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Numerical simulation of surge wave instability of long distance transport of multiphase flow

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MASTER THESIS

for

Linge Dan

Spring 2018

Numerical simulation of surge wave instability of long distance transport of multiphase flow

Numerisk simulering av tetthetsbølge ustabilitet av langdistanse transport av flerfasestrøm

Background and objective

Ramp up of production rates in wet gas pipelines can give long surge waves arriving at the
receiving separator, this can cause severe problem for the operation of the separator. The mitigation of surge wave is a challenging issue and should begin with the understanding of the mechanism of the

surge wave formation. For this, the numerical simulation of commercial software can be very useful.

The objective of this work is to conduct the numerical simulation of surge wave propagation in a long pipeline by using the commercial software.

The following tasks are to be considered:

1. Literature survey of surge wave of multiphase flow to get the understanding of the surge wave formation mechanism and propagation behaviour in a pipeline
2. Numerical simulation of surge wave process by using OLGA or LedaFlow codes, the comparison of these two software on such problem is conducted
3. The performance of the commercial software ware on dedicated experimental data (lab, or field) will be evaluated.

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Within 14 days of receiving the written text on the master thesis, the candidate shall submit a research plan for his project to the department.

When the thesis is evaluated, emphasis is put on processing of the results, and that they are presented in tabular and/or graphic form in a clear manner, and that they are analyzed carefully.

The thesis should be formulated as a research report with summary both in English and Norwegian, conclusion, literature references, table of contents etc. During the preparation of the text, the candidate should make an effort to produce a well-structured and easily readable report. In order to ease the evaluation of the thesis, it is important that the cross-references are correct. In the making of the report, strong emphasis should be placed on both a thorough discussion of the results and an orderly presentation.

The candidate is requested to initiate and keep close contact with his/her academic supervisor(s) throughout the working period. The candidate must follow the rules and regulations of NTNU as well as passive directions given by the Department of Energy and Process Engineering.

Risk assessment of the candidate's work shall be carried out according to the department's procedures. The risk assessment must be documented and included as part of the final report. Events related to the candidate's work adversely affecting the health, safety or security, must be documented and included as part of the final report. If the documentation on risk assessment represents a large number of pages, the full version is to be submitted electronically to the supervisor and an excerpt is included in the report.

Pursuant to “Regulations concerning the supplementary provisions to the technology study program/Master of Science” at NTNU §20, the Department reserves the permission to utilize all the results and data for teaching and research purposes as well as in future publications.

The final report is to be submitted digitally in DAIM. An executive summary of the thesis including title, student's name, supervisor's name, year, department name, and NTNU's logo and name, shall be submitted to the department as a separate pdf file. Based on an agreement with the supervisor, the final report and other material and documents may be given to the supervisor in digital format.

☐ Work to be done in lab (Water power lab, Fluids engineering lab, Thermal engineering lab)
☐ Field work

Department of Energy and Process Engineering, 15. January 2018

Zhilin Yang
Academic Supervisor

Research Advisor:

Foreword

The aim of this Master Thesis is to achieve the numerical simulation of surge wave in long-distance pipeline. While understanding the formation mechanism of surge wave, it pays more attention to propagation process. Because the unstable flow of surge wave will bring challenges to the operation of gas field platform receiving equipment, numerical simulations are necessary for this research. In fact, there is not much research on this type of multiphase flow, I am very happy that I can have such a chance to do work about it.

During the work of the thesis, I am very grateful to my academic supervisor Zhilin Yang. I would like to thank him for giving me a topic that is very suitable for me to complete. When I started the project, he gave me a lot of directions to think about, so that I can from different perspectives to conduct numerical simulation studies. Thanks to him for providing the PVT file and real case in the simulation process, making the whole work more perfect. Because English is not my native language, Zhilin also helped improve my writing skills during the writing of the thesis. I am very grateful for his guidance.

Linge Dan Trondheim 08.06.2018

Abstract

The surge wave is an unstable flow phenomenon that may occur in the wet gas pipelines. The dramatic decrease in gas flow rate or the stopping of gas production due to other reasons would cause the liquid accumulation at the low spots of the pipelines, because the gas cannot drive the liquid forward. Ramp up again of the gas flow rate can make the accumulated liquid to be swept into the pipeline and at the same time cause the holdup peak to form surge waves. The surge wave propagates a long distance and has a long duration. Surge waves can carry a large amount of liquid which may exceed the capacity of the receiving equipment at the end of the pipeline and adversely affect the operation of the equipment, such as the separator.

Surge waves is a challenge for flow assurance. From the literature survey, OLGA predicted the surge wave of the three-phase flow earlier than the actual surge wave. The PMS (pipeline management system) module in Flow Assurance System is more useful in the prediction and simulation of surge waves for the field production. In the Mater thesis, the surge wave propagation of gas-liquid two-phase flow in long pipeline is the key research point. OLGA2016.2.1 and LedaFlow Engineering v2.3.254.029 were used to complete the numerical simulation.

The numerical simulation is divided into three parts. The first is to reproduce the experiments of gas-liquid two-phase surge wave completed at NTNU Lab by software, the pipeline was 57.84 meters in length and 60 mm in diameter. Comparing with the results of previous versions of the software, OLGA2016.2.1 had good simulation performance only at observation points near the entrance to the horizontal pipeline, and the simulations of the LedaFlow program for the surge wave were still not ideal, of the eight analysis cases, only two results were similar to the experimental results. The geometric configuration of the pipeline was modified to study the effect of up and down pipes on wave speed. This is useful for the geometrical setup of

long-distance pipelines.

