blitt studert i dette arbeidet, ett fortrengnings-tilfelle gjennomført i samarbeid med Framo Engineering, og en gjennomblåsnings-test som allerede har blitt utført ved Norges Tekniske Naturvitenskapelige Universitet (NTNU). Fokusområdet i dette arbeidet har omhandlet arbeid med simuleringer av disse testene i simulatoren LedaFlow 1D og LedaFlow Q3D, samt å sammenligne resultatene med hverandre og med forsøkene. I tillegg til simuleringsarbeid omfattet oppgaven også gjennomføring av fullskala fortrengningstester i samarbeid med Framo Engineering.

Ved å simulere og analysere forskyvning i ulike simulatorverktøy er det mulig å forutsi fortrengningsgraden. Løsninger for hvordan å fortrenge på best mulig måte, med hvilke type fortrengnings-medium og med optimal injeksjonshastighet på fortrengnings-mediet kan finnes. På samme måte er det mulig å forutsi slugge-strømning, slugge-mønster og størrelse. Kun små variasjoner i en rørlednings helning kan føre til endringer i slugge-egenskaper. Derfor er det en fordel å bruke en simulator til å forutsi slugge-strømning i hvert spesifikt rør.

Når det gjelder fortrengningstestene, var trenden med å simulere i LedaFlow 1D at det resulterte i en lavere fortrengningsgrad enn hva som var tilfellet i testene. Av å simulere testene i LedaFlow Q3D, med justerte parametere for å oppnå best resultat, førte det til fortrengningsgrader som var ganske lik de eksperimentelle verdiene.

Når det gjelder gjennomblåsningstestene viste simuleringer i både LedaFlow Q3D og LedaFlow 1D at mer væske ble blåst ut av systemet enn hva tilfellet i forsøkene. Innløpstrykket i LedaFlow 1D og LedaFlow Q3D hadde omtrent den samme utviklingen som i forsøkene. Den viktigste forskjellen var at LedaFlow 1D nådde trykket en høyere topp ved starten og at trykket i både LedaFlow 1D og LedaFlow Q3D falt fortere ned til en stabil verdi.

[3] Periodisk gass og væskestrøm

[4] Undervanns-intervensjon: undervanns-systemer eller komponenter blir hentet ut fra rørlinjen for å utføre reparasjon på dem eller for å bytte dem ut.

Abbreviations

Aspect ratio, AR	Ratio between cell length in x direction and cell length in y direction
CFL	Courant Friedrich Levy number
DPS	Dynamic particle size
FPSO	Floating production, storage and offloading unit
GVF	Gas Volume Fraction
Holdup	Liquid volume fraction
KLIF	Klima- og ForurensningsDirektoratet
LSI	Large scale interface
LedaFlow	A multiphase, transient flow simulator, one-, and multidimensional (1)
OLGA	A multiphase, transient flow simulator, one-dimensional (2)
OSPAR	A commission regulating discharges of hydrocarbons offshore (3)
Stratified flow	Layered flow of several phases
TKE	Turbulent Kinetic Energy
Transient	A process that changes with time
Usg	Superficial gas velocity
VOF	Volume of Fluid

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1. Introduction

In this chapter a brief introduction about Flow Assurance and some issues related to that term is discussed. An overview of the report will be presented and the scope of the project will also be outlined.

1.1 Flow Assurance

Flow assurance management is critical to successful and economic operation of oil and gas production systems. The term Flow Assurance is an area of engineering that costs a great deal of money if not managed correctly. The flow conditions offshore require methods to take care of the negative consequences.

IFE (Institute for Energy Technology) defines Flow Assurance in such way:
"The term 'Flow Assurance' covers broadly the same meaning as the term 'multiphase transport technology': Design tools, methods, equipment, knowledge and professional skills needed to ensure the safe, uninterrupted transport of reservoir fluids from the reservoir to processing facilities." (4)

In order to operate successfully and economical it is critical to handle flow assurance in a good manner. Oil and gas companies are operating in deeper waters where the flow assurance challenges are greater due to extreme pressures and temperatures and greater distances to processing facilities. At the sea bed one can find temperatures even below water freezing point. These factors combined with presence of free water and gas in pipelines, makes the production challenging. Hydrates, scale, asphaltene, corrosion and emulsion generates easily in such hostile environments.

Hydrate formation is the main problem to avoid since it causes the greatest consequences (5). If a hydrate plug grows big enough to fill the whole cross section of the pipeline, the production must stop and the plug must be removed. This process could be very time demanding and leads to a huge amount of money lost for the oil and gas companies. Hydrate formation in pipelines can be avoided by injecting an inhibitor into the stream. In this way the flow is capable of handling high pressure and low temperature.

Another issue that often arises in subsea pipelines is slugging (6). Especially slugging in risers must be taken into account or else it can cause great damages on equipment and the environment. Only small variations in pipeline elevation can cause changes in slug characteristics.

In this work, the two issues mentioned are in focus as well as another flow assurance matter; to remove in situ hydrocarbons from pipeline systems in order to prevent oil spill to the sea when retrieving subsea components.

1.2 Experiments

In order to understand displacement and slugging in systems better, small-scale or full-scale tests are conducted.

A setup of a pipeline will be reviewed with respect to prevention of both hydrates and oil spill. Experiments will be conducted where the purpose is concerning water and oil removal. The first case is to mimic an inhibition test, but because an immiscible oil (Exxsol D80) is to be used as inhibitor it will rather be a displacement test. In the latter case water is to displace the initial oil (Azolla ZS 32) in the system. The two displacement cases will be carried out at a Frank Mohn facility in collaboration with Framo Engineering in Bergen.

When it comes to the last issued mentioned, slugging in risers, two small-scale experiments will be studied. These have already been conducted at the laboratory at Norwegian University of Science and Technology.

1.3 Tools available for prediction of fluid displacement in pipes

Multiphase flow simulators are today used to understand and validate the tests. It has become more common to use these tools and several oil and gas companies require verification of them.

Multiphase flow simulators, one-dimensional (1D) and multidimensional, are used to recreate cases and to verify the use of different subsea systems. They can predict flow behavior and predict slugs in a system. Transient simulators are used to give an approximate estimate of displacement, and they play a major role in verification of displacement.

1.4 The simulation tool to be used: LedaFlow Q3D

The simulator LedaFlow has been developed to predict flow assurance issues in the oil and gas industry. The program can offer models in both 1D and Q3D (Quasi-three-Dimensional). Q3D modelling is an approximation of full 3D pipe flow which averages the flow over horizontal slices over the cross section of the pipe, while still taking into account the effect of pipe walls on the flow in a reasonable accurate way. It is less time demanding than full 3D simulation since the calculation grid is two-dimensional, and it gives much more detailed information about the flow than 1D models. It would be of an interest to see how Q3D results matches results from experiments and to compare them with 1D simulations. In this report the use of the Q3D version has been the main focus.

1.5 Purpose of the test

The main objective of this master thesis consists of investigating how well the LedaFlow Q3D predicts displacement, flushing and slug development compared to experimental tests and LedaFlow 1D simulations.

It is expected that LedaFlow Q3D will predict better results in terms of displacement level than LedaFlow 1D. This is due to their different area of applications. As well, previous simulations with LedaFlow Q3D have predicted higher displacement level than what is the case in reality, and in flushing cases the simulations have predicted more flushing (7). Regarding LedaFlow 1D simulations, the previous work has been limited, but it has shown that it predicts higher displacement compared to reality (7). It is of an interest to check whether these trends apply in this work as well.

In addition, execution and analysis of the displacement cases is an aim in this work. The course of both displacement and slugging is an aim to understand. The course of both displacement and slugging is an aim to understand, and how well theory in that matter suites simulations.

1.6 Presentation of the report

The thesis starts with a presentation of a theory part in chapter 2. Information about the different flow assurance issues considered as well as information about simulators, especially LedaFlow will be presented. Chapter 3 concerns the executions of the displacement tests and their results. In chapter 4 the two displacement cases are compared and discussed. Further on, chapter 5 is about construction and simulation of the respectively cases. Chapter 6 and 7 concerns results to each of the cases simulated. In chapter 8 severe slugging will be presented and the results will be discussed. Lastly chapter 9 concerns cross case discussion and conclusions.

2 Theory

In this chapter some flow assurance issues are discussed. When and how problems can occur for then to treat the flow in such a way that problems are avoided, are in focus. Hydrate control, flow control in pipes and components prior intervention of components or subsea systems as well as slugging in s-risers are subjects discussed. The chapter concludes with information about the simulation tool used; LedaFlow 1D and LedaFlow Q3D.

2.1 Hydrates

Hydrates are ice-like crystalline compounds which can form when gas molecules are in contact with water and when these four factors are present (8):

1) Low temperature (<20^0C)
2) High pressure (>20-25 bar)
3) Free water
4) Light hydrocarbons/gas (C1-C4)

It is important to know when there are possibilities for hydrate formation, and whether they will cause a problem or not. Sometimes hydrates tend to go with the flow rather than accumulate on the pipe wall. Thus flow condition has an impact in hydrate build-up. Regarding this issue it is also very important to have a good knowledge about the fluid's composition and understanding both the fluid- and the heat flow properly. (5)

2.1.1 Problems with hydrates

During stop in production or shut-in, due to the stop of hot condensate/gas from the reservoir, pipe cools down and temperatures below hydrate formation can occur. At that condition hydrate plugs can form. Hydrate plugs can fill the entire diameter of the pipe and cause the flow to stop. Once a hydrate plug forms, it may take very long to dissociate, resulting in costly production losses. This is an undesirable situation and can lead to rupture of the pipe, damage of objects in pipeline, such as pumps, valves and instrumentation, and stop of oil/gas production (9). When that point is reached, dissociation of the plug is needed. This may take a very long time. All this will lead to a huge amount of money lost for the oil and gas companies, and is mainly why hydrate prevention strategy is a priority area within this field. Figure 1 shows a hydrate plug which has blocked the whole cross section of a pipe (10).

Figure 1: Hydrate plug removal

2.1.2 Solutions for preventing hydrate formation

To prevent hydrates from forming one must ensure that the four requirements for hydrates formations, 1)-4), are not present. Possible prevention strategies may include:

- Avoiding long shutdowns
- Using insulation
- Heating, re-circulating hot water or gas, or electrical heating
- Chemical inhibitor injection
- "Cold Flow" technology (a new technology where the hydrates are formed, but under controlled conditions in specialized equipment) (11)

Hydrate prevention in form of chemical inhibition is in focus in this work.

2.1.3 The importance of fluid displacement prediction

Whenever you have a low spot, there is a higher risk of hydrate formation during restart operation. This is due to water accumulation in the low spots due to gravity. An undulating pipe has several of these risky spots. A jumper section, which is a section of a pipeline that connects the wellhead with the manifold, represents a high risk area when it comes to hydrate formation. Upon restart, gas mixes with and displaces the water accumulated in the low spot. This will lead to hydrate generation if no inhibitor is used. It is a huge advantage to have ha good prediction of displacement progress to know how much inhibition media to inject and the necessary mass flow rate of it to displace enough water to ensure safe operation.

2.2 Subsea Intervention of retrievable components

Before retrieving a subsea system for reparation of it or to replace it, it is crucial to have control over the content inside the system. A discharge of the content inside the system to the sea will naturally occur and hydrocarbon discharge to the sea is highly undesirable. The oil and gas company have to relate to strict regulations regarding hydrocarbon discharge. This is due to environmental matters, to not cause the environment any harm. In case of any oil spill to the sea the oil will be absorbed by the environment and it will take very long time to decompose the hydrocarbon chains. It will harm the nature, living organism, fish, birds and animals. Therefore before initializing a subsea intervention of a system it is important to remove as much as possible of the hydrocarbon inside the system. It is done by displacing the in-situ liquid with a displacement fluid.

There are different regulations driven by commissions depending on the location of operation in the world. Each country has its own regulations. In addition, in the North-East Atlantic, minimum requirements for regulations on both discharges of hydrocarbons and reporting are driven by OSPAR. OSPAR is a convention driven by representatives from 15 countries and the European Commission, representing the European Union. The legal practice is oil discharging at a maximum concentration limit of 30 mg/l (3).

Regarding an intervention operation if there are expected some amount of hydrocarbon discharge to the sea, the situation is an exception and an application must be sent to KLIF (Klima- og ForurensningsDirektoratet), the Norwegian directorate for climate and pollution. In that letter it is expected to find an explanation for why it is necessary to release the oil, how the oil content are calculated, and whether actions can be done to minimize the emissions. Furthermore, another application is required if the oil concentration exceeds 30 mg/l. In some situations KLIF can provide specific permission to discharge a given amount of oil. (12)

2.3 Slugging

Slugs are liquid streams with a gas pocket in-between which separates them. Slugs often occur in pipelines offshore and can be many hundred meters long. Slug length, slug frequency, liquid holdup and pressure drop vary with time and this makes the slug prediction difficult.

2.3.1 Types of slugs

"Steady state" slugs can be classified as either hydrodynamic slugging or as terrain induced slugging. Hydrodynamic slugging or normal slugging is characterized by many liquid slugs being generated along the length of the pipeline and occurs at higher gas and liquid flow rates. "Transient slugging" can also occur in pipelines as a result of changing operating conditions, pigging or during start-up operations. Terrain induced slugging occurs due to unstable flow path, such as bends or low spots. This type of slugging is more dynamic and less understood than hydrodynamic slugging. Since every flow line has its own elevation profile, every flow line has its own slug characteristics. The worst type of terrain slugging is severe slugging which occurs when the pipeline geometry abrupt changes from horizontal to vertical direction. Severe slugging is often seen in risers, and is characterized by extremely long slugs (50-1000 pipe diameters). This usually occurs when both liquid and gas flow rates are relatively low. The phenomenon requires stratified liquid flow in the pipeline. In addition, it requires that the liquid reaches the top of the riser before the gas flow reaches the bottom of the riser during slug formation. (6)

2.3.2 About riser and slugs in risers

Risers are pipelines which connects the offshore facilities (e.g. FPSO or platform) to the pipeline at seabed. S-shaped risers are often used favorably due to a reduction of mechanical stresses in the pipe. Although due to its geometry the s-risers has a tendency to generate slugs.

2.3.3 Problems with severe slugging in risers

Slugging in risers poses significant challenges in terms of hydrodynamic characterization. It is crucial to understand the development of slugging for each operating riser system in order to prevent damages on risers and appurtenant equipment. In riser based systems, large liquid slugs will accumulate in the riser and the pipeline, blocking the flow passage for gas flow. This result in a compression and pressure build-up in the gas phase that will eventually push the liquid slug up the riser and a large liquid volume will be produced into the separator topside. In some cases the separator cannot manage to purge liquid faster than filling of it, resulting in liquid carry-over in the gas stream, causes platform trips and plant shut-down. A vessel called "slug catcher" in front of the separator are normally used to protect the separator against flooding. The cost of both a small separator and a slug catcher combined is smaller than the cost of a single large separator (13). Load variations on the compressors may lead to unnecessary flaring

When designing a flexible riser one must also consider the huge amount of mechanical stresses that the riser can be inflicted. In case of a long riser with a big inner diameter and a very long slug with a high velocity running through the riser, the mechanical stresses inflicted to the riser are enormous and the actual riser need to be designed to handle these stresses. Long slugs with high velocity can also cause high pressure difference on equipment topside, such as separators and pumps. The pressure differences may also lead to reduced well performance.

Pigging operations and changes in flow rates should be considered when sizing a slug catcher. Slugs caused by pigging are usually much longer than any other types. However, it is impractical to design a slug catcher to hold all the liquid that is brought out of the pigs. The control of the pig speed and the process control system on the slug catcher is very important. [2]

2.3.4 The progress of severe slugging

The process of severe slugging can be divided into four stages (14). The first step is called slug formation or liquid buildup, where liquid entering the pipeline as stratified flow accumulates at the bottom of the riser, blocking the pipe cross-section and causing the gas to compress. Due to low flow rates, the gas is unable to push the liquid upwards.

As the liquid blocks the pipe cross-section the gas flow is unable to penetrate through the accumulated liquid. This results in compression of the gas upstream of the bend. Once the upstream pressure has increased to a higher pressure than the hydrostatic pressure of the fluid downstream of the bend, the liquid slug will move forward and be produced. This stage is called Slug Production (14)

Then, Bubble Penetration stage starts. As the slug is produced, the gas penetrates into the liquid in the downstream section, causing a reduction of the hydrostatic pressure in the column and the gas expands. This leads to a rapidly acceleration of both gas and liquid up the downstream section. The gas will blow out the liquid column with a high velocity.

As the liquid in the riser is swept out, a thin liquid film which is remaining in the riser walls gets depleted by the gas flow over time. This is due to the fact that the pressure reaches to a minimum and the liquid is no longer gas-lifted, resulting in fallback of liquid in the downstream section. This stage is called Gas Blowdown. The liquid will accumulate in the bend causing the slug cycle to repeat itself (15). Figure 2 shows the development of the slugs by illustrating the four stages mentioned (13).

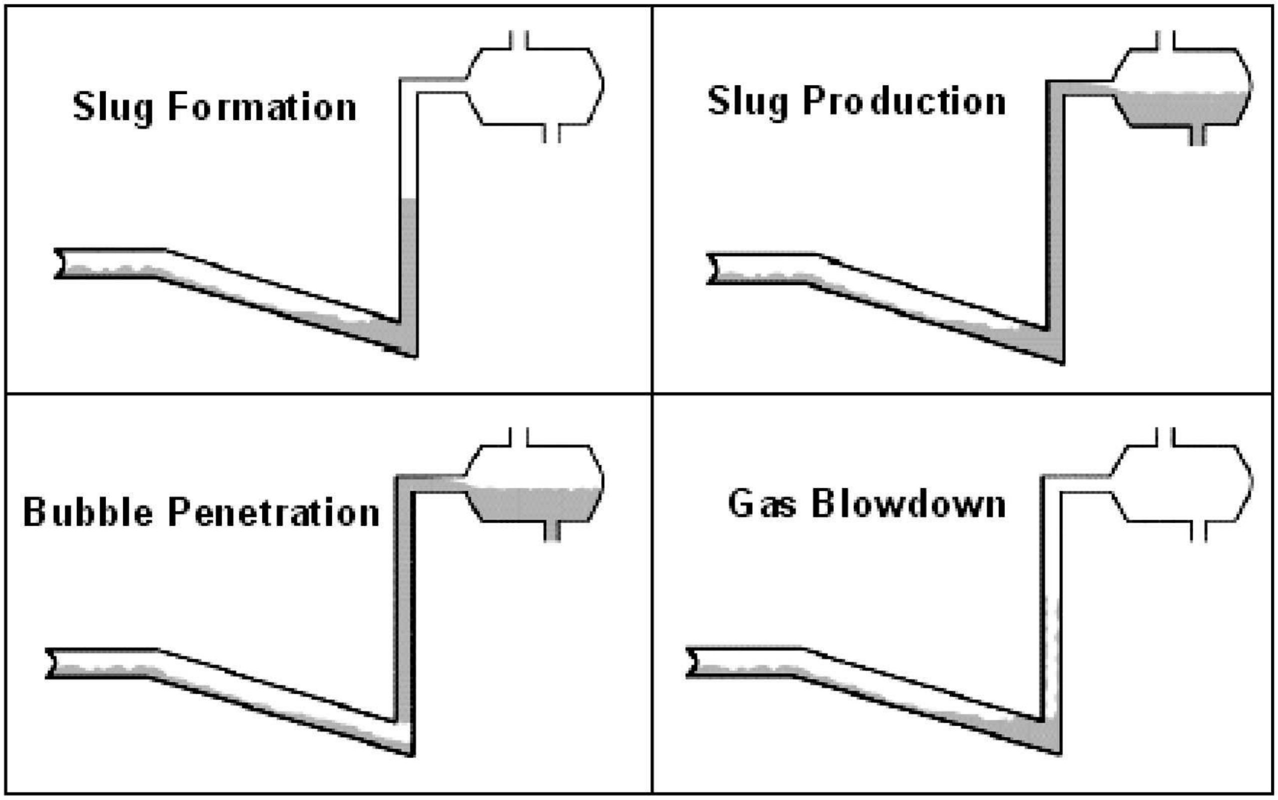


Figure 2: Slug development in riser with four characteristic stages

2.4 Multiphase flow simulation tools

Both 1D and multidimensional tools are used today in the oil and gas industry. The tools are used to predict flow behaviour in pipeline systems. Simulation tools based on mechanistic modelling in the oil and gas industry are mainly 1D, such as OLGA or LedaFlow. The use of 2D or full 3D CFD tools, such as FLUENT is limited, mainly due to very long calculation time. Due to the difference in simulation time they have different area of utilization. While 1D applies best for kilometre long pipelines, multidimensional system suites best for pipeline systems with shorter distances.

The transient simulator LedaFlow has been built with focus on flow challenges in the oil and gas industry. The program includes two types of modelling; 1D and Q3D. The development has been built based on both existing and new large-scale data taken from the SINTEF multiphase laboratory, taken over a nearly ten year period. (16)

2.5 LedaFlow

1D model gives a flat velocity profile for the different phases, whereas multi-dimensional models give a more near-reality approach with a smooth continuous profile. Figure 3 the velocity profile in LedaFlow 1D to the left and LedaFlow Q3D to the right (17). In multi-dimensional models, the possibility for backflow is included (17). The same accounts for the liquid volume fraction profile. One-dimensional models assume flat profiles for liquid hold-up as can be seen in whereas a multi-dimensional approach gives a smooth continuous variation of liquid hold-up. This is illustrated in Figure 4 with holdup profile for LedaFlow 1D to the left and LedaFlow Q3D to the right (17).