The simulation of long-distance pipelines is the second part of simulation, up and down pipes with uniform length were first considered. The whole pipeline has length of 1,325 meters and a diameter of 0.3 meters. There was a slug flow with 2.5 seconds, but the wave speeds of the up and down pipes were significantly different. The holdup reached the maximum at the first low spot, and then propagated forward and gradually decreases. When surge wave entered horizontal pipeline, the peak of holdup is around 0,012.

The downward pipe accelerates the wave speed. The existence of different wave speeds is the important condition for the merger of surge waves. By changing the geometric configuration of the long-distance pipeline, a pipe with a length of 850 meters and a diameter of 0.3 meters was set up, keeping all inclinations at 1.14 degrees. At the first low point of the pipeline, the holdup peak value was higher than that of in previous case, however, holdup value dropped also more dramatically.

Only one wave was set at the entrance, and the merge of the surge wave in the long-distance pipe cannot be observed, therefore two consecutive gas flow changes were introduced. When the first wave propagated forward, the second wave experienced the acceleration of the down pipe and could catch up with the first wave, so that before reached horizontal pipe, the two waves merged. And for this case, OLGA and LedaFlow had similar results.

Therefore, through numerical simulation, we can know that in practical production, the propagation of the surge wave is not a single wave forward, since the changes in the flow rate, the liquid accumulations in the low spots would flow by the form of surge wave after the flow rate recovers. Small surge waves merge with each other due to the shape of the pipeline or the terrain to form a large surge wave. The merger of waves makes the propagation of the entire surge wave to last longer.

The last part of the numerical simulation was based on field data. By adjusting the fluid flow rate during the running time, the phenomenon of surge wave can be observed, satisfying the fact that the flow regime was stratified, had a holdup peak, and lasted a long time. Therefore, the ability of the OLGA simulated surge wave can be evaluated.

Table of Contents

1.Introduction

1.1 objectives

The surge wave is a kind of unstable flow, and its appearance will damage the receiving equipment on the platform. Numerical simulation of surge wave propagation in long distance and large diameter wet gas pipelines has important meanings to field production. The software has advantages when debugging the settings of various parameters, especially finding the suitable flow rates to form surge waves. In order to study the variation of wave velocities in the pipelines and observe the merger of surge waves, the appropriate geometry of the pipelines and the size of the flow rate at the entrance need to be found. Although the specific three-phase surge wave study was not included, the effect of water content on the duration of the surge wave was considered.

Commercial software does not fully replicate the operating conditions in the field. However, through simulating field case in OLGA, the effect of fluid flow rate on the formation of surge waves can be found. The goal is to study whether unstable flow would occur at the end of the pipe when fluid flow is at a lower value.

1.2 Structure of the thesis

The thesis contains six chapters in total where the first chapter is an introduction. Literature survey was used to understand the formation mechanism of surge waves, it is presented in chapter two. In chapter three, by reproducing the previous NTNU experiments on surge waves in OLGA2016.1 and LedaFlow2.3.254.029, suitable numerical simulation options settings were found. Further, this chapter also focuses the simulations of surge waves propagation in long-distance and large-diameter pipelines, and the effects of wave velocity, number of initial waves, water content on the propagation of surge waves are taken into account too. The fourth part of the thesis is to introduce a field case that can generate a surge wave in the OLGA simulation by adjusting the flow rate. The conclusion is summarized in chapter five and the chapter six shows recommendations of further work.

2.Surge wave phenomenon

2.1 Some definitions

Surge waves are the liquid films of finite lengths travelling in pipes [1, p.5]. and, it is an unstable flowing that usually occurs when the flow rate is low [2, p.1]. When the surge wave appears, there are usually an increase in the holdup of the liquid, but it will not obstruct the gas through the cross-section of pipe. The surge wave is also a type of stratified flow, but because it carries a lot of liquid, the surge wave has a long wavelength and continues to propagate for a long time. [3, p.13]. A surge wave observed in the previous experiment is shown in Figure 2.1 below.

Figure2.1: surge wave diagram from previous experiment [5, p.3]

Early experimental research by IFE (Institute for Energy Technology) explained this phenomenon in more detail. In IFE's studies, the surges only occupied a fraction of the pipe cross-section and they typically had dry wall on both sides. If a surge, which height increased with time (fixed point of observation) was denoted a positive surge. A negative surge was one in which the height decreased with time [1, p.9]. This is exemplified in Figure 2.2.

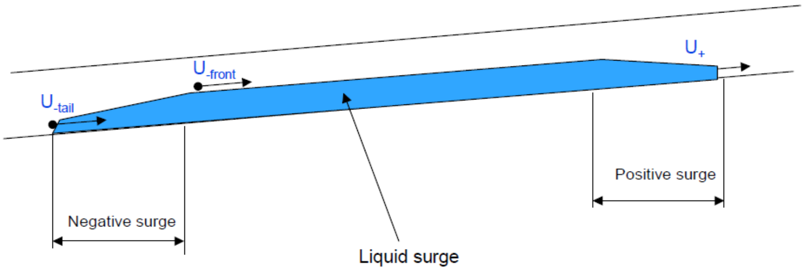


Figure2.2: Surge wave notation by IFE [1, p.9].

2.2 Formation mechanism

Surge waves in gas condensate pipelines are a well-known phenomenon and normally occur after ramp-up of production or a start-up. [7, p.3]. The drop in the reservoir pressure brings about a drop in the production, and the drag force between the gas-liquid phase will drop, and the liquid will accumulate in the pipeline [3, p. 14]. If the productivity increases again, the liquid then flows in the form of surge waves at the outlet of the receiving device, changes in the liquid content will limit the minimum allowable time for ramping up production without overfilling or flooding the receiving facilities [4, p.2]. For long-distance, large-diameter pipelines, although they rarely operate below a minimum turndown rate, it is possible to run at a low rate, thus managing liquid volumes during the production ramp-up or restart is necessary. [21, p.1].

Surge waves in the pipelines can also be called liquid flow oscillations. These oscillations are very slow, the typical oscillating time that can be observed is about 1 hour, and they can stay in the 100 - 200 km pipeline for 1 or 2 days before the liquid flow stabilizes. This is because the velocity of the liquid wave in the oscillation is very close to the transport velocity of the liquid in the pipeline. [5, p.13].

One of the important factors for the formation of the surge wave is liquid accumulation. Liquid accumulation variations are dependent on gas velocity. During production shut down, liquid accumulates along the flowline along low points. Because of the high content and low transport efficiency of the liquid, production at low flow rates can result in flow instability in the pipeline. Then when the production ramp up again, the liquid propagates as a surge wave in the flowline. if the production rates increase, the gas velocity increases and improves the ability to transport liquid, resulting in smaller liquid accumulation in the pipeline [3, p. 14].

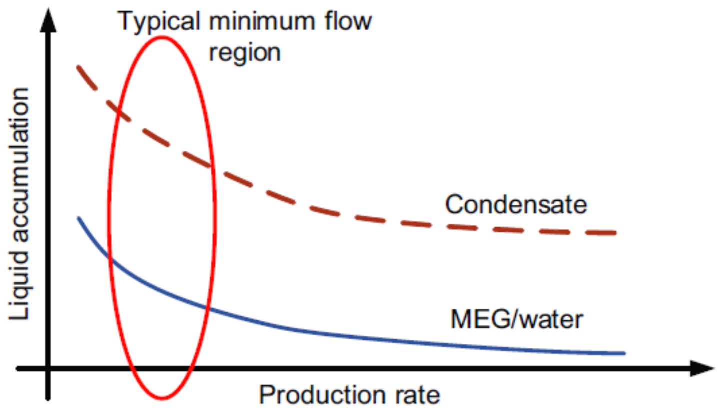
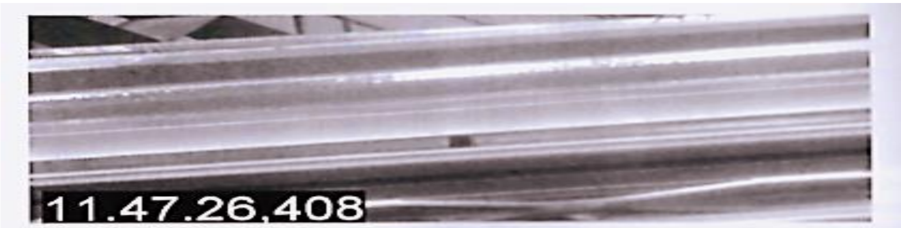


Figure2.3: Conceptual relationship between production rate and liquid content of condensate and MEG/water [4, p.2].

Seeing the figure above, the liquid content is liable to drastically change when the production rate is at a lower value. If an increase in productivity, it will result in a transition in the pipeline from a state containing a large amount of liquid to a state containing less liquid. If the pipeline is operated in this region, even small changes in production rate can cause large liquid surges [4, p.2].

In fact, the ability to product at low flow rates at low reservoir pressure is important to tail-end production. Increased liquid hold-up and surge waves in the pipeline may cause transportation problems during the tail-end production. With surge waves, it is not possible to obtain an optimum process handling [7, p.3]. Since accumulated liquid in a pipeline is a function of gas flow rate [6, p.9]. It need to define the minimum production flow to avoid the presence of surge waves.

The surge wave is a special flow in the gas-condensate pipelines. According to flow regimes, it belongs to the stratified flow, but it is different from the general stratified flow. For surge waves, there are some distinguish characteristics: firstly, there is a sudden increase in the pressure drop when interfacial waves above a certain size are formed. Secondly, large surge waves usually have breaking wave-fronts [5, p.4]. The following two pictures are from the experiments conducted in the NTNU lab, they showed the stratified flow and surge wave in the horizontal pipeline



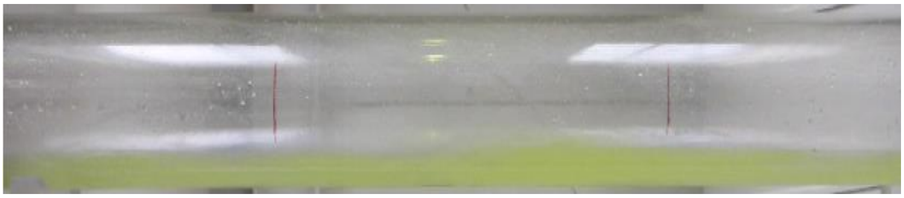


Figure2.4: the stratified flow (the first plot) which is obtained by the experiments by Magnus Kallager, and surge wave (the second plot) which is obtained by the experiments by Steinar.

In fact, the surge waves observed in the experiment do not have a breaking wave-front, it can only be seen in large surge waves. In another wave, the roll wave, usually has a steep wave front, which is not to be confused with the surge wave. Roll waves are the largest amplitude waves that occur in the two-phase pipe flow, which front tends to roll over and create a breaking wave [8, p. 2]. Compared to surge waves characterized by slow oscillations, long duration, low amplitude and smooth wave-front, the roll wave is a completely opposite type of wave phenomenon [3, p. 16]. Figure2.5 shows the roll wave observed in the experiment, it is an air-water flow.