Figure 3 Velocity profile: 1D to the left and Q3D to the right

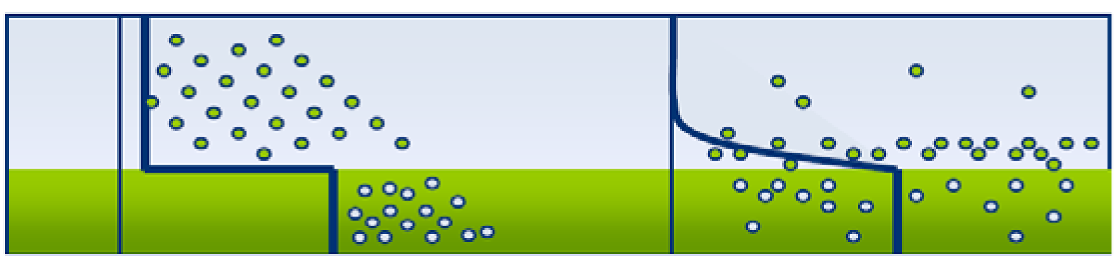


Figure 4: Hold-up and Droplet Fraction Distribution: 1D to the left and Q3D to the right

2.5.1 About LedaFlow 1D

In Leda Flow 1D one can build a model and predict the flow of a multiphase system, two-phase oil and gas or three-phase oil, water and gas.

The flow is divided into different fields and an equation set is derived for each field. The number of fields includes each fluid-continuous region and all possible types of particulates. Thus for two-fluid flow the total number of fields is four (the two continuous layers, the one fluid dispersed in the other and the opposite fluid dispersed in the other). For three-fluid flow there exist nine fields. The fields are characterized by volume fractions, field velocities, enthalpy, temperature, physical properties, and composition. The equations solved for each of the respective fields are transport equation and continuity equations.

Leda Flow 1D offers models for Heat and mass transfer and compositional tracking. In addition the program has models implemented for valves, controllers, wells and bends.

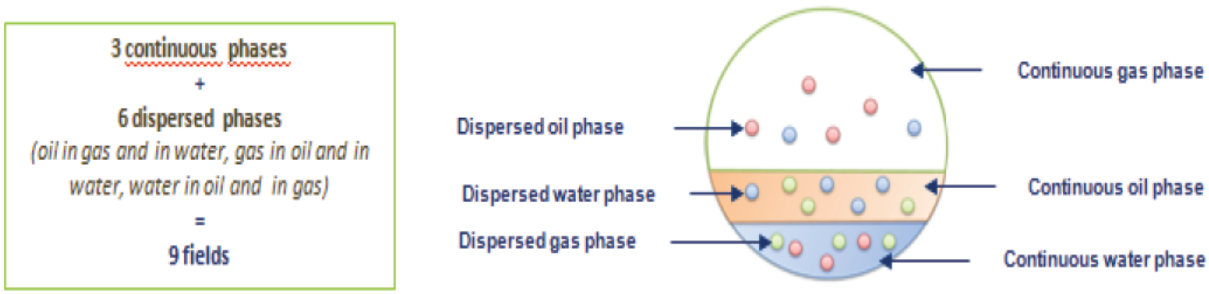


Figure 5: View of a multi-field, multi-fluid flow **(16)**

2.5.2 About multi-dimensional simulation and LedaFlow Q3D

Leda Flow Q3D was made to meet industry needs for improved simulations for oil and gas pipe transport and the related flow assurance issues. While 1D simulation may give inaccurate results, and 3D simulation is time demanding and is only able to handle either dispersed or separated flows, but not a combination of both (18). The LedaFlow Q3D model takes the best of each approach and has the potential to give better results.

Q3D modelling of pipe flow is like 2D, but takes into account the side walls. Local wall-normal distributions of various flow variables such as phase velocities, holdup, bubble and droplet size are captured. In 1D models such flow details and velocity profiles cannot be predicted. Thus 1D modelling does not give a detailed picture of the flow propagation. (19)

In the Q3D model, a multi-level approach is applied and Eulerian volume- and ensemble-averaged turbulent transport equations are derived. The starting point is the multi-phase volume-averaged Navier-Stokes equations. As for Leda 1D modelling, the flow is divided into separate fields (four fields for two-fluid flow and nine for three-fluid flow), and an equation set is derived for each field. (18)

Different fluid-continuous layers are separated by a large-scale interface (LSI). That is another feature that makes Q3D unique. As mentioned, a problem with multidimensional models is that they cannot handle both dispersed and separated flows. They are typically suited for dispersed flows without phase inversion but not for separated flows, whereas the volume of fluid (VOF) type of models are well suited for separated flows while it has problems with dispersed flows.

LSIs are constructed and tracked in time, and using specially designed sub-models, equations of the transport of mass, momentum and energy at these interfaces are solved. LSI keeps track of the amount of droplets and bubbles transferred between each continuous liquid layer.

A reduction of computational time without losing important physics of the flow regarding the pipe geometry has been one of the objectives in LedaFlow Q3D. The total number of equations in the system has been reduced by combining transport equations for fields belonging to the same phase, to create a set of phase equations. In addition a slice averaging of the flow over transversal slices has been applied. This method results in a two-dimensional set of transport equations, in which and additional closure terms are present to model the fluxes acting at the side walls of the pipe. In this way, the most important of these fluxes (wall shear stress and turbulent kinetic energy production) are present locally at each grid cell across the pipe. Flow physics changes due to wall disturbances are taken into consideration and give the Q3D model a more detailed picture than two-dimensional modelling while still being computationally efficient compared to 3D modelling (19). Figure 6 shows the meshing in a pipe in LedaFlow Q3D (19).

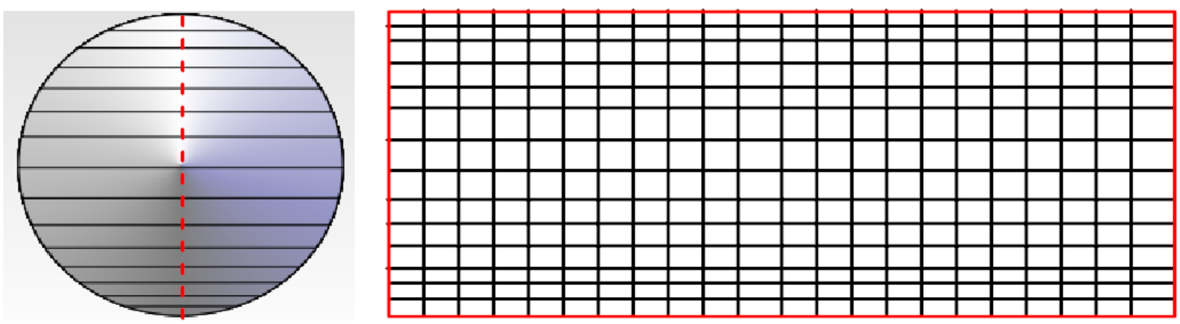


Figure 6: A Q3D mesh for the pipe geometry

In LedaFlow Q3D turbulence is modelled by a filter-based model, where the transport equation for the sub-filter turbulent kinetic energy (TKE) for each phase is solved and the turbulent dissipation is represented by an algebraic closure. The conservation equations for turbulent flow are obtained after averaging of the transport equations. Flow features, smaller than the applied filter size, are modelled by the resulting equation, while the large scale features are resolved. (18) This approach is used for all the field transport equations.

Prediction of change in dispersed phase size is important for the correct prediction of liquid holdup, pressure drop and flow regimes. Turbulent interactions between dispersed phases with each other and with their carrying continuous phase have been taken into consideration in LedaFlow Q3D. (19)

3 Displacement tests

In this chapter displacement tests conducted are presented. The tests consisted of oil (Exxsol D80) displacing water and then water displacing oil (Azolla ZS 32). The purpose of the tests and their relevance for industrial applications, as well as execution of them are discussed here. In addition the test results will be presented and discussed in this chapter. The tests were conducted in collaboration with Framo Engineering AS as a part of the master thesis.

3.1 Displacement test

A multiphase pump is often needed subsea to get an improved oil recovery after a while as the oil reservoir empties for oil and the pressure reduces. When taken in use a multiphase pump, the pressure can be maintained and the reservoir lifetime increases. Figure 7 illustrates a subsea production system with several yellow templates (protection framework) on the sea bed (20). Multiphase pumps are located inside such templates.

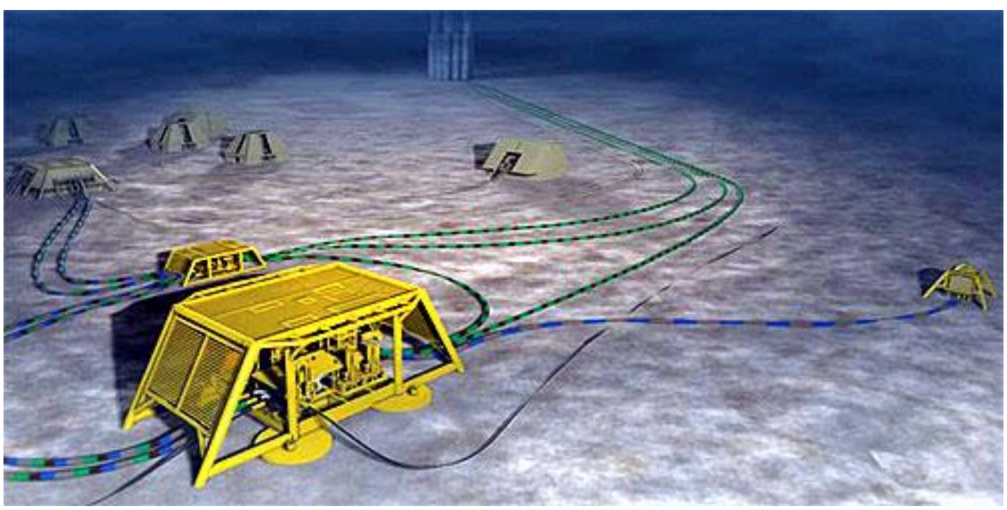


Figure 7: Subsea production system

Before installing such a subsea component system there are several factors that must be taken into careful consideration. The pump is often located several hundred meters underneath the sea surface, thus the pressure is high and temperature low. With respect to flow assurance, the combination of these two factors will pose a high risk of hydrate generation. Another aspect that must be considered in the designing part of a pump system is to ensure safe and legal intervention of the system by removing hydrocarbons prior to subsea intervention.

Figure 8 gives an overview of the setup of a real pump system, with a by-pass section, a mixer prior the pump itself and a splitter after that. As can be seen from the figure, an injection point for displacement medium injection is often located ahead of the mixer.

The purpose of the mixer in the flow line before the pump is to behave as a liquid container. Without such a mixer, the pump will be exposed for transient-flow conditions and has to cope with transient slug-flow conditions with periodically pure liquid flow or pure gas flow. The rapid change of suction conditions will cause sudden load change, which may harm the pump. With the use of a mixer the pump operates in stable conditions which increase its lifetime significantly. The purpose of a splitter after the pump is to split the phases and to send back some liquid to the mixer in case of very low liquid content in the mixer (21).

A rig has been built to carry out full scale displacement tests at one of Frank Mohn's facilities in Bergen (Figure 9). The rig is to represent a retrievable part of a subsea module. It includes a multiphase pump, an inlet piping system and an outlet piping system. Most often, only the pump section will be retrieved from the system.

Figure 9 illustrates the setup from the full-scale tests conducted. The setup was meant to mimic the real pump arrangement. The first vertical section and bend is to represent the volume of a mixer. The same principle applied to the splitter. It is not included in the setup, instead a vertical pipe section is to represent its volume.

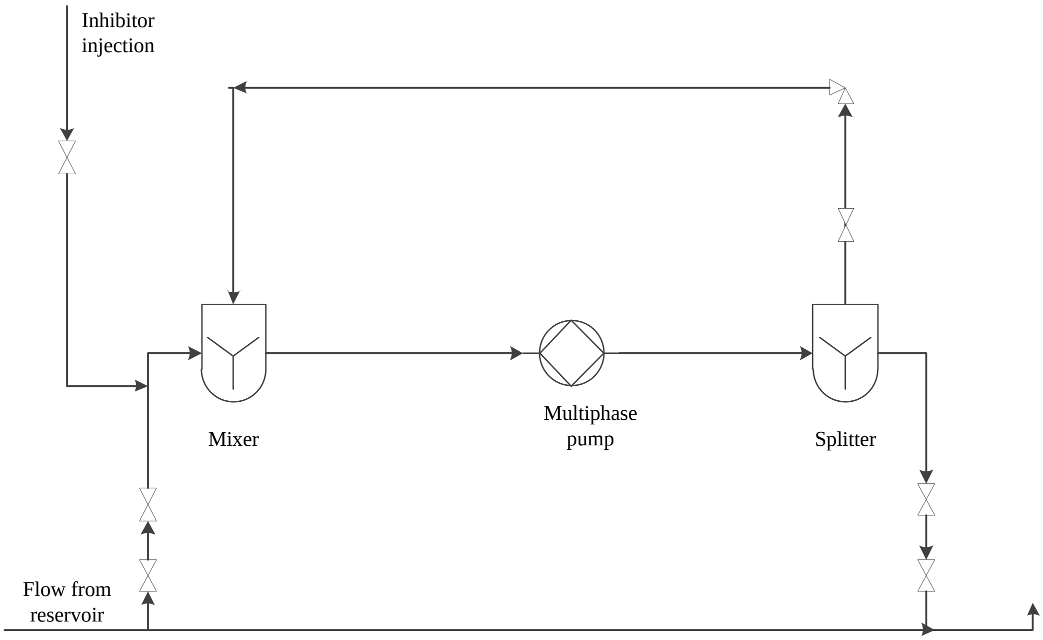


Figure 8: Sketch of a typical subsea pump system (simplified)

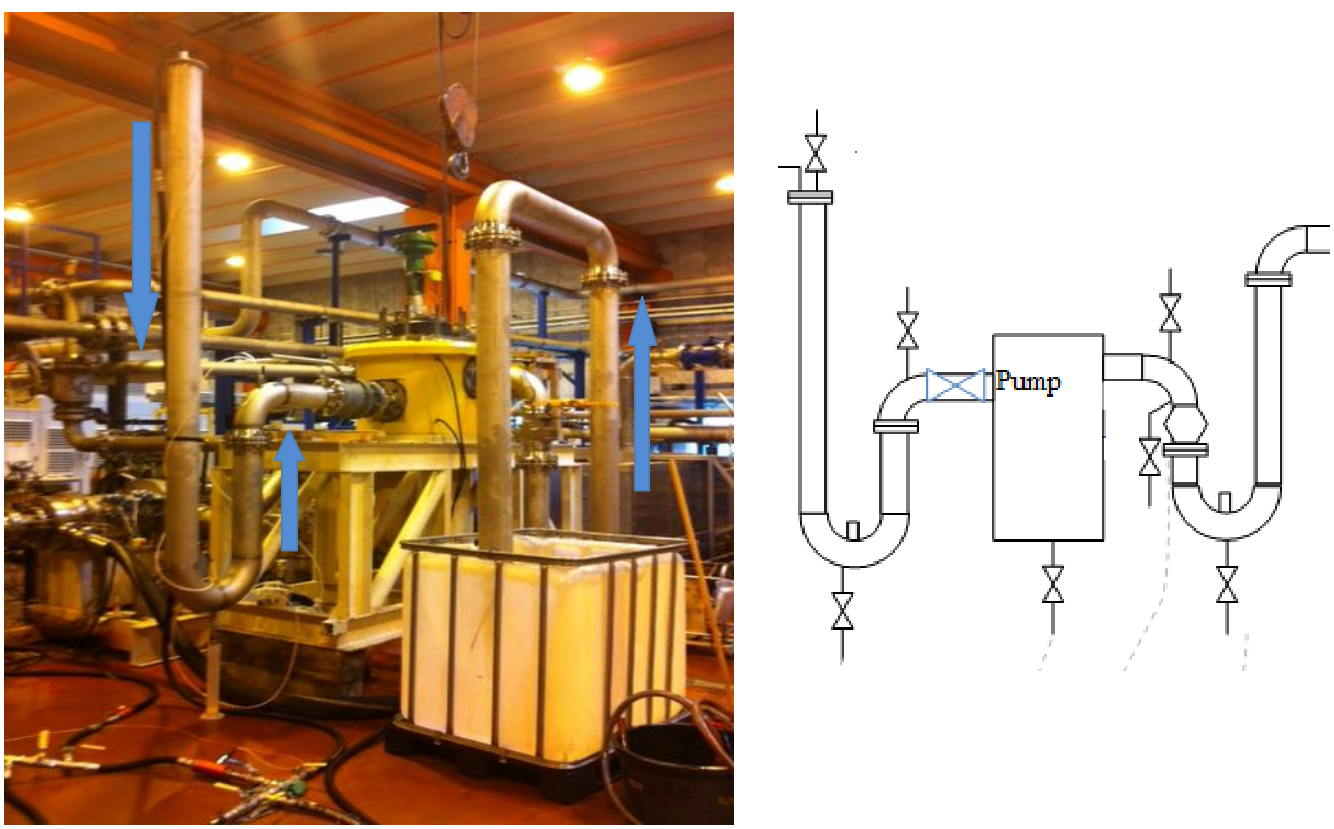


Figure 9: Multiphase pump arrangement from experiments

3.2 Tests with Exxsol D80 displacing water

Flow assurance in terms of hydrate control was the first subject to look deeper into regarding the test setup explained above. The purpose for this test was to check if one injection point with the chemical inhibitor, Methanol was sufficient to sustain a hydrate controlled flow through the pipe system. The inhibitor injection point is located ahead of the mixer, illustrated at the top left in Figure 8 and Figure 9.

When injecting Methanol to a fluid stream, the chemical mixes with the flow and allows operation in more extreme environments, low temperature and high pressure, by moving the hydrate formation curve to the left (5). Figure 10 shows in what conditions it is safe and not safe to operate in terms of hydrate formation (5). Figure 11 illustrates the effect of adding 10% or 20% Methanol to the water (5). Methanol, which is a small molecule do not contribute to hydrate formation because it is hydrogen bonded and hence interferes with the hydrogen bonding among the water molecules (8). In addition, methanol is highly soluble in water, whereas the solubility of methanol in hydrocarbons is very small. (8)

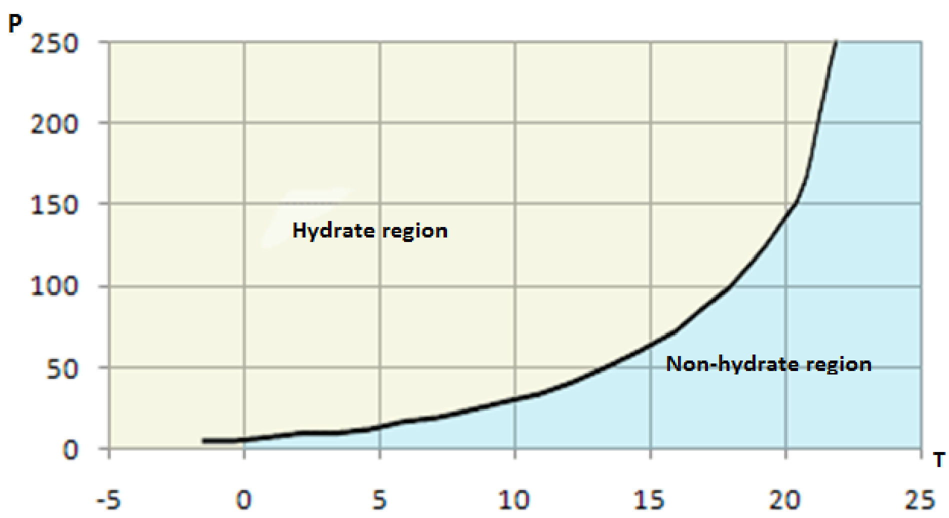


Figure 10: Hydrate formation curve showing safe operational area and hydrate region

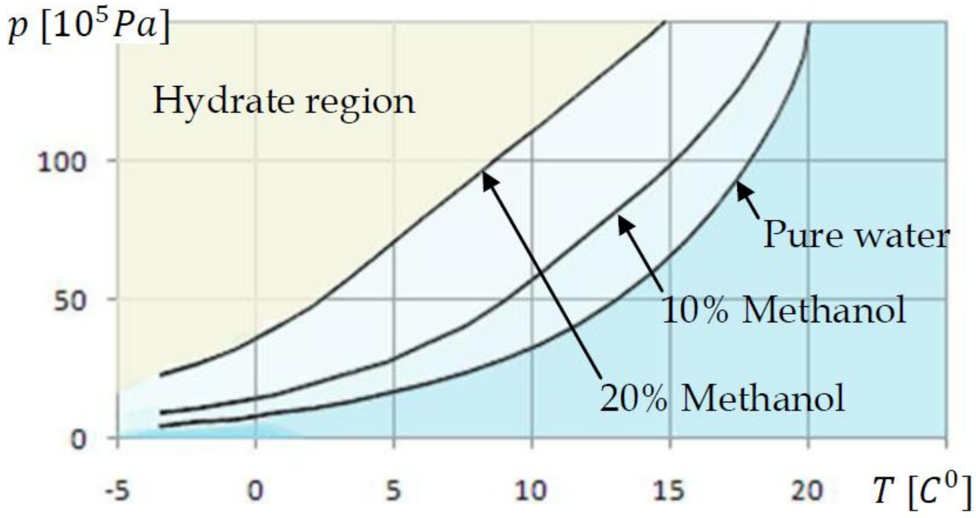


Figure 11: Hydrate formation curve, with Methanol concentration affection included

In this work, however, the injection medium used was not Methanol, but Exxsol D80. The main reason for using Exxsol D80 instead of Methanol is due to the major damage Methanol could cause to the environment and people. The medium is, not good to breathe, highly flammable and what makes it even worse in use is that the flames are invisible (8). Exxsol D80 does not represent any severe danger in use. Still, exposure of the chemical may cause human health risks and it must be disposed of in an environmentally safe manner (22). Therefore, work on Exxsol required the use of protective equipment.