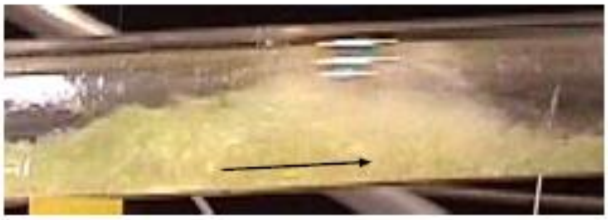


Figure2.5: roll wave in the lab [3, p.16]

Another flow regime that needs to be distinguished from it is slug flow. Slug flow has two types of hydrodynamic slug and terrain-induced slug flow. slug flow is the mixed flow, the holdup and pressure always fluctuate. In actual production, riser slugging is a problem in oil dominated flow, the main reason is the change of terrain. surge waves are a problem in gas dominated flow, which due to the reduction in production [3, p. 15]. Considering the process of propagation, Slug flow obstructs the entire cross-sectional area of the pipe, while the surge wave occupies only a small part. Surge waves can travel for distances of 100 kilometers for an hour, while slug flows are usually less than 500 pipe inner diameters long [9, p. 8]. The following figure illustrates the slug flow phenomenon in the pipeline.

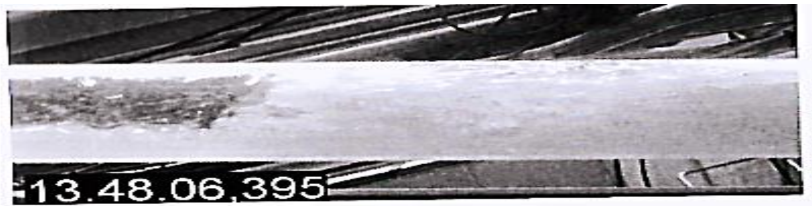


Figure2.6: slug flow in pipeline, which is obtained by Magnus Kallager' experiments in NTNU

The early research of the surge wave focused on two-phase flow, but because of the complicated production conditions in the gas-condensate flowlines, surge waves usually appear in the form of three-phase flow. In order to prevent the formation of hydrates in the pipeline and block the pipeline, affecting the transportation of gas-condensate flowlines, the mono ethylene glycol (MEG) is usually injected. The MEG is then transported through the flowline along with the well stream, back to the platform where it is regenerated [3, p.16].

From the data which belong to Mikkel and Midgard gas-condensate fields, the surge is divided into two parts; condensate surge and water/MEG surge. the condensate surge arrives firstly, and then the water/MEG surge. a slight decrease is found in the gas rate when the condensate surge arrives topside, while a slight increase again with the arrival of the water surge. The condensation rate drastically decreases during the water/MEG surge. After a surge, stable condensing and gas rates are restored, while water and MEG return stops [10, p.11].

In the existing operation model, surge waves are actually difficult to predict accurately [11, p.8]. Therefore, in a low-flow production pipeline, it is necessary to control a situation where surge waves may occur. Surge waves are mainly a greater issue at offshore platforms than at large onshore plants [4, p.7]. For offshore production units, the liquid buffer volume will be limited as weight and area [4, p.1].

In the Åsgard B field, the ability to control and handle liquid surges depends on robust production chokes intended for continuous use [4, p.6]. The gas flow rate increases if the receiving pressure is reduced, the increased gas flow rate in the pipeline can carry more liquid, thus reducing or avoiding liquid accumulation. [11, p.2].

2.3 Simulator performance

To better understand surge waves, some commercial transient multiphase fluid software can be considered. The OLGA software is the most commonly used one, but it does not seem to make a good prediction for the emergence of surge waves under the field conditions [5, p.13]. For the condensate surge and water/MEG surge, we cannot reproduce MEG surges under OLGA low speed test conditions. The speed must be significantly reduced to show similar behavior as seen in the low-rate test [4, p.7]. A comparison of OLGA with field measurements shows that OLGA generally provides a large low prediction of the onset gas rate for liquid accumulation, which leads to an underestimation of the liquid content at low rates [12, p.5].

OLGA is not ideal for predicting surge waves in three-phase flow, but according to previous studies, it has performed well in the simulation of surge waves in two-phase flow at low-rate test. Therefore, in this Mater thesis, two-phase flow will be selected for numerical simulation.

Another model simulator is PMS (pipeline management system), which is a module of Flow Assurance System. In the Ormen Lange production system, the PMS can calculate and present the condensate, water and MEG transportation. [6, p.5]. The upgraded PMS even gives accurate predictions of the liquid surge waves in the pipelines and the liquid level in the slug catchers. Figure2.7 shows a series of pressure drops and liquid holdup profiles in pipeline, including the corresponding calculated and measured liquid level trends in the slug catcher [6, p.9].

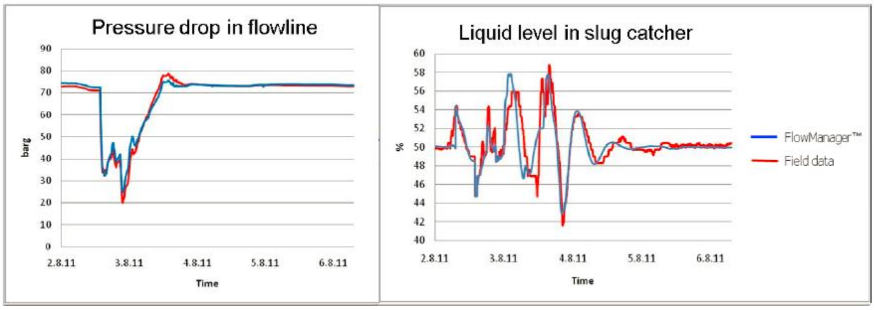


Figure2.7: Pressure drop and liquid level simulation from PMS module in Ormen Lange filed [6, p.12]

2.4 Surge wave in gas-condensate pipelines

In this part, literature surveys will be used to better understand the formation mechanism and propagation of surge waves in gas-condensate pipelines.

2.4.1 Huldra- Heimdal

The surge waves mainly occur at the tail-end production phase of Huldra field.

Huldra is a gas-condensate field which located in the Norwegian region of the North Sea. The previous maximum production rate of the Huldra field was approximately 11.5 MSm3/d. In the produced rich gas, a mixture of water/MEG and condensate had also been contained, and long subsea pipeline to the Heimdal platform was used for final processing and export [7, p.1].

When the Huldra field was in tail-end production, the lower limit of operational transportation for the rich natural gas pipelines from Huldra to Heimdal was 7.5 MSm3/d, the technical cut-off limit was estimated to be approximately 2.7 MSm3/d. multiphase pipes which are from Huldra to Heimdal represented increasingly difficult operational challenges due to the very large liquid accumulation in the pipes. a limited liquid storage capacity of receiving equipment had difficulty on facing the surge wave [7, p.1].

The ability to solve to this comprehensive challenge affect the lifetime of Huldra. The following figure shows the pipeline system from Huldra to Heimdal.

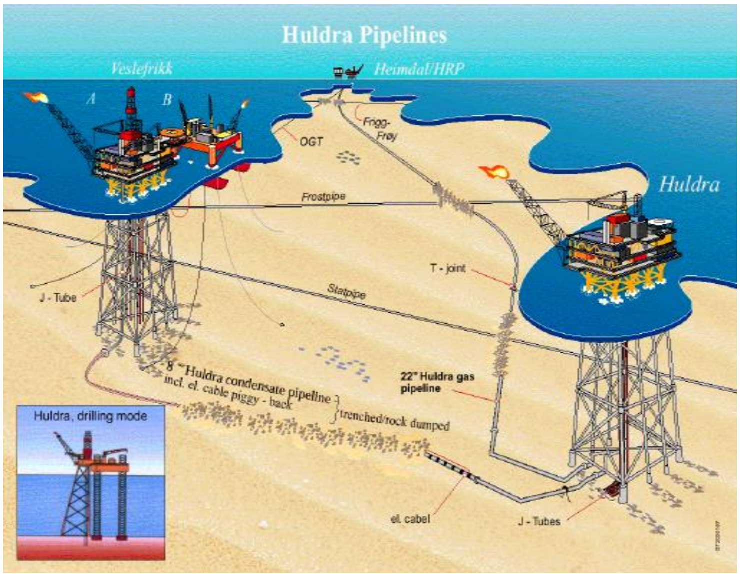


Figure2.8: pipeline system from Huldra to Heimdal [7, p.9]

Surge waves usually occurred after the restart of production or after an increase in the rate. Figure2.9 shows these surge waves during a time period after a production start-up. For the Heimdal process, an inlet vessel has a limited volume, and the surge waves from the Huldra to Heimdal pipeline made it not possible to obtain an optimum process handling [7, p.3].

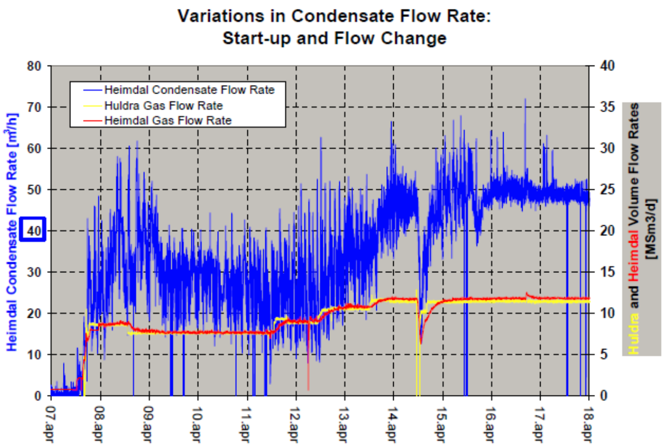


Figure2.9: Surge waves measured at Heimdal [7, p.10].

The simulation was also considered to be applied to this case. From the figure below, it can be found that the initial surge can be well predicted, but in reality, the surge wave lasted longer than the simulation results. The reason may be that the models tend to smooth the surges out as they travel through the pipeline [11, p.8].

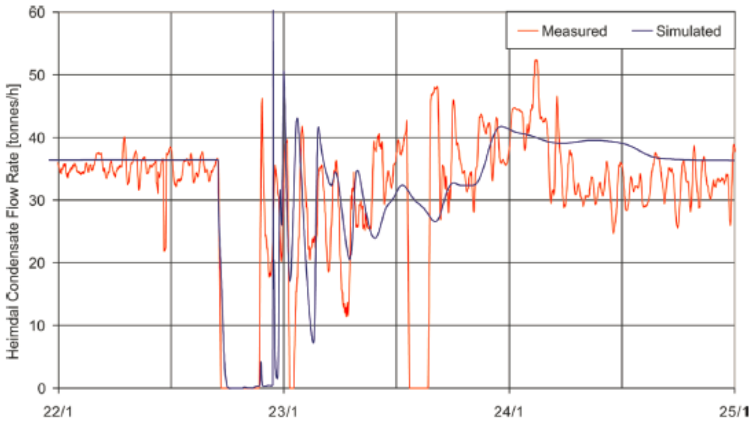


Figure2.10: Measured and simulated condensate rate at Heimdal [11, p.9].