An argument for the choice of displacement is that Exxsol D80 has a density very similar to what Methanol holds (respectively $798\frac{\mathrm{kg}}{\mathrm{m}^3}$ for Exxsol and $791\frac{\mathrm{kg}}{\mathrm{m}^3}$ for Methanol at 20˚C). On the other hand, whereas Exxsol D80 is immiscible with water, Methanol behaves quite contrary and mixes with water. Therefore this test becomes a displacement test and not an inhibition test, where Exxsol D80 is to displace accumulated water rather than interfering with it.

Five displacement tests were to be conducted where two of them were repeatability tests.

3.3 Water displacing Azolla ZS 32

As explained in chapter two it is important to avoid any hydrocarbon spill to the sea. Therefore, strict testing of subsea systems is required in the oil and gas industry. The reason for displacing Azolla with water was to check how much Azolla that was left in the system after displacing it with water.

Azolla is a viscous oil with a viscosity of 86,3 $\frac{\mathrm{mm}^2}{\mathrm{s}}$ at 20˚C, and is immiscible with water. The oil has a density of 875 $\frac{\mathrm{kg}}{\mathrm{m}^3}$ at 20˚C and therefore heavier than Exxsol.

Nine tests with two different initial GVF was to be carried out:

- seven tests with initially 68% oil in the system, and
- two with a completely oil filled system

3.4 Experimental setup, Exxsol displacing water

The test was conducted at a Frank Mohn facility, at Flatøy, Bergen. The test setup used was an already existing setup from earlier tests performed. The setup was of full-scale size and contained all valves and other equipment to mimic an industrial pump system. All pipe sections and bends are 6" SCH10S with an inner diameter equal to 161.5mm. All bends had a center radius of 229mm. The test setup is shown in Figure 12 with the inlet section starting at the top of the vertical pipe section to the left of the figure.

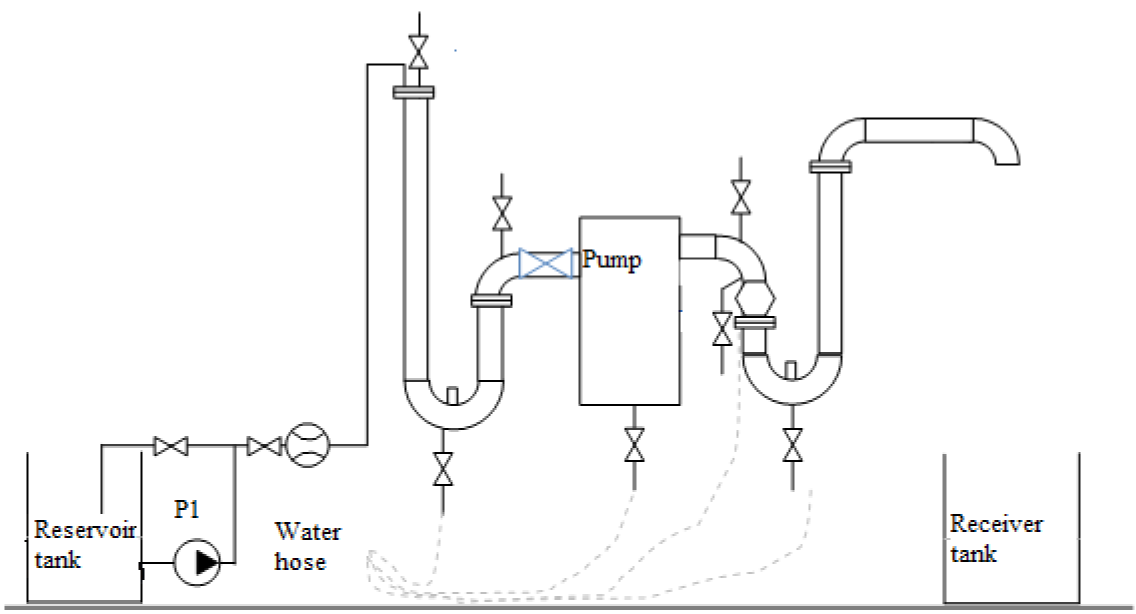


Figure 12: Experimental setup Exxsol displacing water

3.4.1 Inlet section

The rig starts with a 3090mm long vertical pipe segment followed by a 180^0 bend. Another vertical pipe segment, 750mm connects the bend to a 90^0 bend. After that there is a 440mm long pipe segment which is connected to a 400mm long ball valve, V11. It is the ball valve that separates the inlet and the pump section. However, one third of the ball valve volume falls under the inlet section. Figure 13 shows the inlet section with additional arrows indicating the flow direction.

Figure 13: experimental setup, Inlet section

3.4.2 Pump section and outlet section

Even though the tests were conducted and results found and analyzed from all three sections in the setup, the pump section and the outlet section will not be discussed in this work. The main reason for this is due to a desire on confidentiality from Framo Engineering side. In addition, the applicable sections will not be treated further on with the simulator LedaFlow as the inlet section will be.

3.5 Measuring the volumes

First thing that needed to be done in order to carry out the tests was to find the correct volumes inside the pump system for each section. It was important to start with a correct initial GVF in each of the parts as planned and calculated. The volumes were first calculated and then measured. Simplifications were made during the calculations, and regarding the inlet section V11 (Ref: Figure 13) was estimated to hold the same inner diameter as the rest of the system. The inlet section was of a volume equal to 112 liters while the measured volume of the same section was 113 liters. The deviance in the volumes was very small with respect to the large volume the section represented, thus the deviance was negligible. The volume that was used in further work was the measured volume.

3.5.1 Procedure in measuring the volumes

First the correction factor to the counter connected to the water hose was found. We filled 10 liters of water into a bucket, and based on the change in volume registered on the counter system, a correction factor was calculated. This procedure was repeated until a representative factor was achieved. Then we measured the volumes of the three sections by filling them completely and then drain each of the sections into 15 liters buckets and measure the volumes drained. During this task the V11, which separated the inlet from the pump section was kept closed. While filling the volumes it was important to keep control on the venting valves. When water was dripping from them the injection was stopped. After some seconds when the water had settled the injection was restarted again, with a low injection rate until water once again was observed out of the venting valves.

3.5.2 Errors occurring while measuring the volumes

Errors that took place and had an impact on the results of the measuring of the distinct volumes included:

- Difficulty in measuring the correct amount of liquid. Only approximate values could be reached due to large volumes and inaccurate reading from the 15 liters buckets. The large number of these buckets could lead to a wrong number of the total volume registered.
- Correction factor for the counter connected to the water hose not 100% correct. The correction factor may vary during the day due to variations in pressure in the hose due to variation in use of water in the rest of the building.

3.6 Experimental procedure: Exxsol D80 displacing water

Before starting the tests, a correction factor for each of the mass flow rates used had to be found. An injection pump was used to boost up the mass flow rate of Exxsol. 40 liters of the oil was filled into a bucket, and based on the registered volume from the turbine flow meter the correction factor was calculated. This procedure was repeated until a representative factor was achieved. A new factor needed to be found for each rate (e.g. a factor of 0.8 might be reasonable for a rate of 2.5 m^3/h, while a factor close to 1 is required for a rate of 5 m^3/h). After that the initial conditions were ascertained; that there were no liquids inside the system, that all valves were closed, that the reservoir tank was only containing Exxsol and that the receiver tank was empty.

It was desirable to conduct the tests with an initial total GVF (gas volume fraction) for the whole system to be 32%. However, in this test setup it was physically impossible to reach such a low GVF without liquid flowing into the pump section, and therefore and unequal initial GVF was used for the three parts. For the inlet section, the applied GVF (and the lowest possible) was 59.6%. Then, the liquid column in the pipe reached up to the 90° bend. This initial GVF applied for all the tests conducted.

After the wanted GVF was reached all valves were closed and the injection of oil was initiated by pumping Exxsol D80 from a reservoir tank to the start of the setup. The injection continued with a predetermined mass flow rate and time. Then the pump was shut and consequently the injection stopped. V11 was then closed in order to divide the inlet section from the pump section. After a no-touch time of approximately 10 minutes to let the phases separate, each section was drained and measured. Dye was added to the oil in order to separate the oil from the water. Detailed description of the test procedure can be found in Appendix A.

The five displacement tests that were conducted with details of each test are presented in Table 1.

Test ID	Injected volume, water (l)	Number of process volumes of Exxsol injected	Injected volume Exxsol (l)	Exxsol D80 injection rate (m^3/hr)	Exxsol injection time (s)
A1-A	289.68	2	852	2.5	1226.88
A1-B	289.68	2	852	2.5	1226.88
A2	289.68	4	1704	2.5	2453.76
A3	289.68	2	852	5	613.44
C5	289.68	1	426	2.5	613.44

Table 1: Tests details, Exxsol displacing water

3.7 Experimental results and discussion, Exxsol displacing water

The levels of displaced water (sweep efficiency) in the inlet section for all the tests are shown in Figure 14. The displacement levels were calculated by dividing the removed water by the initial amount of water inside the section.

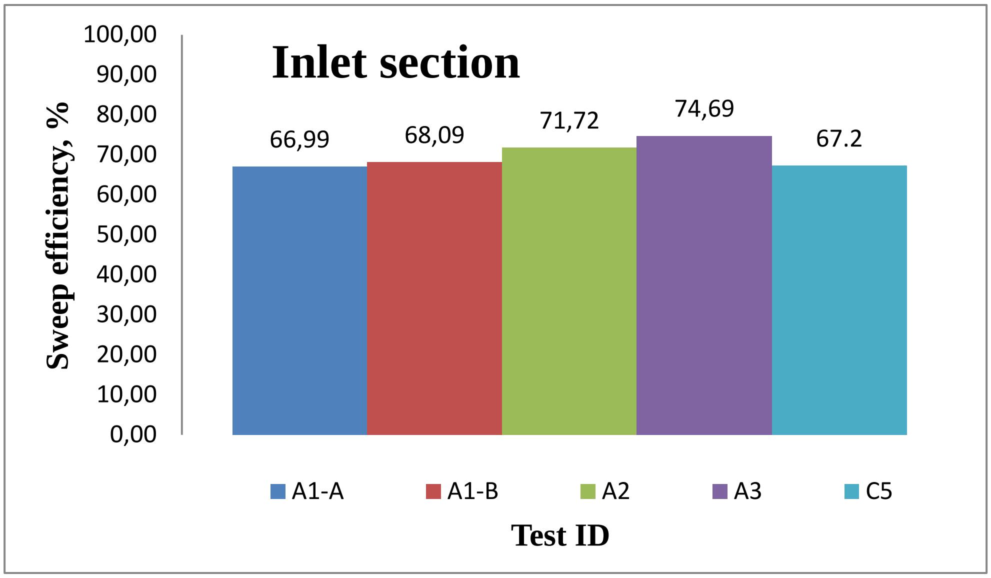


Figure 14: Displacement levels of tests where Exxsol displaces water

As can be seen from, the displacement tests resulted in high sweep efficiencies in the inlet section in all the tests conducted. As can also be seen from Figure 14 is that a change in mass flow rate has a larger impact on the sweep efficiency compared to what a change in duration of displacement has. In general, it was observed that changes in mass flow rates injected and duration of displacement led to small variations of sweep efficiency. For instance, the execution of test A3 resulted in the best test results in terms of displacing the most water. This test was run with the highest mass flow rate ($5\text{m}^3/\text{hr}$).

The test that pointed out to be the one giving the lowest level of sweep efficiency was test C5. It was carried out with a low mass flow rate ($2.5\text{m}^3/\text{hr}$) and with a small amount of displacement medium injected (1* total volume).

3.8 Experimental Setup, Water displacing Azolla

Before the testing with Azolla the test setup needed to be modified in order to do the reverse testing; water displacing oil and not the opposite. The water hose was connected to the flow line before the turbine flow meter. In this way the mass flow rate of water could be measured. In addition some additional hoses and valves were implemented to the setup so that it was easy to connect the oil hose to the filling points V4, V6 and V10 (ref: Figure 15). On the line after the flow meter an extra hose was connected. That was only used when the correction factor were to be found so that there were no need to tamper with the setup each time the correction factor needed to be found.

3.9 Experimental Procedure, water displacing Azolla

Figure 15 shows the setup of the test case where Azolla was to displace water.

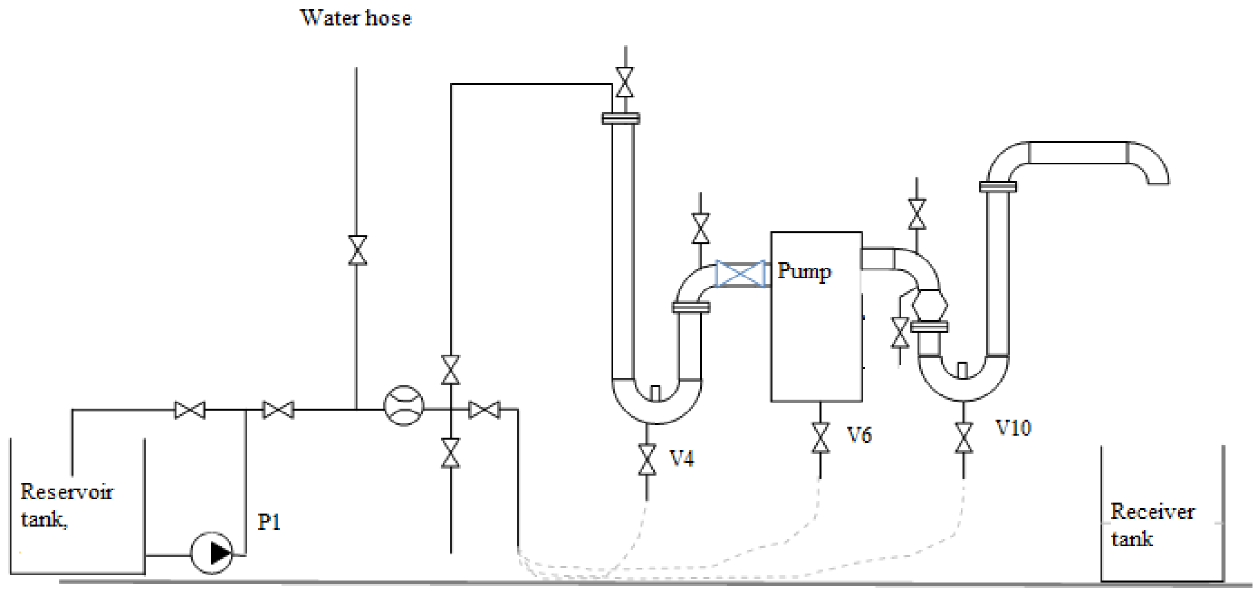


Figure 15: Experimental setup, water displacing Azolla

Before starting the experiments with Azolla the containment in both receiver tank and reservoir tank were removed. The tanks were washed and the reservoir was filled with Azolla. As in the procedure for testing with Exxsol the first task was to make sure of that the given initial conditions were maintained. The initial conditions were the same as for testing with Exxsol except for the containment in the reservoir tank which were to be filled with Azolla, not Exxsol. As for testing with Exxsol the correction factor needed to be found for the oil. But in this case as well as oil, water was also flowing through the flow meter and therefore a correction factor for water needed to be found as well. The procedure was the same as for finding the correction factor for oil. Then everything was set for starting the tests.

The principle of the test procedure was the same as for the tests with Exxsol displacing water. After the initial conditions were established, the medium that was to be displaced, in this case Azolla was injected through injection points at the bottom of each section to reach the wanted GVF for each section. Then the displacement started by opening the water hose leading the water to flow through the system from the inlet.

The rest of the displacement procedure went on in the same procedure as the displacement test with Exxsol, but with a no-touch time of 40 minutes. This was necessary due to the properties of

Azolla, leading to a longer separation time with water. Detailed description of the test procedure can be found in Appendix B.

In total nine Azolla tests were conducted, where one of the tests was a repeatability test. Seven of the tests had an initial total GVF in the system of 32% while two tests cases were initially oil filled. As for the tests when Exxsol was displacing water, the tests with an initial GVF of 32% for the system the inlet held an initial GVF of 59.6%. An overview of the tests is shown in Table 2.

Test ID	Initial GVF Azolla, %	Injected volume, Azolla (l)	Process volumes, water injection	Injected volume water (l)	water injection rate (m^3/h)	Water injection time (s)
D1	32	289.68	1	426	2.5	613.44
D1-B	32	289.68	1	426	2.5	613.44
D2	32	289.68	2	852	2.5	1226.88
D3	32	289.68	2	852	4.7	652.60
D4	32	289.68	4	1704	2.5	2453.76
D5	32	289.68	0.5	213	1.25	613.44
D6	32	289.68	4	1704	4.7	1305.19
E1	0	426	4	1704	4.7	1305.19
E1	0	426	2	852	4.7	652.60

Table 2: Test details, Water displacing Azolla

3.10 Experimental results and discussion, water displacing Azolla

The percentage of displaced water for each test in the inlet section is shown in Figure 16. The values are calculated by dividing removed Azolla from the system after ended testing by the initial volume of Azolla.

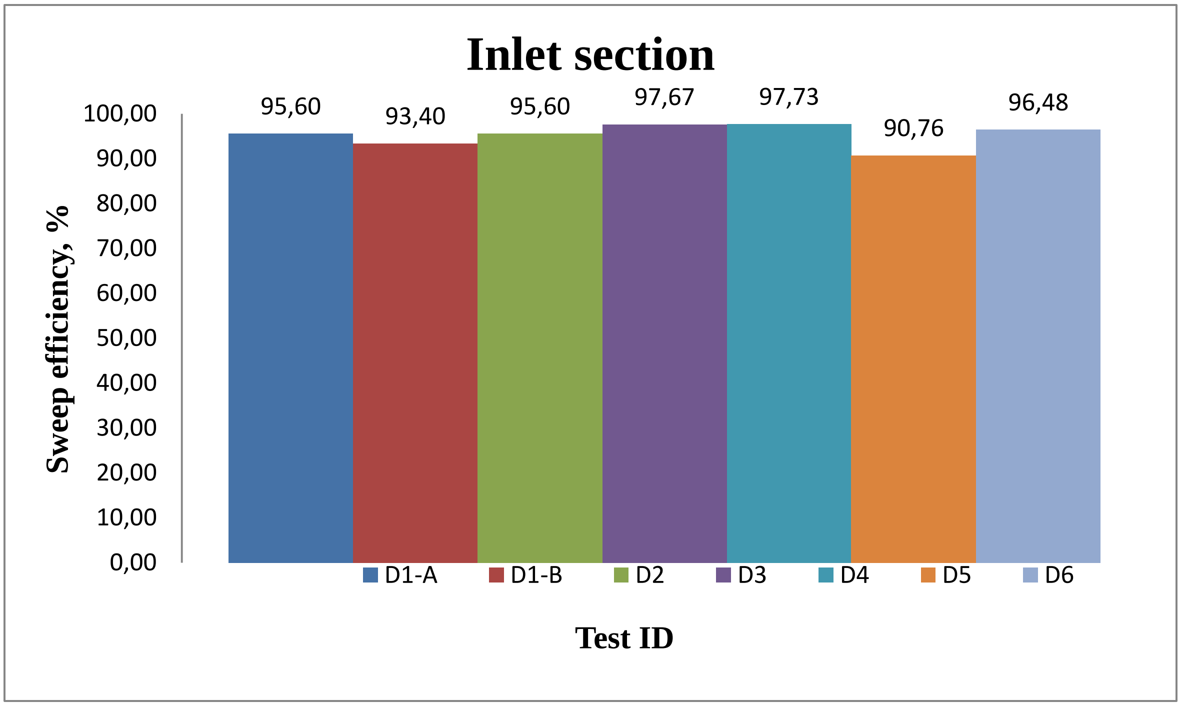


Figure 16: sweep efficiencies for tests conducted where water displaced Azolla (59.6% Azolla initially)

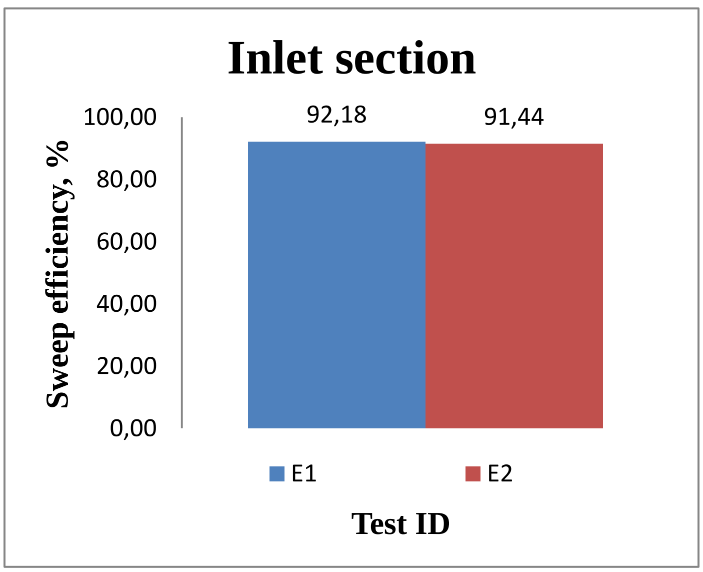


Figure 17: sweep efficiencies for tests conducted where water displaced Azolla (initially oil filled)

Results from the tests conducted with an initial GVF of 0%, E1 and E2 are presented in Figure 17

As can be interpreted from Figure 16 the level of displacement is not that much affected by change in mass flow rates or for how long the displacement went on. In fact the only test case which did not result in sweep efficiency near to 100% was test D5. In that test the mass flow rate was $1.25\mathrm{m}^3/\mathrm{hr}$ and the amount of displacement medium used corresponded to half of the volume of the whole arrangement.