Two approaches were considered for using in the pipelines from Huldra to Heimdal to cope with the appearance of the surge wave. One is the Implementing active flow control at Heimdal and the other is the Improved process control at Heimdal. For the first, the surge wave amplitudes are dampened by controlling the inlet valve, but a potential problem is when the gas and liquid flow rates are restricted, surge waves may be changed into liquid slugs. In the second method, the intelligent control of all the process equipment wound be an idea. All the devices are better linked, and the liquid levels can be adjusted ahead of each surge wave [7, p.3].

2.4.2 Ormen Lange

The Ormen Lange field is located 120 km off the north-west coast of Norway and was approval for development in April 2004.Ormen Lange is a gas and condensate field, in sea depths between 800 and 1 100 meters, which has been developed with up to 32 wells from up to four subsea templates. [13, p.2]. Figure 2.11 shows the field layout.

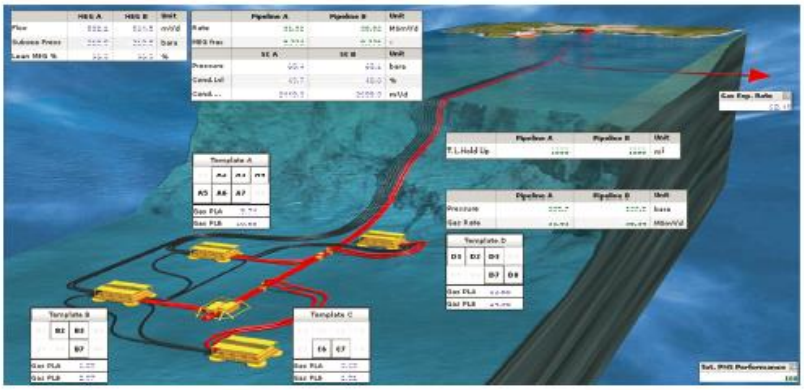
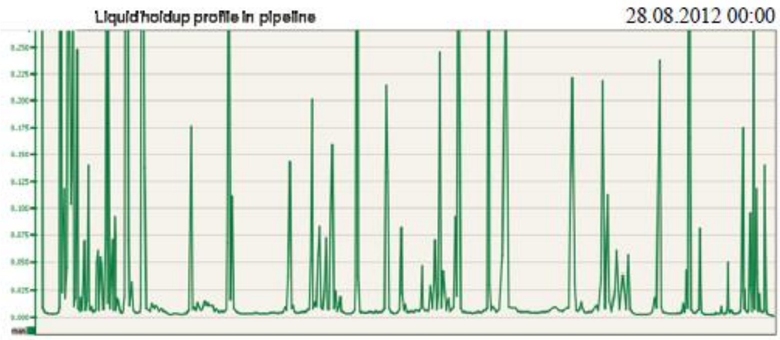
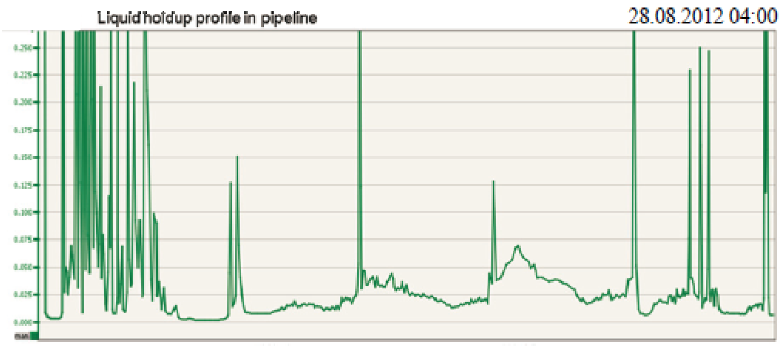


Figure3.11: Illustration of the Ormen Lange field layout [13, p.2].

The development of the Ormen Lange field is one of the largest and most demanding industrial projects in Norway. For the Ormen Lange field, flow assurance faces the challenge, liquid surge, since the liquid is easy to accumulate at a low rate. Untreated fluids transported over long distances (120 km) in hilly terrains can cause surge wave in the pipelines. [6, p.1].

In Ormen Lange's flow assurance system, the PMS (pipeline management system) module is used to calculate pipelines flowing conditions and the values of receive devices [13, p.1]. From the following liquid holdup profiles, the first one shows liquid accumulation in the pipeline after shut-in of all wells. After 4 hours, all liquid accumulated in the Storegga hill were propagating through the pipeline as a large surge wave [6, p.9]. Until 18 hours. there was no significant liquid accumulation and fluctuation in the pipeline, since the large surge wave arrived in the slug catcher.





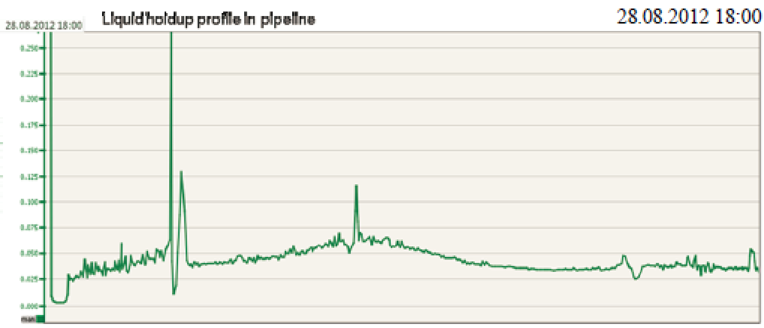


Figure2.12: liquid holdup profiles in Ormen Lange field [6, p.10].

Because PMS plays a very good role in predicting the surge wave and monitoring the changes of liquid holdup, the ramp-up speed gets the optimization so that the flooding of the slug catchers is avoided. For the flow assurance engineers, PMS is a good tool to gas transporting [13, p.13].

2.4.3 Midgard and Mikkel-Åsgard B

Midgard and Mikkel are both gas-condensate fields, X, Y and Z three templates have been developed in the Midgard field. a 37 km,18-inch pipeline has been used to transport production from Mikkel to Midgard. The two fields are tied to Åsgard B, a semi-submersible platform, through a 40 km, 20-inch production loop. An overview of the Midgard and Mikkel production loop and Åsgard B picture are shown in Figure 2.13 [4, p.2].

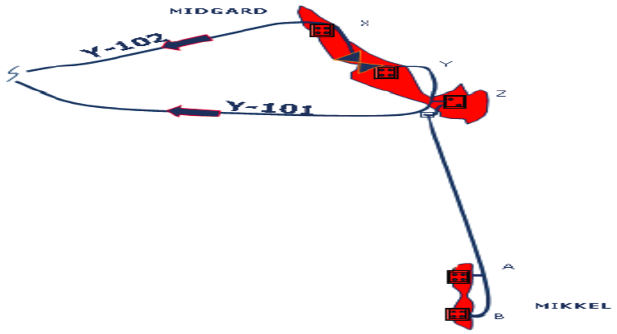


Figure2.13 (1): Midgard and Mikkel

Figure2.13 (2): Åsgard B.production loop [4, p.2]. (Photo: Øyvind Hagen / StatoilHydro)

In order to prevent the formation of hydrations in pipelines at low temperatures, the MEG (mono ethylene glycol) is used into the pipelines. The MEG is injected at the wellhead and transported back to Åsgard B along with the well stream, where the rich-MEG is regenerated. Åsgard B has limited facilities for the regeneration of rich MEG solutions [4, p.3]

At low production rates, by measuring the liquid content in the pipeline, it can be seen that even with gas production rate remaining unchanged, the return of condensate and water/MEG oscillated for several days.
The figure below shows the oscillations after 4 days of steady gas rate. A surge of condensate first appeared, and the effect on the gas flow rate slightly decreased. A surge consisting of the MEG occurred followed by the condensate surge, and the MEG surge made the gas flow rate return to normal [4, p.4].

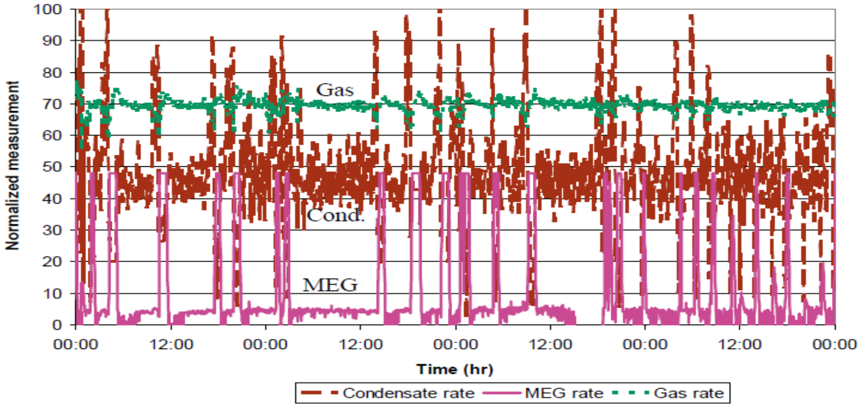


Figure2.14: Rates of gas, condensate and MEG during low rate test [4, p.4].

There are flat peak rates of MEG rate in excerpt of the rates figure, the reason is that the peak rate of MEG exceeded the range of the flow transmitter. From condensate surge to MEG surge, a slight drop occurs in pressure, except that, the pressure measured upstream the topside choke at Åsgard B keeps constant. As far as the duration is concerned, the difference between the two surge waves is also not obvious. While at the end of the MEG surge, the condensation rate returned to normal [4, p.5].

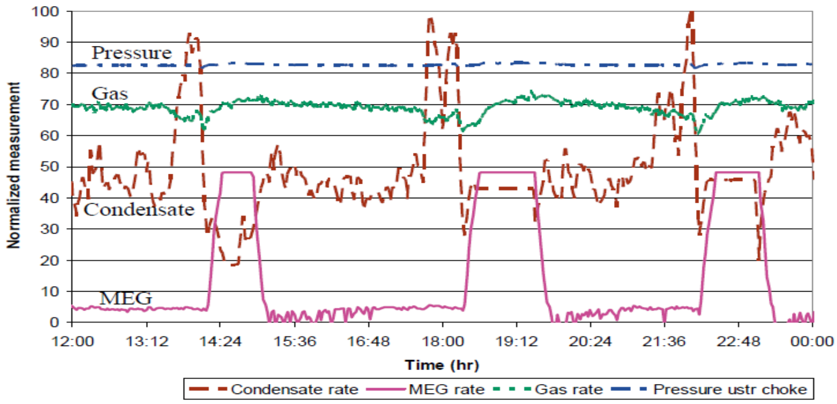


Figure2.15: Excerpt of rates of gas, condensate and MEG and topside pressure [4, p.5].