Regarding the tests that were completely oil filled the same trend was observed, with high sweep efficiencies were measured in the inlet section. From Figure 17 it can be seen that the tests gave a slightly poorer displacement for test E2 than for E1 (the test in which the injection duration was twice as long) but due to errors (explained underneath 4.2) it can be concluded that the level of displacement was the same.

When comparing the sweep efficiencies from the displacement tests with the two different initial conditions and comparing Figure 16 and Figure 17, one must keep in mind that it is only test D3 and D6 that can be compared to E1 and E2. This is because it is only test D3 and D6 with initial 32% total GVF that have been tested with the same velocity as the tests E1 and E2 was tested with, or nearly the same velocity ($5\mathrm{m}^3/\mathrm{hr}$ versus $4.70\mathrm{m}^3/\mathrm{hr}$). When comparing there are two points that can be highlighted:

- The same trend of displacement occurs in tests of both initial conditions, and
- The level of displacement is about the same for all the four test cases considered. There are only small deviances from the results and these can be explained by the errors (4.2)

It can be mentioned that the sweep efficiencies in the outlet section, which had approximately the same geometry was quite alike the sweep efficiencies in the inlet section. This makes the results from the inlet section more reliable.

4 Cross case discussion of the displacement tests

In this chapter, the displacement tests will be discussed. Both the results from the tests where Exxsol was displacing water and the results from the tests where water displaced Azolla will be evaluated. Finally conclusions and errors will be presented.

The two different test cases, where one was about displacing water with Exxsol and the other one was about displacing Azolla with water, are not really directly comparable. This due to

- First oil is displacing water in one case and in the other case the reversed displacement action was taking place, and
- Two different oils with distinct properties were used.

However it is interesting to measure the case results against each other. To start with the similarities from the results of the displacement cases, the trend was that a change in mass flow rate of the displacement medium had a greater influence on the results than a change in duration of the displacement caused. Although this was very hard to see for the latter case concerning Azolla displacing water due to the high displacement levels.

Both of the two types of displacement tests and with the two different initial GVFs gave good overall displacement in the inlet section. However, the displacement levels when water displaced Azolla was higher than for the case where Exxsol displaced water (~95% versus ~70%). The reason for this was assumed to be first and foremost due to the density differences between the displacement medium and the displaced medium.

By looking at the mediums accounted in the tests (Ref: Table 3) it is natural that water (which is heavier than Azolla, Ref: Table 3) displaced the oil better than Exxsol (which is lighter than water) displaces water. Another factor that contributes to the displacement course and that plays a role in the displacement levels is viscosity difference between the displacement medium and the medium to be displaced. In this matter Azolla is a viscous oil and may affect the water front nose when the water displaces the oil.

4.1 Conclusion of the displacement tests conducted

Due to the similarities of the displacement results when testing with Azolla and water with both of the two initial GVF one can conclude that the initial GVF in the system have quite small influence on the displacement of the system. On the contrary, factors that are assumed to play a role in the displacement results are:

- The geometry of the system contributes to the displacement progress and therefore the displacement level.
- The properties of the medium that is originally in the system and the properties of the medium that is injected: Gravity will naturally pull down the heaviest medium to the bottom.
    - Density differences. Gravity will naturally pull down the heaviest medium to the bottom. When Exxsol (which is lighter than water) is to displace water, some of the Exxsol will sneak past the bend in its inner curve instead of pushing the water throughout the pipe. Regarding the displacement course of water displacing Azolla the high displacement level can be explained by the fact that water is heavier than the oil and will push the oil easily throughout the bend (ref: Table 3).
    - Viscosity differences. Another moment that could have effect on the course is the viscosity differences (ref: Table 3). The parameter could influence the form of the displacement mediums front nose during the displacement course, which again could affect the level of displacement.

4.2 Challenges and Errors

As well as for calculating the volumes, errors easily occur when measuring the remaining liquid content in each of the parts in the setup as well as establishing and sustaining a correct mass flow rate injected. Several factors that may lead to errors affecting the results were:

- The possibility to have small amounts of water in the reservoir tank, due to:
    - Pumping back from receiver tank before water and oil had separated completely
    - Inaccurate discharging of the 15 liter buckets into the reservoir tank in case of small amount of water in the buckets.
- The possibility of having small amount of water dispersed in the oil phase when measuring the oil (Azolla)
- Difficult to measure correct amount of liquid, only approximately values could be reached due to large volumes and inaccurate reading from the 15 liters buckets. The large number of these buckets could lead to a wrong total volume.
- Correction factor for the turbine flow meter was not 100% correct. It was difficult to find the correct correction factor because of the large bucket volume and therefore;
    - Difficult to fill it up with the correct volume, and
    - Difficult to find the correct time.

This led to small margins required to make the correction factor change.

- Correction factor for the counter connected to the water hose was not 100% correct. The correction factor varied during the day due to variations in pressure in the hose due to variation in use of water in the rest of the building.
- Not correct mass flow rate injected:
    - Mass flow rate would increase and decrease a little bit from what we tuned it to be at the beginning. Important to keep an eye on the simulator while simulation running so that one could tune the mass flow rate back to what it should be when it changes.
    - Difficulty to tune the mass flow rate to the wanted rate. Often the mass flow rate had a deviance of $0.2m^3/hr$ below or above the ideal mass flow rate.
- The desired mass flow rates was reached first after some seconds during ramp up of injection flow

5 Simulations of displacement tests

In this chapter it is stepwise explained the course of constructing the cases with implementing the geometry, properties and numerical settings followed by initializing and running them. Due to limitations regarding complexity of the geometry (e.g. LedaFlow Q3D cannot operate with several diameters), only the inlet section of the pump arrangement was simulated in LedaFlow 1D and LedaFlow Q3D.

5.1 Numerical simulations in LedaFlow

The experimental arrangement was recreated in LedaFlow 1D and LedaFlow Q3D. The simulations were to mimic the experiments conducted and therefore mass node was used at the inlet whereas pressure node was used at the outlet. In this way the inlet mass flow could be controlled and the atmospheric pressure at the outlet was specified.

Assumptions that were made for this case:

- Isothermal flow (constant temperature) – therefore the energy equation was not solved and values for conductivities and heat capacities were not implemented
- Incompressible flow

5.1.1 Constructing the cases

The first step in the simulation process was to set up the case: set fluid properties, numerical settings, pipe geometry, the boundary conditions, and to set the meshing.

5.1.2 Fluid properties

PVT properties used in the simulations were set manually. Values used for density, viscosity and surface tension at 20°C are implemented (Ref: Table 5 and 6). Atmospheric pressure and temperature are also specified. For the simulations where Exxsol was to displace water, properties for air, water and Exxsol was implemented in LedaFlow. Regarding the simulations of Azolla displacing water the same properties were used but the oil properties were changed.

Medium	Densities [kg/m^3]	Viscosities [Pa*s]
Air	1.229	1.73E-05
Exxsol D80	798	0.0018929
Azolla ZS 32	875	0.07549
Water	998.6	0.001139

Table 3: Fluid properties at 20°C

Relations	Surface tension [N/m]
Gas-Oil	0.0207
Gas-Water	0.072
Oil-Water	0.0344

Table 4: Surface tensions for different phase relations at 20°C

5.1.3 Final steps of set-up of the case and running simulation

The case was constructed by implementing x and z values for each extremity of the arrangement and then discretized (adding bends) by setting a radius at the points. Then the appropriate x and z mesh (number of cells in x and z direction (with respect to pipe direction)) was set. However, for the 1D cases only x mesh could be specified. As well, a diameter similar to the experimental diameter (16,15cm) was specified.

Then a realistic wall roughness ($1.5 * 10^{-5}$m) and boundary conditions were set; values for superficial gas velocity in the mass node at the inlet and atmospheric pressure (1.01325bar) in the pressure node at the outlet.

Numerical settings, such as maximum time step, sample time, simulation time, starting time and CLF[5] were set. To enable the simulations, these values were not similar for each case due to numerical and physical differences, which made the degree of difficulties for the simulations different. The next step was to initialize the cases, followed up by running them.

[5] CFL is a constant that decides the minimum time step by using the transportation time from one cell to another in either x or z direction.

5.2 1D Simulations

The two different displacement cases were set with properties as mentioned earlier. Fluid properties, numerical settings, pipe geometry, the boundary conditions, and the meshing were specified.

The pipeline was set to contain 200 equally sized cells in the x direction. The reason for the high number of cells was to achieve an initialization with correct liquid level, to minimize the deviance of initial liquid volume inside the system from what was the case in the test.

For the tests where the initial total GVF of the whole system was 32%, the GVF for the inlet section was 59.6%, thus the inlet contained 45.43 liters of liquid. The cases were initialized with specifying the content in each cell. With a pipe length of 5,49m divided into 200 cells it lead to having 85 gas filled cells from the inlet of the pipe followed by 81 cells with water and finally the remaining cells gas filled.

Regarding the tests where the initial total GVF was 0% the cases were initialized with only Azolla present in the inlet section. Figure 16 and Figure 17 illustrates the setup with the initial conditions.

After specifying the content in each cell in the 1D cases, the cases were simulated.

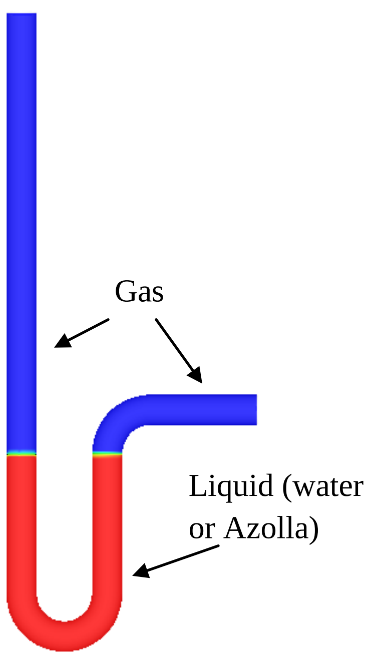


Figure 17: Initial state, GVF=59.6%

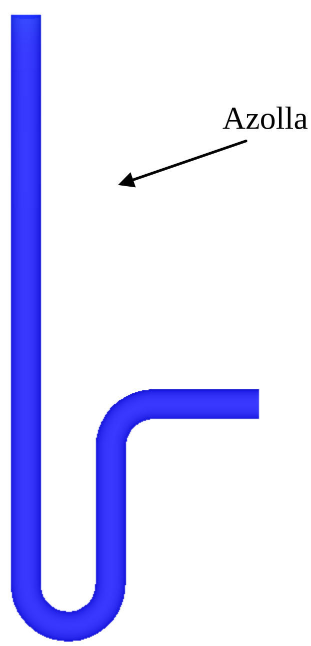


Figure 16: Initial state, GVF=0%

5.3 Q3D simulations

The procedure with setting up the cases in LedaFlow Q3D was the same as for LedaFlow 1D, but also with the number of cells in z direction taken into account. For the cases with 59,6% initial GVF, uniform mesh was used, but at the beginning and at the end of the pipeline a coarse mesh was used, whereas elsewhere a rather fine mesh was set in order to resolve as much of the actions as possible. The cell sizes were respectively 0.07 and 0.0228 meters. However, the cells in z direction were equally sized with a size of $8.075 * 10^{-3}$mm With a total length of the pipeline equal to 5,49m it led to having an aspect ratio, AR[6] of 8.67 for the coarse mesh and AR=2.82 for the fine mesh. It is assumed that these aspect ratios are good enough to use in the simulations in the respective cases.

Then the cases were initialized by setting the content inside the system; the first 2,34 meters was set to contain only gas, the next 2,22 meters was set water filled while the rest of the system were containing gas. Then the simulations of the cases were started.

[6] Aspect ratio= $\frac{cell\ length\ in\ x\ direction}{cell\ length\ in\ z\ direction} = \frac{\Delta x}{\Delta z}$

6 Exxsol D80 displacing water: Simulation Results and discussion

In this chapter the simulation results, both from LedaFlow 1D and LedaFlow Q3D are exposed and compared with each other as well as with the experimental results. Not all of the test cases conducted experimentally were carried out in LedaFlow Q3D, since numerical stability problems occurred due to large density differences gave very long simulation times for some of the cases. All of the test cases were simulated in LedaFlow 1D.

6.1 Comparison of displacement

When simulating in LedaFlow, in particular LedaFlow Q3D there are several factor that affects the simulations and can be changed in order to achieve the most optimal simulation.

Regarding the displacement tests with Exxsol displacing water it was soon detected that running the simulations of the tests with normal default values in LedaFlow Q3D led to deviations from the experimental results. The default values for the different droplet- and bubble sizes are listed in table 7. Consequently some parameters needed to be changed in order to achieve simulation results closely linked to the experimental results.

Droplet, bubble specification	Size (mm)
Air bubble in oil	1
Air bubble in water	1
Oil droplet in air	0.5
Oil droplet in water	0.5
Water droplet in air	0.5
Water droplet on oil	0.5

Table 5: Default values of droplet/bubble size

For the test cases with Exxsol as displacement medium and water as the medium to be displaced, test A3 was used as a base case to find the changes that needed to be made. Test A3 had an injection mass flow of Exxsol of $5\mathrm{m}^3/\mathrm{hr}$ and the injection lasted for 613.44s. As mentioned earlier, in the A3 experiment 74.7% of the water was displaced.

Figure 18 shows the end state with the water and gas content inside the system when default values for the droplet size were used. The simulation was stopped after 159 seconds because almost everything of the initial water had been swept away at that point. Only 1.45 liters was remaining in the system.

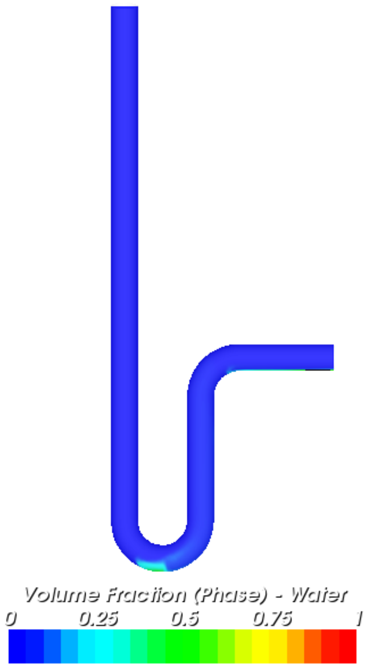


Figure 18: Test A3 with default values used. Stopped after 159 sec

Dynamic particle size (DPS) calculation is a tool which can be enabled in LedaFlow Q3D. This was done for the A3 test to see how the displacement course would elapse in that case. When running a case with DPS enabled it should lead to a more accurate and correct simulation. Due to limited amount of experimental data for droplet/bubble sizes in typical flow situations the model has only been partly validated. In some cases the droplet size is too low or high (such as several centimeters) and points to inappropriate tuning of model parameters.

In this case the droplet size varied from 0.02mm to 1cm which is reasonable. As can be seen from figure 23, most of the water was swept away quite fast for this situation as well, but compared to the simulation with default values more water was remaining at any time during the displacement. The simulation was stopped after 94 seconds when 87% of the water was displaced.

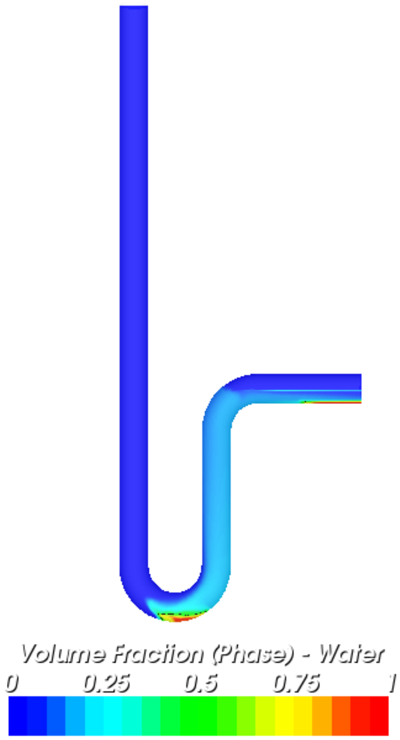


Figure 19: Test A3, after simulating with DPS on.

The search in finding a reasonable simulation parameter setup pursued and simulations with different values for constant droplet size was implemented. It was observed that simulating with a constant droplet size of 3mm gave feasible results: 79.0% of the water was displaced. Figure 20 shows the end state after simulating with a constant droplet size of 3mm. After 515 seconds the simulation was stopped. This was because the final water content inside the system remained at a level at the end of the simulation time, see Figure 21. The volume could therefore be established. Due to the good result it was determined that the use of a constant droplet size of 3mm should be used when simulating the tests with Exxsol displacing water.

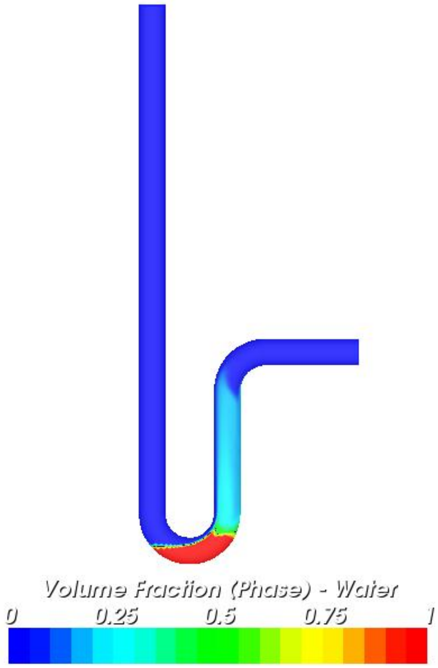


Figure 20: After simulating with a droplet size of 3mm

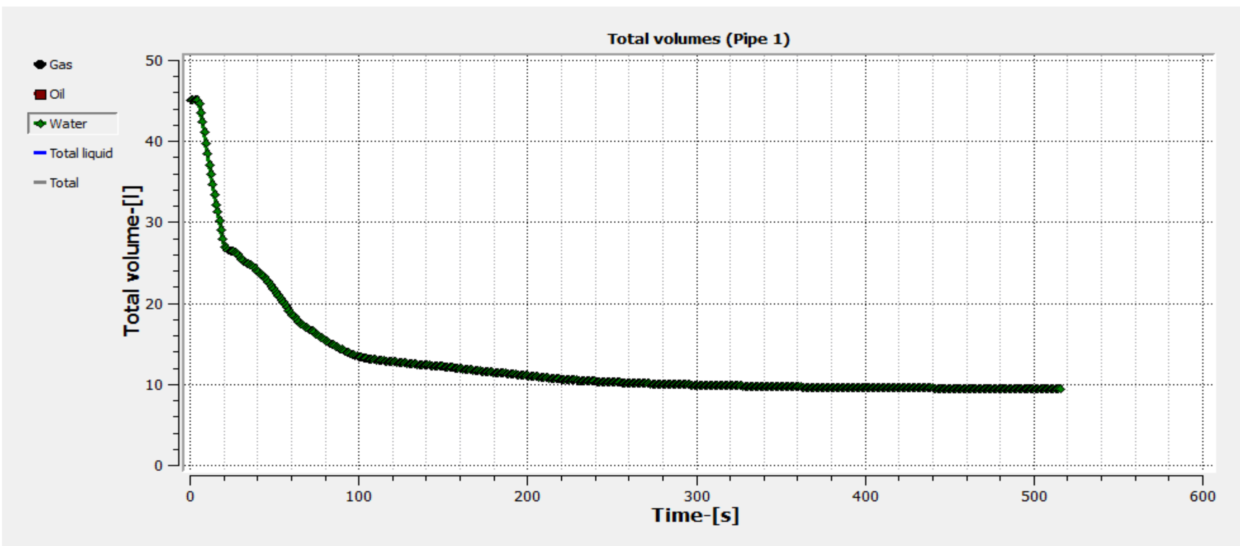


Figure 21: Total volume of water in the system

When simulating test A3 in LedaFlow 1D it resulted in displacing 60.7% of the water in the system, see Figure 22. Thus a lower displacement level than what was the case in both the experiment and from LedaFlow Q3D simulations. The 1D result differed more from the experimental results than what results from Q3D simulations did.

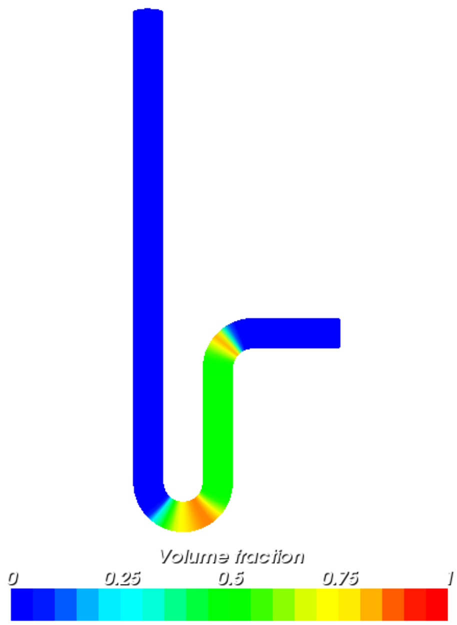


Figure 22: Test A3 in LedaFlow 1D

The test cases A1 and A2 were not simulated in LedaFlow Q3D, only in LedaFlow 1D. This was due to the time limitation and the great instabilities running these tests caused.

Figure 23 shows end results in LedaFlow 1D for the two considered tests (one figure due to the same result for test A1 and A2). It turned out that test A2 (that ran twice as long as test A1) contained only 0.0082 liters more water after simulation than what test A1 did. When simulating the two tests in LedaFlow 1D it resulted in a displacement of water of 47.8%. In the experiments the displacement level was greater; 67% and 68% for test A1 and 71.7% for test A2.

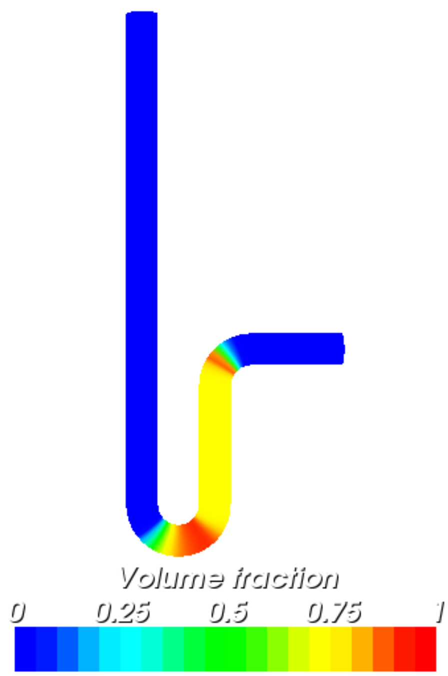


Figure 23: End state after simulating A1 and A2 in LedaFlow 1D

Table 6 shows the displacement levels after execution of test C5 experimentally and in LedaFlow 1D and Q3D, and Figure 25 and Figure 24 shows the end stat for the test after simulating in respectively LedaFlow 1D and LedaFlow Q3D. Whereas simulating the test in LedaFlow 1D led to low sweep efficiency, LedaFlow Q3D simulation resulted in sweep efficiency very close to what was achieved in the experiment. The simulation in LedaFlow Q3D was conducted with implementing a constant droplet size equal to 3mm because it was found reasonable to use for test A3 accounting for the same mediums and states as in this case.

Test execution	Displacement level, %
Experiment	67.2
LedaFlow 1D	47.8
LedaFlow Q3D	70.0

Table 6: Displacement levels from test C5 from LedaFlow 1D and Q3D and from experiment

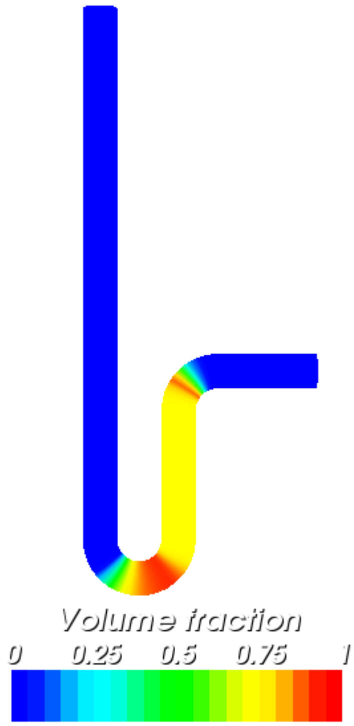


Figure 25: Test C5 in LedaFlow 1D

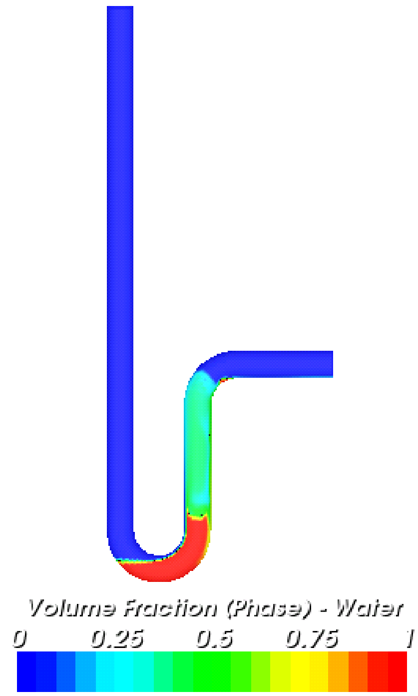


Figure 24: Test C5 in LedaFlow Q3D

6.2 Summing up

When comparing the results from LedaFlow 1D, LedaFlow Q3D and from the experiments, it is obvious that in all the test cases LedaFlow 1D predicts a lower displacement level than what was the case in the experiments. On the contrary, LedaFlow Q3D predicts a displacement close to the actual displacement from the experiments. Table 7 gives an overview of the displacement levels from all of the cases conducted with Exxsol displacing water.

The good results from LedaFlow Q3D occurred when tuning the size of droplets to a hold a constant value of 3mm. This may be the reason for achieving such good results in LedaFlow Q3D, but other parameters may also be tuned to optimize the simulations. Still, because only two tests were simulated in LedaFlow Q3D, and thus measured up to the experiment, the reliability of the results is somewhat uncertain.

	Displacement level, %		
Test ID	From experiment	From LedaFlow 1D	From LedaFlow Q3D
A1	68	47.8	Not simulated
A2	71	47.8	Not simulated
A3	74.7	60.7	79
C5	67.2	47.8	70

Table 7: Displacement level from experiments and LedaFlow 1D and Q3D simulations (A1 and A2 was not simulated in LedaFlow Q3D)

7 Water displacing Azolla ZS 32: Simulation Results and discussion

This chapter deals with the results from LedaFlow Q3D and 1D simulations of the test where Azolla was displaced by water. Comparisons of results from the simulated tests with experimental results are discussed. As for the previous tests not all of the tests were simulated in LedaFlow Q3D.

7.1 Results and comparison of displacement

An overview of the experiments and simulation test results regarding water displacing Azolla with an initial GVF of 59.6% is given in Table 8. Points that can be highlighted are:

- As in the experiments, the displacement levels of all the tests is quite the same in LedaFlow 1D
- LedaFlow 1D predicts a lower displacement level than what was reached in the experiments
- A change in injection mass rate has a higher impact on the displacement level than the duration on the displacement.

			Displacement level, %	
Test ID	mass rate (m^3/hr)	Injection time (s)	Experiment	LedaFlow 1D
D1	2.5	613.44	94	67.7
D2	2.5	1226.88	95.6	69.16
D3	4.7	652.6	97.7	78.3
D4	2.5	2453.76	97.7	69.3
D5	1.25	613.44	90.7	61.9
D6	4.7	1305.19	96.5	78.4

Table 8: Displacement level from experiment and from LedaFlow 1D simulations when GVF=59.6%

When considering the tests in LedaFlow Q3D, the same procedure in evaluating droplet sizes in order to find the best way to simulate the tests as for the Exxsol/water cases was used. First test D3 was simulated with default values as for the test A3. The findings were that everything of the oil was displaced. The next stage in the optimization process was to set constant droplet size values. The values were set to be 3mm. That simulation case was very slow and unstable and therefore stopped after 59 seconds. But within that time the oil content inside the system had stabilized well and the result from the simulation test was that 88% of the oil was displaced.

After simulating test D1 with the specified constant droplet size (3mm) for 175 seconds the simulations was stopped. It resulted in displacing 85.6% of the Azolla. Figure 26 illustrates that the total volume inside the inlet section is kept constant after a simulation time of about 175 seconds.

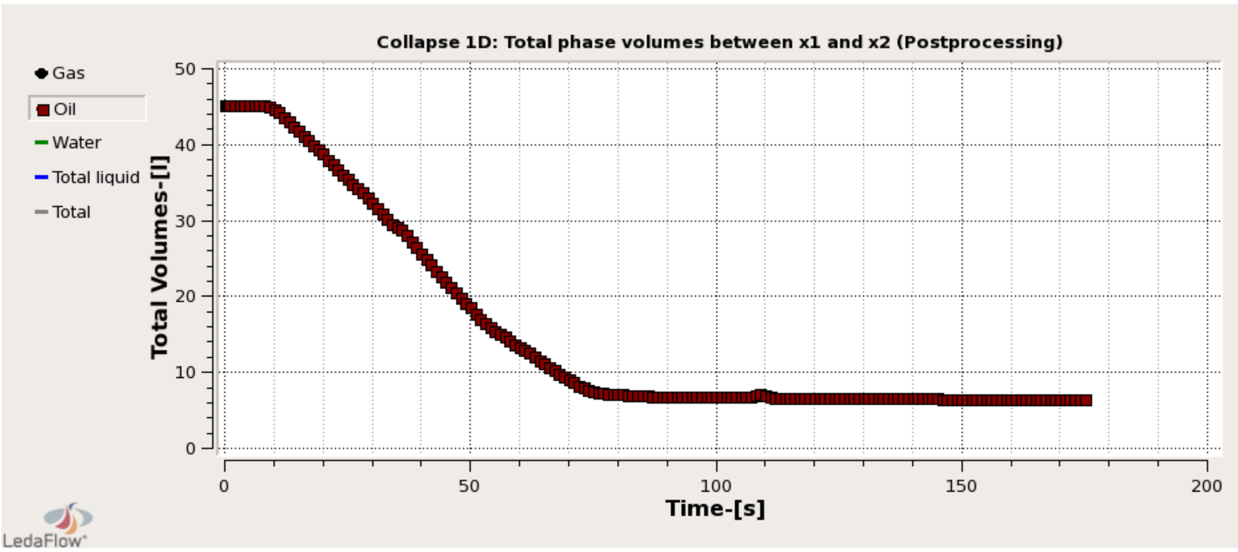


Figure 26: Total water volume fraction for test D1 with 3mm droplet size

An overview of the experiments regarding water displacing Azolla with an initial GVF of 0% is given in Table 9. For both of the tests E1 and E2, LedaFlow 1D predicted a higher displacement level compared to the test results.

			Displacement level, %	
Test ID	mass rate (m^3/hr)	Injection time (s)	Experiment	LedaFlow 1D
E1	4.7	1305.2	92.18	98.64
E2	4.7	652.6	91.44	98.64

Table 9: Displacement levels from experiments and LedaFlow 1D simulations when GVF=0%

When simulating the test E2 in LedaFlow Q3D it went a bit faster than with the previous tests. This was due to less instability, which again assumed to be because of the fact that there were only two phases and the phases were of quite alike density.

Tests with different droplet sizes was tried out and it was discovered that by simulating the test E2 with default values for droplet size and simulating the same case with a constant particle size of 4mm led to about the same level of displacement, respectively 91.34% and 90.30%. Thus both of the simulations gave good results (ref: Table 9).

At the end of the LedaFlow Q3D simulation the oil content inside the system was held approximately constant. Therefore it could be assumed that the displacement level in test E1 would assumed to be approximately the same as for test E2.

8 Severe slugging in s-riser

This chapter concerns blow-through experiments in an s-riser. The test setup, execution, construction of the case in LedaFlow 1D and LedaFlow Q3D will be presented. After that follows a results and discussion part. Challenges encountered and errors contributing to the end results will also be presented. In addition the phenomenon severe slugging will be discussed.

8.1 Experimental setup

A small scale slugging experiment was conducted at the laboratory at Norwegian University of Science and Technology (NTNU). Figure 27 shows the geometry of the s-riser tested. The rig is instrumented with an absolute pressure transducer at the inlet and two impedance ring probes for holdup measurements. All pipe sections, bends and other connections are made in Plexiglas and have an inner diameter of 5cm. The experiments were performed at ambient pressure and temperature. A small separator at the top of the s-riser is kept at ambient pressure by ventilation of the air to the atmosphere. The flow line has a 1° downward slope towards the riser base to promote liquid blockage in the bend.

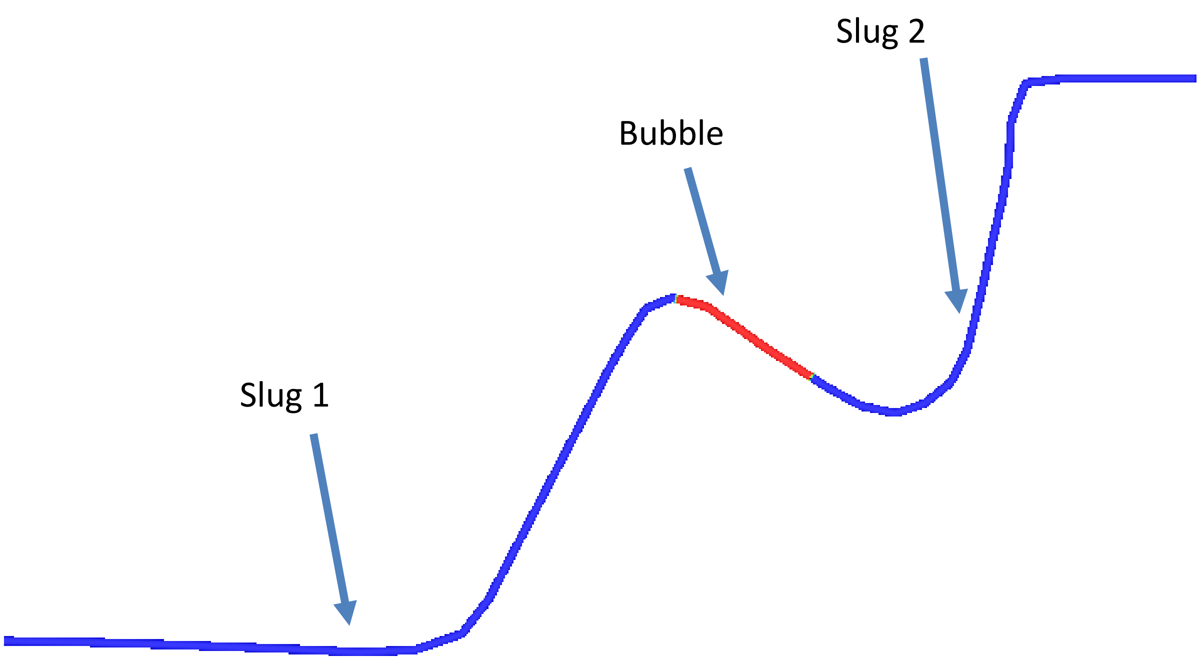


Figure 27: Setup s-riser. Blue line represents water filled pipe sections while red line represents gas filled pipe section

8.2 Experimental procedure, blow-through test

The initial conditions is implemented in Figure 27, where the flow line is water filled up to the top bend, then a big gas pocket is present and fills two third of the pipe line towards the next bend. Further, the rest of the system is filled with water.

The execution of the experiment went on as follows:

- First the initial conditions was established
- Gas flow established by blowing to the atmosphere through a bypass
- Gas flow directed from the bypass into the s-riser by manual operation of valves.

The gas flow was kept constant during the testing. Two different tests were executed with two different gas velocities, 1.86 m/s and 3.15 m/s.

8.3 Numerical simulations in LedaFlow

The rig was recreated in the simulator Leda Flow. Simulations in LedaFlow Q3D and LedaFlow 1D were to be done. In order to sustain atmospheric pressure at the outlet of the system, a pressure node was implemented in LedaFlow Q3D. To initialize the mass flow of gas throughout the pipeline, a mass node was used at the inlet.

Assumptions that were made in the cases:

- Isothermal flow (constant temperature) – therefore the energy equation was not solved and values for conductivities and heat capacities were not implemented
- Compressible gas flow. This was implemented due to the gas' properties and its ability to be compressed. The compressibility factor was set to be 1.229bar. This was to make the simulations closely linked to the reality.

8.3.1 Constructing the case

The first step in the simulation process was to set up the case: set fluid properties, numerical settings, pipe geometry, the boundary conditions, and to set the meshing.

8.3.2 Fluid properties

PVT properties used in the simulations were set manually. Values for density, viscosity and water–gas surface tension were implemented (Ref: Table 10). Atmospheric pressure and temperature were also specified.

	Densities $[kg/m^3]$	Viscosities $[Pa * s]$	Air-Water surface tension $[N/m]$
Air	1.229	1.73E-05	0.072
Water	998.6	0.001139	

Table 10: Fluid properties

8.3.3 Final steps of set-up of the case and running simulation

The case was constructed by:

- Implementing the geometry
  - Adding x and z values for points throughout the pipeline. All the applied x and z values are specified in Appendix C. Then the appropriate x and z mesh (number of cells in x and z direction (with respect to pipe direction)) was set. However, for the 1D cases only x mesh could be specified, because it does not take the other direction into account.
- Specify a diameter similar to the experimental diameter (5cm) and a realistic roughness $(2 * 10^{-6} \text{m})$
- Boundary conditions were set
  - A value for superficial gas velocity was set in the mass node at the inlet and atmospheric pressure (1.01325bar) in the pressure node at the outlet.
- Specifying numerical settings, such as
  - maximum time step, sample time, simulation time, starting time and CLF
- Initializing the cases, followed up by running them.

To enable the simulations, values numerical for settings were not similar for each case due to numerical and physical differences, which made the degree of difficulties for the simulations different.

8.4 1D Simulations

The two cases were set with properties as mentioned earlier. Fluid properties, numerical settings, pipe geometry, the boundary conditions, and the meshing were specified.

Regarding the mesh it was set to contain 700 equally sized cells in the x direction. The reason for the high number of cells was to have a correct volume of the gas bubble inside the pipeline.

After initializing the 1D cases as a liquid filled pipeline the gas pocket was inserted. The length of the gas bubble was 1.78 meters starting at the top of the second bend. This length corresponded to 66 cells and the content in current cells was therefore changed from being liquid filled to be gas filled.

8.5 Q3D simulations

The procedure with setting up the cases in LedaFlow Q3D was to do the same as for LedaFlow 1D cases, but also with the number of cells in z direction taken into account. For the two cases the number of equally sized cells in x direction was set to be 600 and 10 in z direction. With a total length of the pipeline of 18.83m the mesh size lead to an aspect ratio, AR to be 6.28.

When initializing the cases it also included specifying how much of the pipe length that was to be filled with water and gas. The gas bubble was placed after 9.84 meters with only water inside the pipeline. After initializing the simulations were started.

8.6 Method and challenges

The first experience involved that when simulating such a system in LedaFlow Q3D it was an absolute necessity to specify a compressibility factor for the gas. When simulating without a compressibility factor for a gas velocity of 1.86 m/s it resulted in great fluctuations in the inlet pressure throughout the simulation. This is evident from Figure 28. These fluctuations in pressure did not occur when conducting the experiment (ref: **Error! Reference source not found.**). Figure 29 shows how the inlet pressure varied during the simulation for the same case but with compressibility factor implemented.

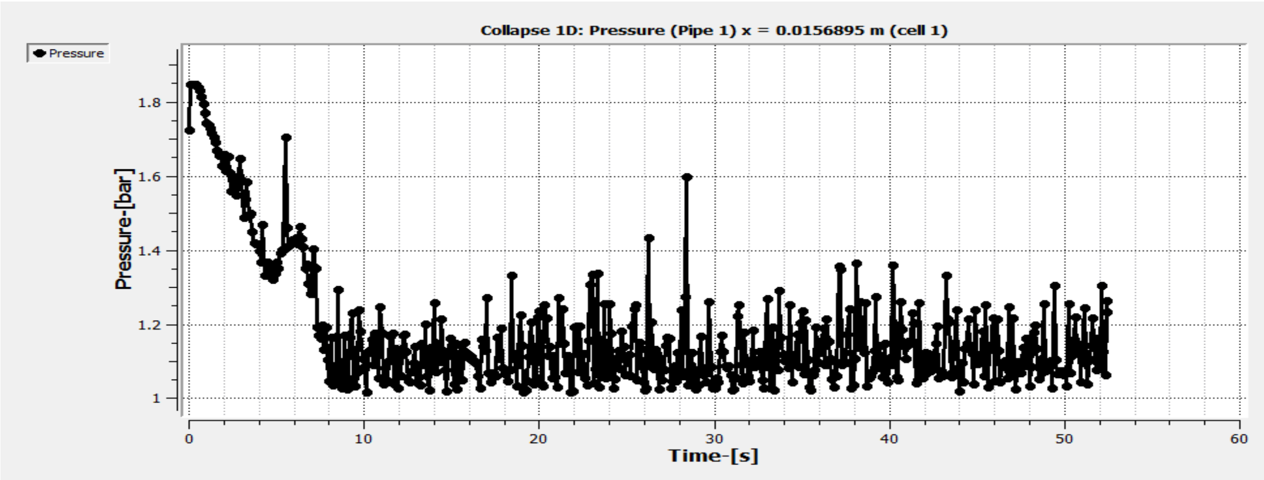


Figure 28: Inlet pressure after simulating without compressibility factor

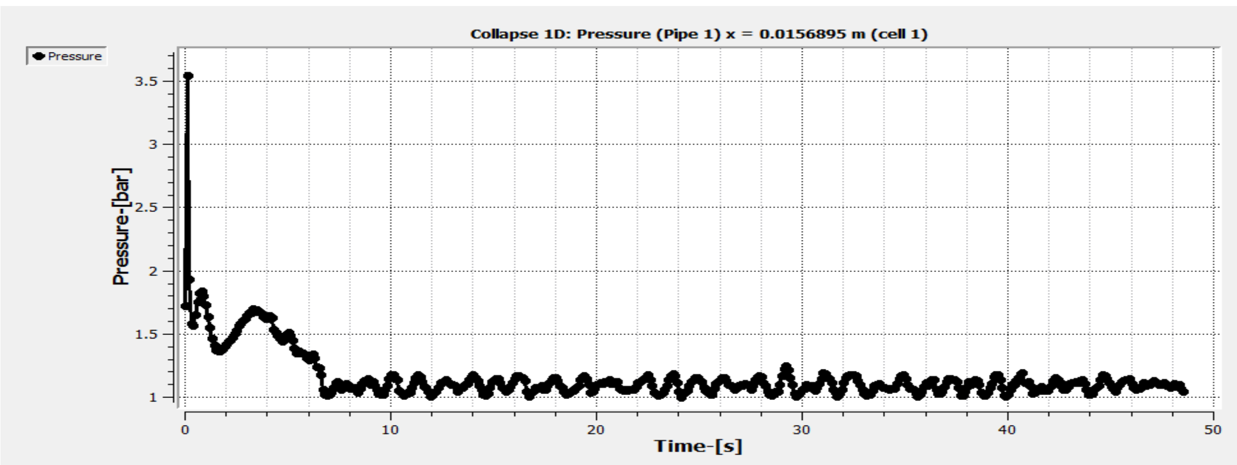


Figure 29: Inlet pressure after simulating with compressibility factor

8.7 Results and discussion of the simulations with Usg=1.86m/s

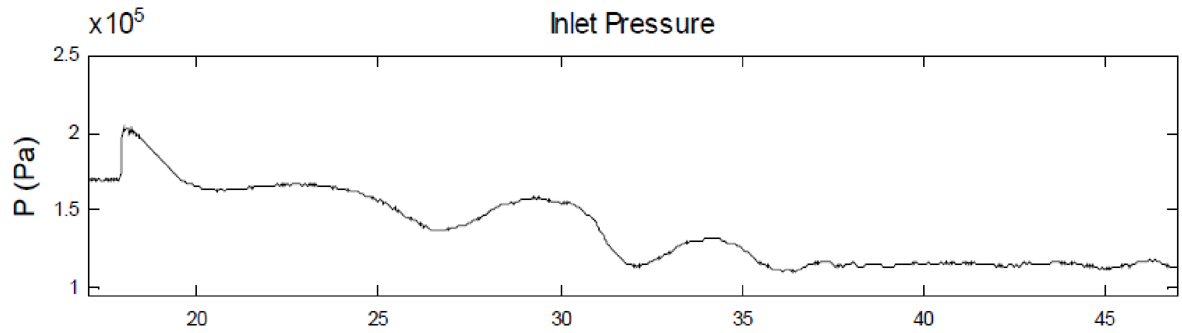
Two parameters were evaluated when comparing the simulation test with the experiment; inlet pressure and water volume fraction at two different locations at the riser. The location of the ring probes that measured the water volume fraction was unknown and an appropriate location for these probes needed to be established. By comparing the water volume fractions from the simulations with the graphs from the experiment showing the water volume fraction at the ring probes, the ring probes was estimated to be located 8.58m and 14.64m from the inlet of the s-riser.

8.7.1 Comparison of inlet pressure

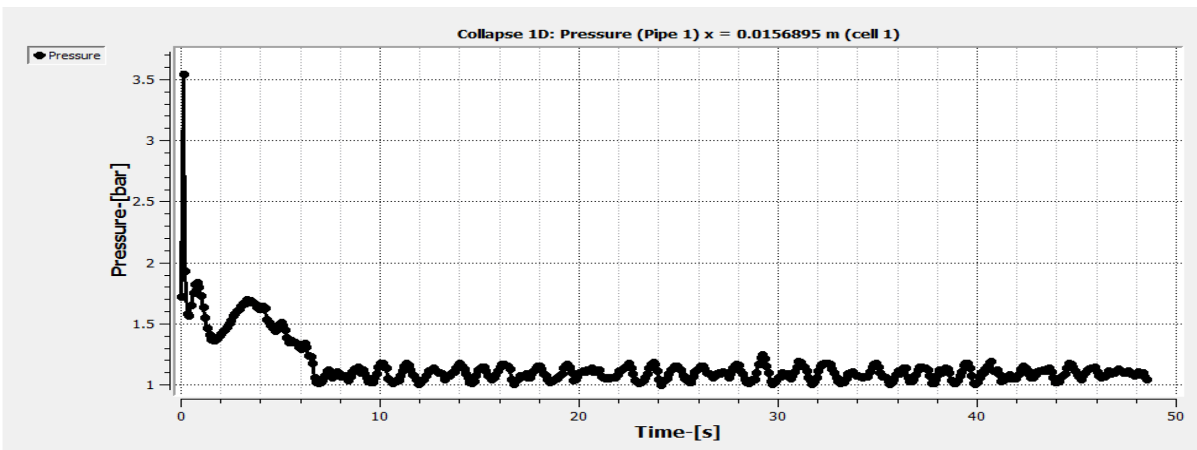
An initial rise in pressure in the start of the test is due to a higher initial pressure in the upstream pipe due to a sudden gas injection. While in the experiment the pressure rises up to 2bar and 3.6bar in LedaFlow Q3D, the pressure in LedaFlow 1D reaches up to 5.5bar. By analyzing A in Figure 30, it can be seen that in the beginning there is no gas inflow. This may be the reason why the pressure does not reach to a higher level. For the LedaFlow 1D and Q3D cases the gas velocity is constant throughout the whole simulation. This may explain the rapid increase and decrease in pressure regarding both LedaFlow 1D and LedaFlow Q3D simulation.

However, as can also be seen by having a quick overview of the pressure variations (ref: Figure 30) is that the trend is the same; after the pressure has decreased to approximately 1.1bar, the pressure does not change much.

A



B



C

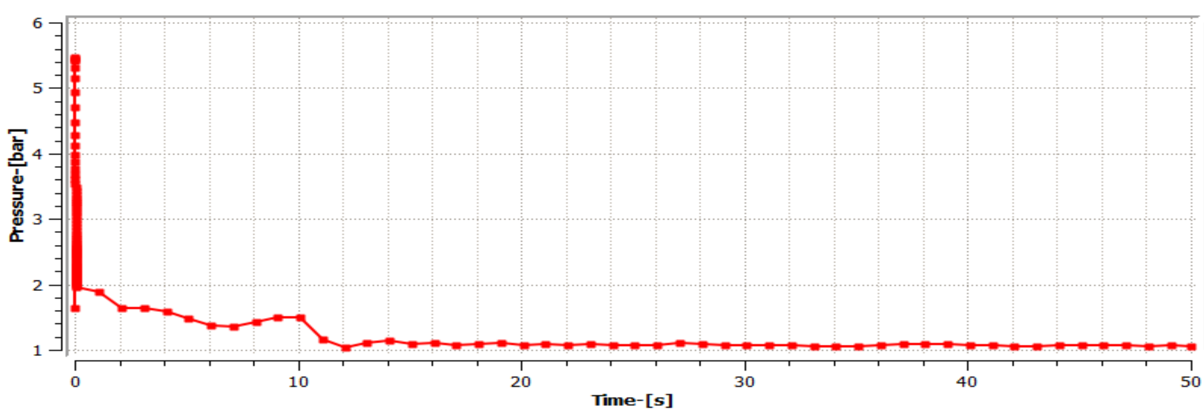


Figure 30: A: Inlet pressure from experiment

B: Inlet pressure from LedaFlow Q3D simulation (Same figure as Figure 29 to bring up points))

C: Inlet pressure from LedaFlow 1D simulation

8.7.2 Comparison of holdup at ring probe 1

When holdup is equal to one at the beginning of the three graphs (ref: Figure 31) it implies that the gas injected has not yet reached the ring probe. It is to believe that the ring probe 1 started recording before the gas injection started. This is due to the very long period with holdup equal to one for the experiment. By comparing A and B in Figure 31 it is obvious that the holdup progress is the very much the same in the experiment as in LedaFlow Q3D. The difference is that in LedaFlow Q3D sweeps away too much liquid, resulting in a lower amount of residual liquid in the first bend. A wave which appears at around 31 seconds in the experiment will occur with a lower holdup in LedaFlow Q3D.

Simulating in LedaFlow 1D does not give the same pattern of holdup in the first ring probe as the previous two cases. Holdup falls quite fast as for the LedaFlow Q3D case, but several water oscillations reaches up to the first probe throughout the test (ref: C in Figure 31).

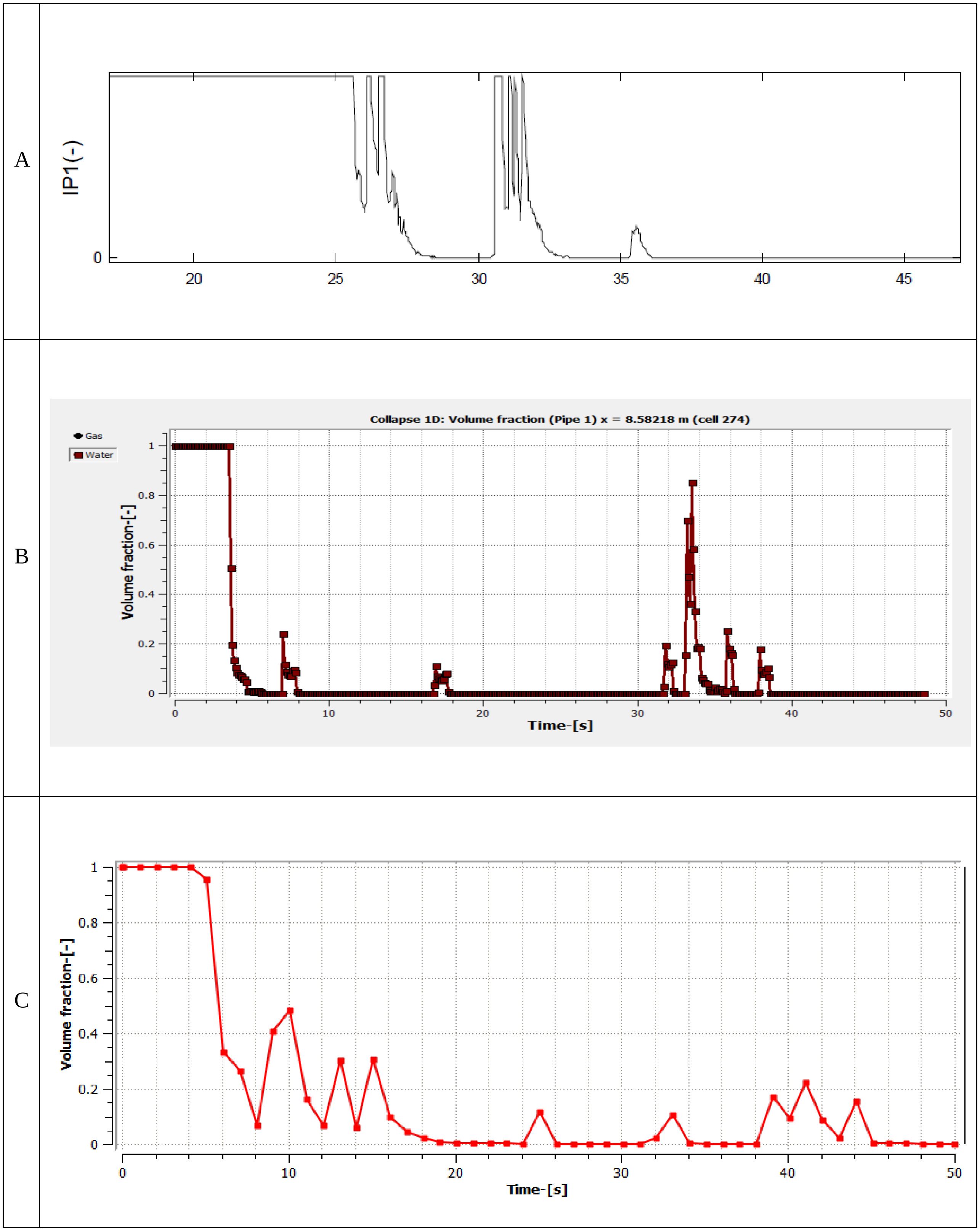


Figure 31: A: Liquid volume fraction at ring probe 1 – from experiment
B: Liquid volume fraction at ring probe 1 - from LedaFlow Q3D simulation
C: Liquid volume fraction at ring probe 1 - LedaFlow 1D simulation

8.7.3 Comparison of holdup at ring probe 2

It is obvious that in the experiment the second bend contains more liquid after the blow through than for both of the LedaFlow cases (ref: Figure 32). The amount of liquid in the bend leads to an oscillation of water reaching up to ring probe 2. As can be seen for the simulation in LedaFlow Q3D and 1D, more liquid was swept away. This leads to smaller liquid oscillations (fewer oscillations which holds less liquid volume fraction) in the second bend. In the experiment the gas bubble will pass the second probe as either liquid or bubbles, while for Leda Q3D the bubble will pass quickly as nearly pure gas. When it comes to LedaFlow 1D the bubble will pass the second probe as stratified flow with about 40% gas where 5-10% consists of bubbles (ref: C in Figure 32). This causes the bubble to pass the probe in LedaFlow 1D and in the experiment in around 5 second, whereas much quicker in LedaFlow Q3D (2 seconds).

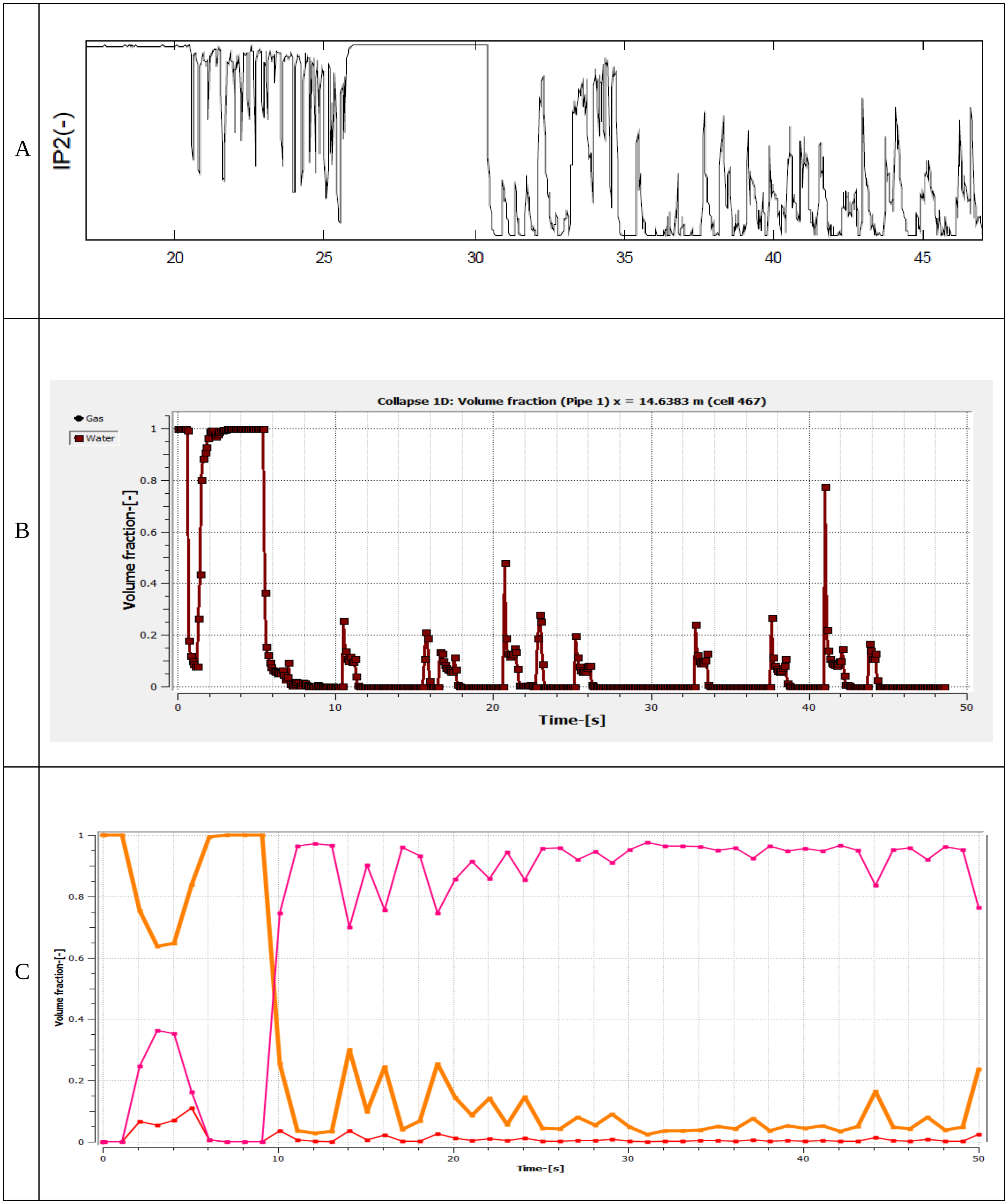


Figure 32: A: Liquid volume fraction at ring probe 2 – from experiment

B: Liquid volume fraction at ring probe 2 - from LedaFlow Q3D simulation

C: Liquid volume fraction at ring probe 2 - LedaFlow 1D simulation. Orange line: water volume fraction. Pink line: volume fraction of total gas. Red line: volume fraction of bubbles

8.8 Results and discussion of the simulations with Usg=3.15m/s

8.8.1 Comparison of inlet pressure

The three cases considered started with different velocity of gas inserted. This affected the inlet pressure:

- In the experiment there is no gas velocity inserted in the first 1.5 seconds, e.g. constant pressure (ref: A in Figure 33). The pressure reaches to a peak at 2.5bar before it reduces gradually until it reaches a level of 1.1bar which it holds until the end.
- The pressure in LedaFlow Q3D oscillates before it reaches a peak at 3.1bar and reduces to a level of 1bar which it holds out the test (ref: B in Figure 33). In LedaFlow Q3D there is a ramp up of velocity, from 0.2m/s to 3.15m/s. The ramp up contained four stages with different velocities and after 1.5 seconds the desired velocity was reached.
- The pressure in LedaFlow 1D increases directly to a peak at 6.8bar before it falls quickly to 1bar which it holds out the test (Ref: C in Figure 33). A constant gas flow was injected from the very start (the reason for such high pressure).

Thus the inlet pressure progress is quite the same for the experiment and for LedaFlow Q3D. The pressure is a bit different for LedaFlow 1D since it rises to such a high pressure. Otherwise, the trend for the progress of inlet pressure is the same.

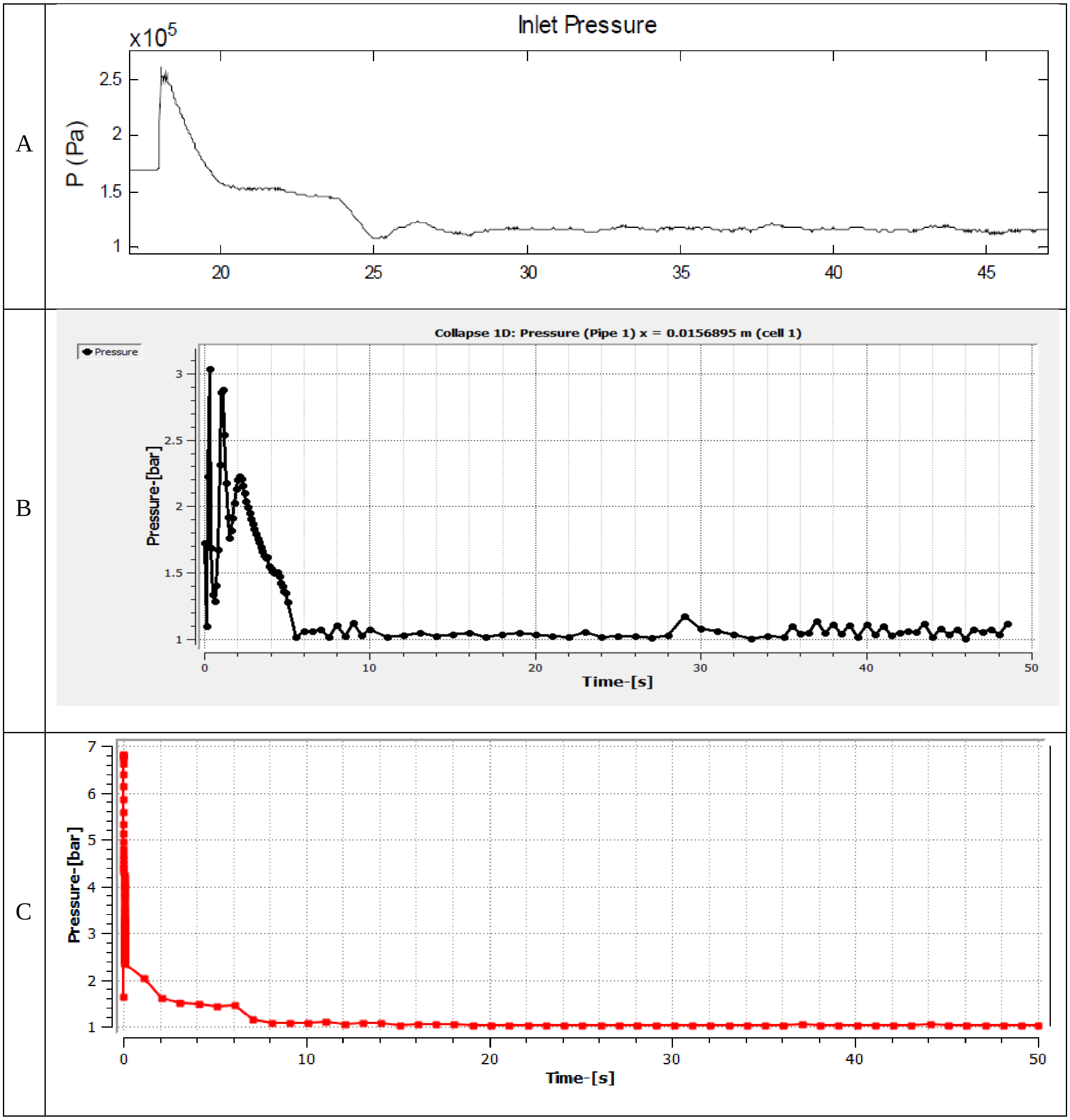


Figure 33: A: Inlet pressure from experiment
B: Inlet pressure from LedaFlow Q3D simulation
C: Inlet pressure from LedaFlow 1D simulation

8.8.2 Comparison of holdup at ring probe 1

Figure 34 can be interpreted in such a way that it remains much more liquid in the first bend after the first liquid wave during the experiment than from simulation in LedaFlow Q3D and 1D. In LedaFlow Q3D and 1D liquid oscillations do not reach the ring probe at all (Ref: B and C in Figure 34). In the experiment small liquid waves reach up to the probe with small intervals in between.

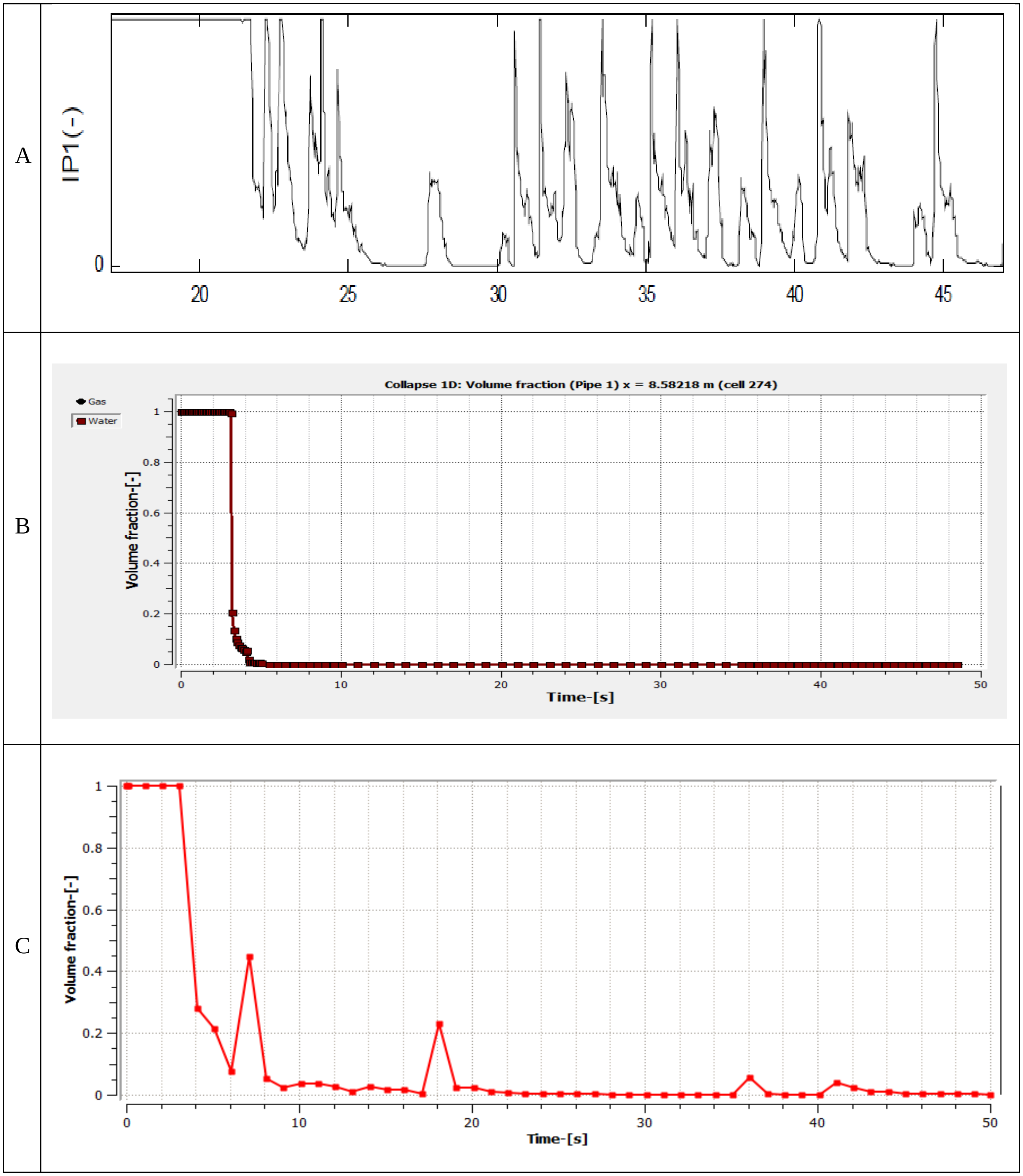


Figure 34: A: Liquid volume fraction at ring probe 1 – from experiment
B: Liquid volume fraction at ring probe 1 - from LedaFlow Q3D simulation
C: Liquid volume fraction at ring probe 1 - LedaFlow 1D simulation

8.8.3 Water volume fraction at ring probe 2

When the liquid has swept away one can find the same trend as for ring probe 1: much more liquid oscillation reaching up to the ring probe during the experiment than during simulations in both LedaFlow 1D and Q3D (Ref: Figure 35). In this case however, some liquid fractions appear at ring probe 2 in LedaFlow 1D (Ref: C in Figure 35).

In the experiment and in LedaFlow Q3D the gas bubble passes the ring probe almost completely as gas. When it comes to LedaFlow 1D the bubble will pass the second probe as stratified flow with about 50% gas where about 20% consists of bubbles (Ref: C in Figure 35). This causes the bubble to pass the probe in LedaFlow 1D in around 2 second, whereas much quicker in LedaFlow Q3D and in the experiment (1 second).

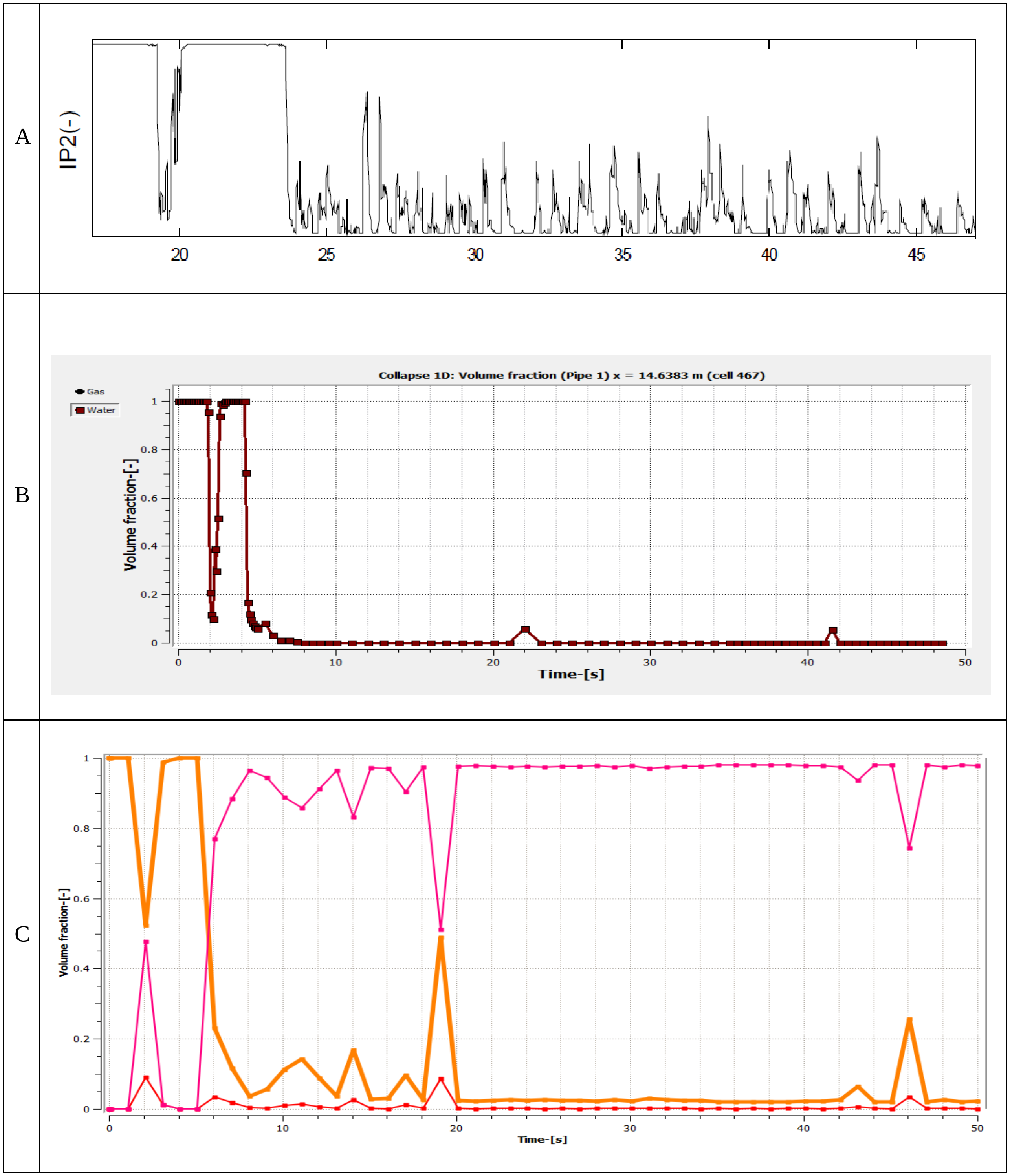


Figure 35: A: Liquid volume fraction at ring probe 2 – from experiment

B: Liquid volume fraction at ring probe 2 - from LedaFlow Q3D simulation

C: Liquid volume fraction at ring probe 2 - LedaFlow 1D simulation. Orange line: water volume fraction. Pink line: volume fraction of total gas. Red line: volume fraction of bubbles

8.9 Comparison of the inlet pressure between the high- and low velocity cases

The trend for the course in inlet pressure is the same for the low velocity case as it is for the high velocity case; LedaFlow 1D predicts the highest pressure at the beginning of the test while LedaFlow Q3D predicts an inlet pressure progress most similar to the experiment. In both LedaFlow 1D and LedaFlow Q3D the pressure reduces faster than what was the case in the experiment towards around 1bar, where it maintains constant throughout the test. All in all, since the pressure at the peak in LedaFlow 1D is so high (5.5bar) compared to the pressure in LedaFlow Q3D and experiment (3.5bar and 2bar) LedaFlow Q3D predicts the most realistic inlet pressure progress. Factors that may affect the inlet pressure is the ramp up of gas velocity and the fact that it seems like during the first 1.5 seconds in the experiments there was no gas injection.

8.10 Comparison of water volume fraction between the high- and low velocity cases

In both of the cases both LedaFlow 1D and LedaFlow Q3D predict a bigger sweep out of water. This leads to less residual liquid accumulating in the bends than what was the case in the experiment. This results in fewer and smaller water oscillations reaching up to the ring probes. More oscillations occurred at the locations of the ring probes for the low velocity case than for the high velocity case. This was expected due to lower gas velocity leading to smaller sweep out of water.

8.11 Challenges and errors influencing the results

The challenges and errors that affected the simulations and results with the s-riser case can be listed up:

- Only roughly correct geometry of the s-riser was given. Two meters of the slightly downhill pipe does not get encountered for, and the bends are quite coarse. This may affect the whole blow through course – how much is unknown.
- Only an estimated value of the volume of the gas bubble was used, thus not 100% correct, and the exact location of it was unknown and also estimated.
- Difficult to interpret the graphs from the experiment due to small graphs and few values.

8.12 Interesting findings from simulating in LedaFlow Q3D

It is of particular interest to analyze the oscillations or slugging behavior in the bends for the s-riser case. When simulating in LedaFlow Q3D one have the possibility of having a good look of the slugging course and to understand more of the slug phenomenon.

Figure 36 to Figure 39 four stages of a contributing in a slugging course as explained in 2.3.4. The slug series is from the case with a superficial gas velocity of 1.86m/s where the first bend has been looked into. It is worth noticing that all of the figures concerned are scaled up 10 times in the z direction. This makes the pictures a bit disturbed.

Figure 36 illustrates the stage called Slug Formation where the pipe cross section is blocked. After that, the Slug Production stage starts and a liquid slug will move forward and be produced. Figure 37 displays this by showing velocity vectors for the gas, which corresponds to gas pushing the liquid slug forward. The Bubble Penetration then starts where a rapidly acceleration of both gas and liquid occurs up the downstream section. This is well illustrated in Figure 38 with velocity vectors implicating the acceleration. Figure 39 illustrates the Gas Blowdown course where liquid falls back down from the downstream section towards the bend. By looking at the next time steps in the simulation the liquid accumulates yet again in the bend and the slug cycle is repeated.

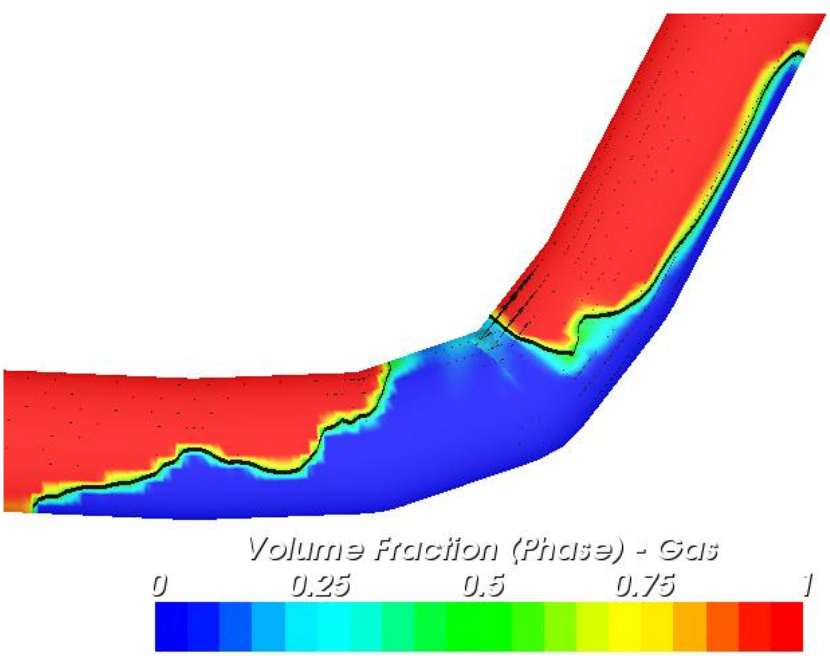


Figure 36: Slug formation: pipe cross section is blocked

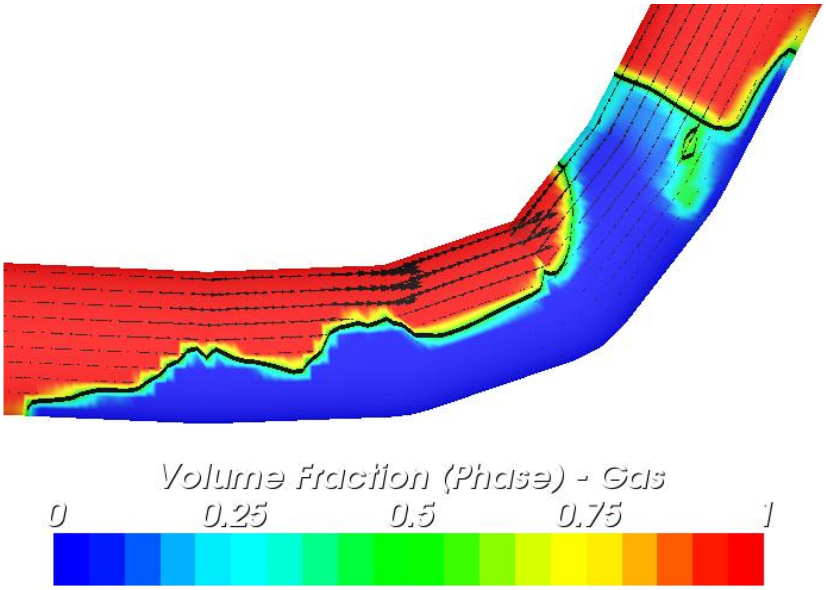


Figure 37: Slug production: liquid slug will move forward and be produced

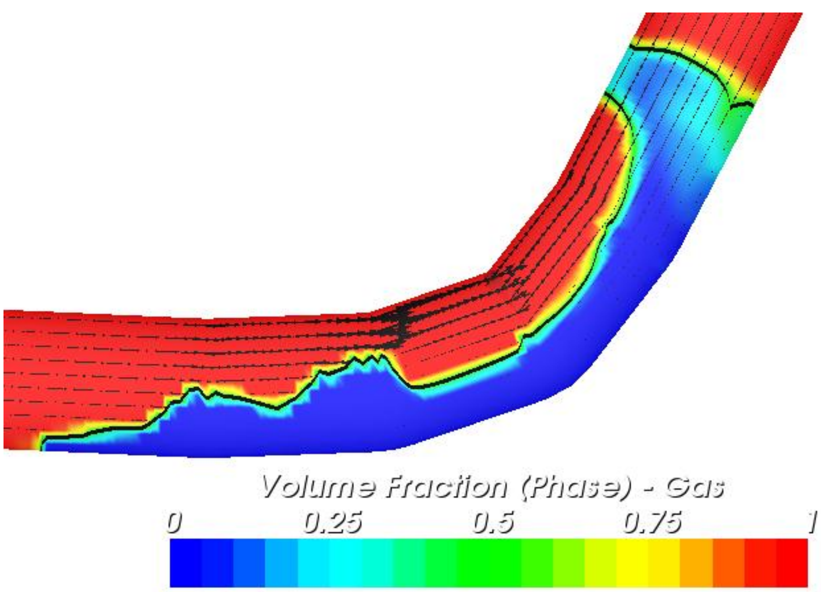


Figure 38: Bubble penetration: rapid acceleration of both gas and liquid

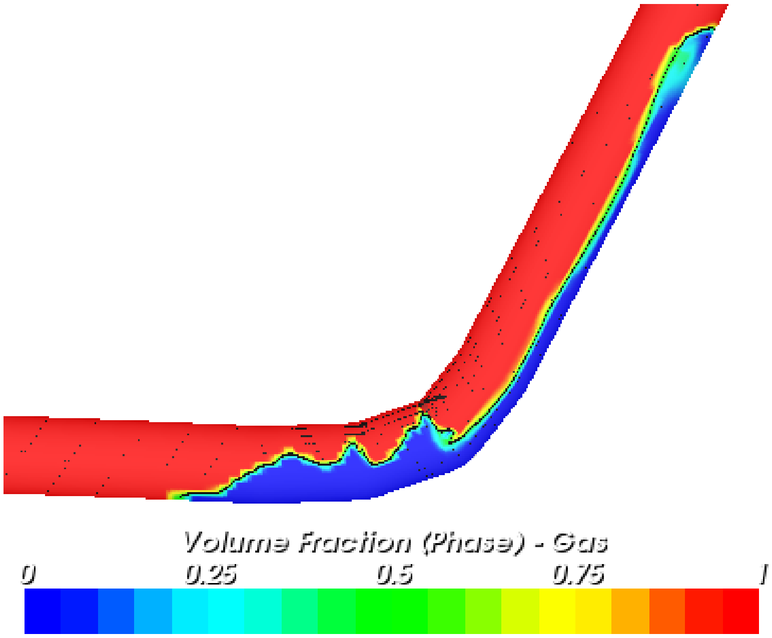


Figure 39: Gas Blowdown: Liquid on its way back down to the bend

When it comes to simulation with a superficial gas velocity of 3.15m/s, this type of characteristic slug course as explained and shown above does not occur. Only small oscillations finds place in the bends due to the small amount of liquid left in the bends after the blow-though.

9 Discussion and conclusion

In this chapter links between the cases considered will be reviewed. Conclusions will be drawn and future work suggestions and recommendations will be given.

9.1 The course of displacement – theory, experiments and simulations

When considering the inlet section it has earlier in this report been mentioned both the displacement results as well as the reason for the level of displacement. By using LedaFlow Q3D one can comprehend the displacement course better, but with skepticism in the mind, because one cannot rely on the simulator 100%, as with all other simulators.

In the chapter about results, discussion and conclusion of the displacement tests a conclusion was drawn that included the inlet section:

- When Exxsol was to displace the water, some of the displacement media would find a path at the inner bend and flow throughout the bend instead of pushing the water forward
    - Naturally this would result in some residual water in the system, hence not 100% displacement of water.
- When water was to displace Azolla, a high displacement level would be reached due to displacing with a heavier medium than the medium that is originally there. A more uniform distribution of the displacement was expected to take place due to the properties of Azolla (a somewhat more miscible with water than Exxsol).

By simulating in LedaFlow these theories was considered. Three test cases; A3, D3 and E2 were considered to check whether the displacement course simulated matched the theory presented. These three test cases were considered because they had nearly the same injection duration, but most importantly they had the about the same injection flow mass ($5m\text{^}3/hr$ and $4.70m^3/hr$)

As can be seen from Figure 40 the light Exxsol is taking the inner bend instead of pushing the water throughout the system. The snap shot is from after 100 seconds with simulation.

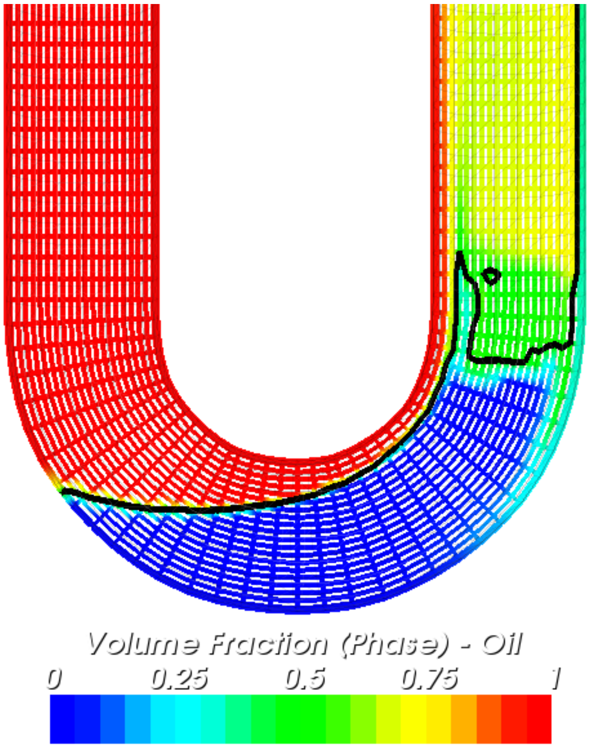


Figure 40: Test A3. Displacement course with Exxsol displacing water

Figure 41 illustrates the displacement progress when water is displacing Azolla. It shows that there is an efficient displacement taking place, with the water clearly pushing most of the oil forward, but at the same time the water falls to the bottom of the bend due to the fact that it is heavier than the oil. In addition it can be seen that for the Azolla case, the two phases mixes faster than for the Exxsol case (Ref: Figure 40 and Figure 41). Thus the simulation corresponds well both to the displacement results and the theory part assumed for such a displacement.

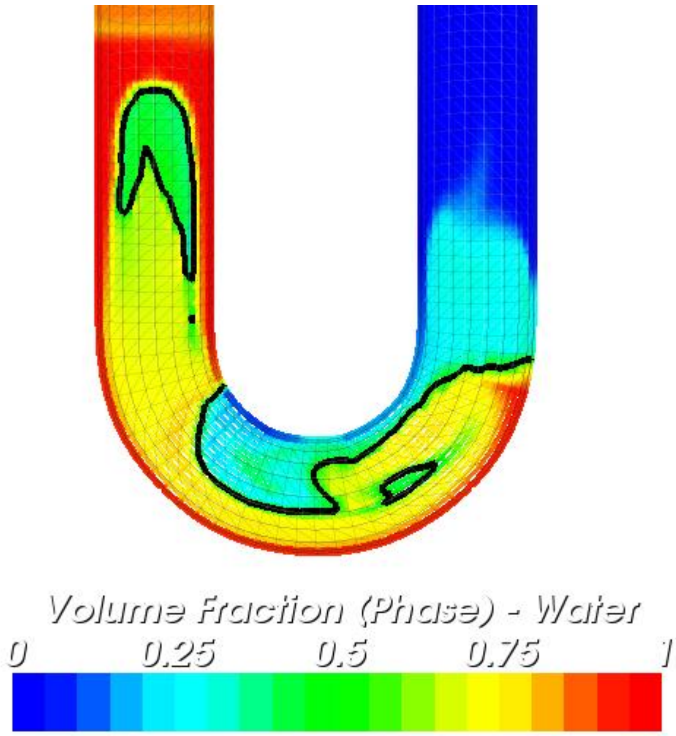


Figure 41: Test D3: Displacement course of water displacing Azolla when GVF=59.6%

Figure 42 illustrates the displacement course for the test E2. The course is quite similar to the displacement course for the D3 test. As can be seen the distribution of the oil and water is in this case even more homogeneous near the bend. This is due to the long vertical section before the bend. The similarity was no surprise due to the fact that the two tests were of the same type of displacement media. Although it was expected that the water injected would meet more friction forces due to the oil filled system. It can be concluded that the mass rate injected was sufficient to reach a high displacement level.

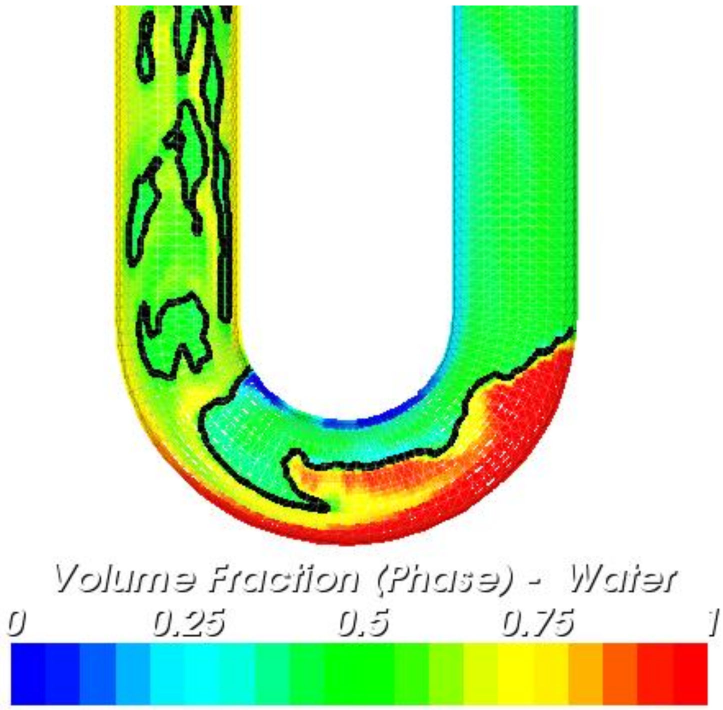


Figure 42: Test E2, displacement course

9.2 Discussion and conclusion about the displacement cases

9.2.1 Exxsol displacing water:

All the experiments resulted in a good displacement in the inlet section (~70%). The trend observed from the tests was that the displacement level from each test conducted did not vary much from one another. Another trend was that by changing the inlet mass flow of Exxsol, it had a bigger impact on the end result than it had by changing the duration of the displacement.

By simulating the cases in LedaFlow 1D it predicted a lower displacement level in all the cases. Nevertheless, the same trends as in the experiments were predicted: a change in velocity of the displacement medium gave greater impact on the results than what a change in displacement duration did. LedaFlow 1D predicted that a change in velocity would cause a bigger change in the result than what was the case in the experiment.

When simulating in LedaFlow Q3D the best solution concerned setting the droplet size to a constant factor (3mm). That lead to a displacement levels of the simulation tests to be nearly equal to what was the case in the experiment. This solution was tried out for two tests, A3 and C5. For test A3 LedaFlow Q3D predicted a bit higher displacement than what happened in the experiment: 79% versus 74.7% in the experiment. For test C5 70% was displaced in LedaFlow Q3D while 67.2% was displaced in the experiment. Thus simulation of both of the two tests in LedaFlow predicted just a little higher displacement and it can be ascertained that LedaFlow Q3D predicted very well for those two cases with the specific parameter adjustment.

9.2.2 Water displacing Azolla

In general, execution of the experiments ended with high displacement levels (almost 100%) in the inlet section. The displacement levels are quite the same as in the tests conducted.

As for the case where Exxsol displaced water, the same trends occurred when simulating in LedaFlow 1D: a change in velocity of the displacement medium has more to say than a change in displacement duration. In addition LedaFlow 1D predicted less displacement as was the case in the previous discussed case with Exxsol as displacement medium. The similarities did not account for the initially oil filled tests, E1 and E2. For these tests LedaFlow 1D predicted in some degree higher displacement levels: ~99% versus ~92%.

When simulating the two tests, D1 and D3 about the case where the initial GVF was equal to 32% in LedaFlow Q3D, the best solution concerned setting the droplet particle size constant and equal to 3mm. That resulted in giving a displacement level that was in some extent lower than in the experiment: ~88% versus ~98% for test D3 and ~86% versus ~94% for D1.

Regarding the tests when the system was oil, E1 and E2, the LedaFlow Q3D gave very well results. Only test E2 was simulated but due to the system holding almost the same oil content for a while at the end of the simulation one can assume that the displacement level for the two cases is approximately the same. Test E2 was simulated with both default values for droplet sizes and with constant particle size (3mm). The two tests gave nearly the same result, respectively 91.34% and 91.34%. From the experiment 91.44% of the oil was displaced in test E2, and ~92% in test E1, thus LedaFlow Q3D gives well results in terms predicting a realistic displacement level and predicting a stop of displacement after a certain time (e.g. after simulating E2).

9.2.3 End discussion and conclusion

For the case where Exxsol was to displace water in the system, it resulted in good overall displacement for the experiments conducted and by simulating in LedaFlow Q3D. Three conclusions can be drawn:

- It is sufficient with utilization of only one injection point regarding the inlet section. It displaces approximately 70%, and that is a good enough displacement level. When replacing the displacement medium with Methanol, it would be safe to operate.

- Simulations in LedaFlow Q3D were run successfully due to results very similar to what was the case in experiments. Also because the displacement progress acted the same way as expected in LedaFlow Q3D. To get to these good results in LedaFlow Q3D the constant droplet size parameter was tuned. By conducting these tests, LedaFlow is more trustworthy as a simulator tool for this type of simulations. It may be questioned whether the basis is too thin to state that simulation, and ideally it should be simulated more.
- Simulations in LedaFlow 1D resulted in the same displacement trends as the experiment did, but with much lower displacement, and are therefore not the best tool to use in this situation. Due to LedaFlow 1D's area of application (designed to operate over longer distances) this was not surprising.

For the case where water was to displace Azolla, it was desirable to remove most of the Azolla in situ the system. By performing experiments and simulating in LedaFlow 1D and Q3D conclusions can be drawn:

- The experiments resulted in very good displacement levels, ~100% for almost all of the cases conducted with an initial GVF=59.6% and ~92% for the initially oil filled cases.
- Overall, LedaFlow Q3D predicts good displacement levels compared to the experiments; a bit lower levels for the tests when the initial GVF was 59.6% and almost equal for the test when the system was initially oil filled. Yet, it must be taken into account that different parameters can be adjusted until maybe a desired level is reached for all of the respectively cases. In addition, the number of tests compared is few and therefore a statement about displacement predictions in LedaFlow Q3D cannot be made.
- LedaFlow 1D predicted again lower displacement levels than for the experiments, except for the cases where the system was initially oil filled. In that case it gave higher levels of displacement. The latter results are peculiar, and show that LedaFlow is unpredictable. The reason for the deviation from the displacement trend prediction high displacement levels for the last two cases may be because it was a two-phase system. Previous work on LedaFlow 1D in two-phase systems has shown that it predicts a higher displacement than what is the case in experiments (7).

9.3 Discussion and conclusion about blow-through

In both of the cases with different gas velocity, both LedaFlow 1D and LedaFlow Q3D predict a bigger sweep out of water. This affects the rest of the course since very little of the residual liquid reaches up to the ring probes that measured the liquid volume fraction.

The inlet pressure in both LedaFlow 1D and LedaFlow Q3D has about the same progress as in the experiment. The results from LedaFlow 1D deviates the most with a higher pressure at the very beginning of the test. However, in general both LedaFlow 1D and LedaFlow Q3D predict the same progress for inlet pressure as for the experiments. A conclusion that can be drawn from studying the inlet pressure graphs is that the acceleration of superficial gas velocity at the beginning has an effect on the pressure.

Because the experiments were not good enough documented (Ref: 8.11), the basis was little when performing and evaluating simulations in LedaFlow 1D and LedaFlow Q3D.

Severe slugging can be seen in the simulations in LedaFlow Q3D and all the belonging four stages that characterize that type of slugging. This contributes to a verification of the use of LedaFlow Q3D. Thus a better understanding of severe slugging can be gained by the use of LedaFlow Q3D.

9.4 Cross case discussion and conclusion – Displacement- and blow-through tests

All in all, the work has been carried out successfully, with good displacement levels from execution of the displacement tests and quite similar results by simulating in LedaFlow Q3D. Regarding the displacement tests, in LedaFlow Q3D the good results were provoked by adjusting droplet/bubble size. LedaFlow Q3D gave quite well results for the s-riser tests as well, but due to little basis from the experiments for working on the case in LedaFlow Q3D, the comparison of them is not to trust completely.

All in all, LedaFlow Q3D has given good results in this work, having in mind the few number of tests studied, and in general, the experience with working with LedaFlow Q3D was that it is a tool with great potential in multiphase simulations. More simulations are needed for verification of the tool.

The experience with simulating in LedaFlow 1D is that it is more unpredictable and that it gave worse results than LedaFlow Q3D. The tool is not designed to treat such small systems and therefore it is not expected that it will give optimal results for the systems applied in this work.

9.5 Future work recommendations

Regarding the s-riser case further work should consist of conducting more experiments, both for the high velocity case and for the low velocity case. Experimental data, such as geometry of the setup and results should be well documented. In that way, necessary information for conducting the experiments in LedaFlow and for analysis of the experimental data is present.

When it comes to the displacement experiments, future work could concern doing the tests with the same rig but with changing some, or the entire pipeline with Plexiglas. Video recordings could then be made in order to view the displacement. It would also be easier to verify the use of LedaFlow by comparing the progress of displacement of the simulations and experiments conducted.

Further on, in order to optimize the simulations and simulation results in LedaFlow Q3D, other parameters can be studied, in combination with each other or alone. An example on a parameter that could have effect on the displacement simulation is the Charnock constant. By changing that constant, the wave formation is taken in consideration if the wave is smaller than the cell.

Another thing to change in order to optimize the simulations for all the two types of experiments is to refine the meshing. In this way more varieties could be encountered. When it comes to simulating the high-velocity s-riser test one can look at the possibilities of ramping up the velocity better (higher acceleration of gas inflow).

Lastly further work on improving Q3D stability for cases with large density differences would be advantageous for LedaFlow Q3D.

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11 Appendix A

11.1 Experimental procedure: Exxsol D80 displacing water

Detailed explanation about the procedure of the test where Exxsol D80 is displacing water is listed in Table 11. Valves (V1-V11) and pump P1 that is mentioned in the table is referred to Figure 43 where their location is presented.

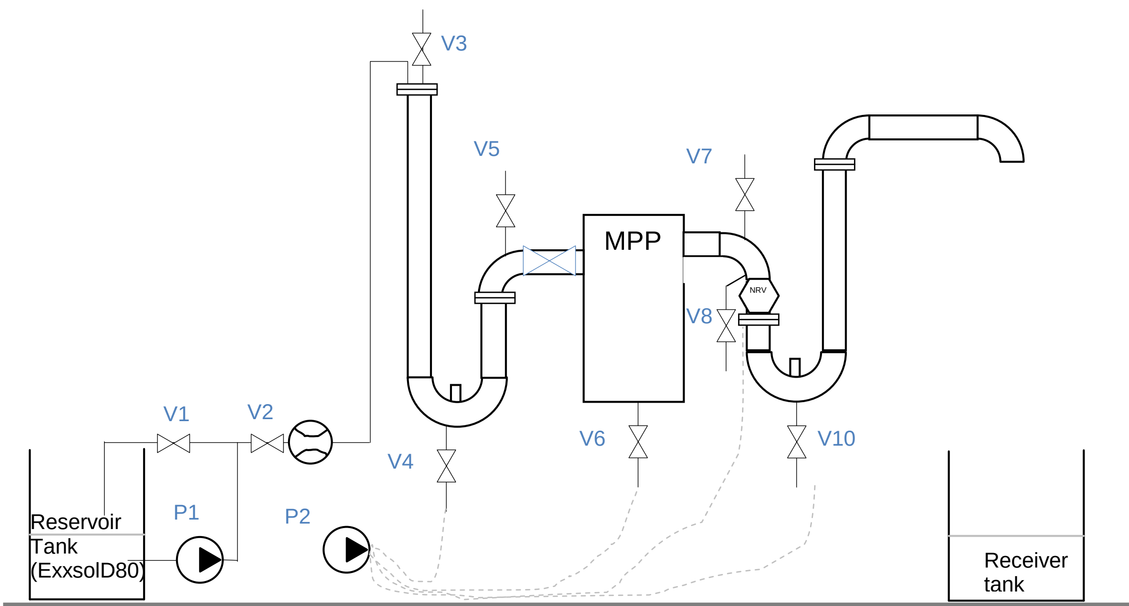

Figure 43: Detailed information, setup Exxsol displacing water

Action	Comment
Verify zero flow on the flow meter	
Open all venting valves (V3, V5 and V7) and V4, V11 (ball valve), V8 and V10	
Inject HOLD litres of water through V4	To achieve the settle out GVF
Close all venting valves (V3, V5 and V7)	
Open V1 (partly)	The injection pump P1 should not be started against a closed valve.
Start the injection pump P1	
Gradually open V2 and close V1 to reach the target flow rate.	Injection of Exxsol D80
Keep injecting Exxsol D80 for HOLD seconds	
If necessary, pump Exxsol D80 from the receiver tank into the reservoir tank.	
Stop injection pump P1, Close V2 and V1.	
Close V11	
Wait at least 10 minutes to let the water and oil separate.	
Drain completely through V4 and measure the amount of oil and water. (Open V3 and V5 after a while.)	
Measure the amount of Exxsol D80 and water in the receiving tank.	
Pump any Exxsol D80 back from receiver tank to reservoir tank.	

Table 11: Experimental displacement procedure Exxsol displacing water

The same procedure for filling and draining of the two other sections was followed.

12 Appendix B

12.1 Experimental procedure, water displacing Azolla ZS 32

Detailed explanation about the procedure of the test where water is displacing Azolla ZS 32 is listed in Table 12. Valves (V1-V15) and pump P1 that is mentioned in the table is referred to Figure 44 where their location is presented.

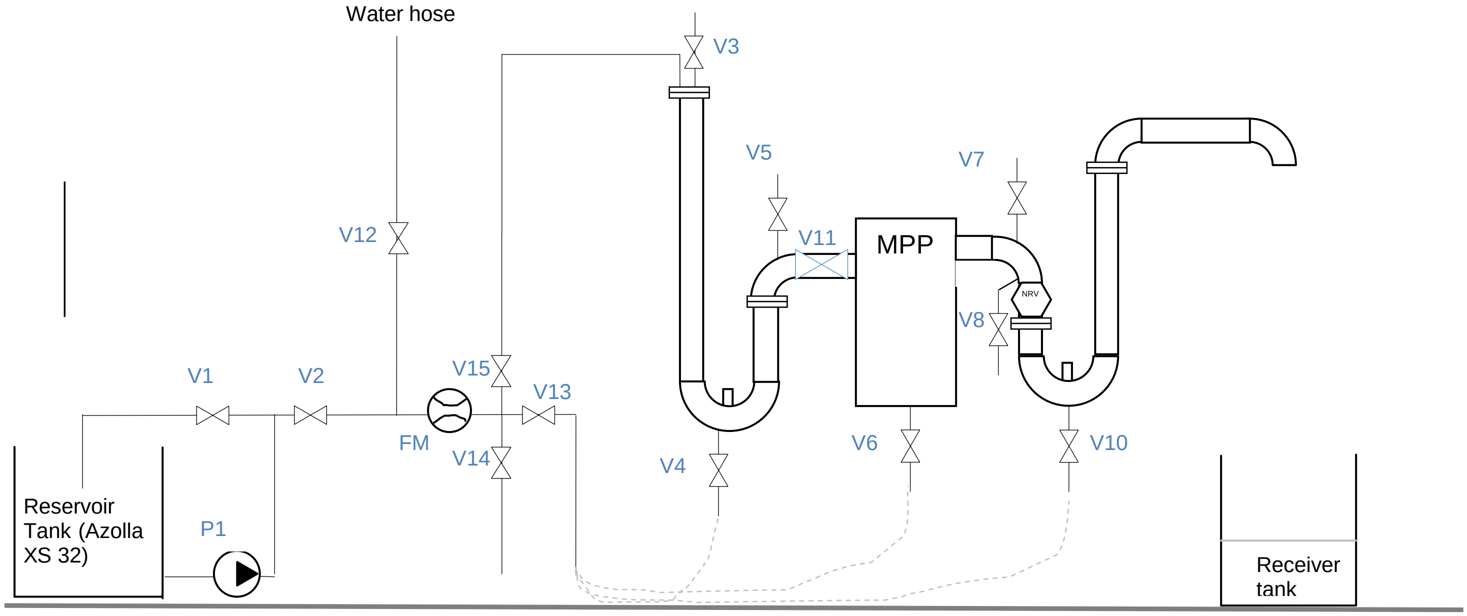

Figure 44: Detailed experimental setup, water displacing Azolla

Action	Comment
Verify zero flow on the flow meter	
Open all venting valves (V3, V5 and V7) and V4, V11, V8 and V10	
Make sure V12, V14 and V15 are closed	
• Open V13 • Open V1 partly • Start the injection pump P1 • Gradually open V2 and close V1 to reach the target flow rate. • Inject HOLD litres of Azolla through V4 • Stop the injection pump P1 and close V2 and V1 and V13	To achieve the settle out GVF
Close all venting valves (V3, V5 and V7)	
Open V15	
Gradually open V12 to reach the target flow rate.	Injection of water
Keep injecting water for HOLD sec	
Close V12 and V11	
Wait at least 40 minutes to let the water and oil separate.	
Drain completely through V4 and measure the amount of oil and water. (Open V3 and V5 after a while.)	
Measure the amount of Azolla and water in the receiving tank.	
Pump any Azolla back from receiver tank to reservoir tank.	

Table 12: Experimental displacement procedure water displacing Azolla

The same procedure for filling and draining of the two other sections was followed.

13 Appendix C

13.1 Geometry specifications for S-riser

Detailed information about the pipe geometry is listed in Table 13. The numbering on the left hand side represents points throughout the pipeline. To the right of the numbers its properties follows; the location of the point in x direction and in z direction. The length units are in meters. The geometry starts at x=52.48m in the table, however it has no influence on the geometry.

	X [m]	Y [m]	Z [m]
1	52.4832	0	0.145085
2	53.4104	0	0.130499
3	54.2812	0	0.105916
4	55.0894	0	0.0763224
5	55.8322	0	0.0483879
6	56.5104	0	0.0181531
7	57.1284	0	0.0410868
8	57.6662	0	0.224283
9	57.9706	0	0.616245
10	59.3566	0	3.26139
11	59.5476	0	3.5897
12	59.7519	0	3.89728
13	60.0676	0	4.02853
14	60.4548	0	3.93111
15	60.7934	0	3.69976
16	61.1265	0	3.46296
17	61.817	0	3.02038
18	62.1811	0	2.81945
19	62.5891	0	2.73109
20	62.9268	0	2.84476
21	63.2217	0	3.07994
22	63.402	0	3.42819
23	63.5017	0	3.82718
24	63.5979	0	4.24084
25	63.6909	0	4.66805
26	63.794	0	5.10468
27	63.8761	0	5.5561
28	63.9028	0	6.02145
29	64.0605	0	6.4442
30	64.5314	0	6.5
31	66	0	6.5

Table 13: Geometry points for S-riser used in LedaFlow.