Production chokes would be used to handle liquid surges, as shown in Figure 2.16, reducing the choke opening has a greater effect on the liquid flow than the gas flow. When the choke begins to take effect, neither the MEG nor the condensate rate will not have a dramatic rate increasing, all values tend to be average. Compared with other methods, this method is cheaper [4, p.9].

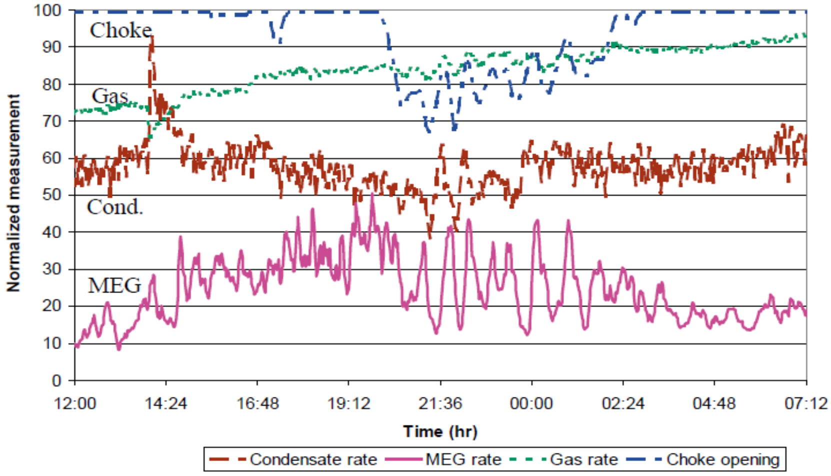


Figure2.16 Impact of choking on the gas-, condensate- and MEG-rates [4, p.9].

Controlling the liquid surges makes it possible to produce at lower flow rates, which is of great importance for improving the recovery of the field when the reservoir pressure depletion.

2.4.4 Snøhvit

The Snøhvit development area consists of three parts, Snøhvit, Albatross and Askeladd. From the subsea to the shore is connected by a 146km pipeline, in which the unprocessed multiphase flow well-streams are conveyed. At the same time, LNG projects have also been developed in the region, it is the first LNG full-scale liquefaction facility ever built in Europe. Snøhvit location and field installations as shown in Figure2.17 [12, p.1].

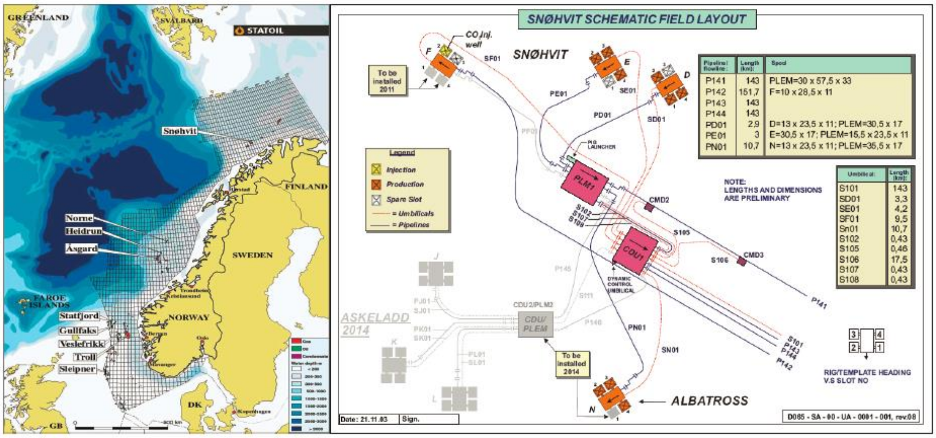


Figure3.17: Snøhvit location and field installations [12, p.1].

During the start-up of the LNG, there were several shut-downs. In order to avoid the accumulation of liquid at the time of shutdown, and then the surge formed due to the increase of the rate after start-up, the better guideline is to make production raise to the same level as before the shutdown, before accumulating large liquid. Therefore, monitoring the accumulation of condensate and MEG becomes particularly important. [12, p.8].

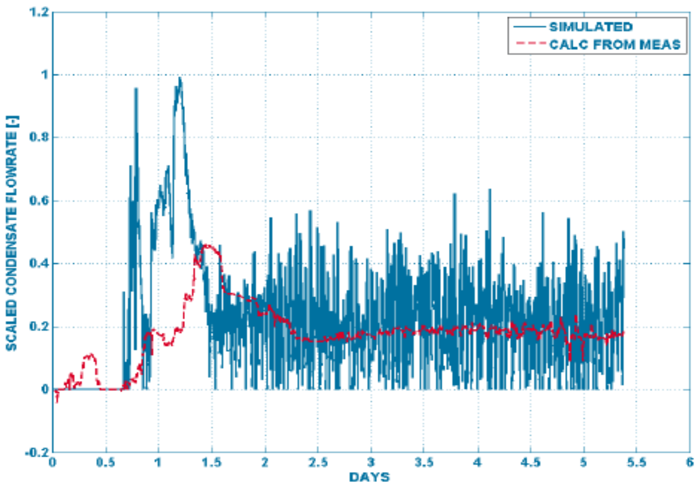


Figure2.18: Condensate flow rates during start-up after a long shut-down [12, p.9].

The above figure is a comparison chart of the predicted condensate rate by tuned OLGA model and measurement rate. From figure, it can be found that the simulated peak value is higher than the measured value in the field, and, in terms of time, tuned OLGA model shows the accumulation of liquid earlier than that of in the actual production [12, p.9].

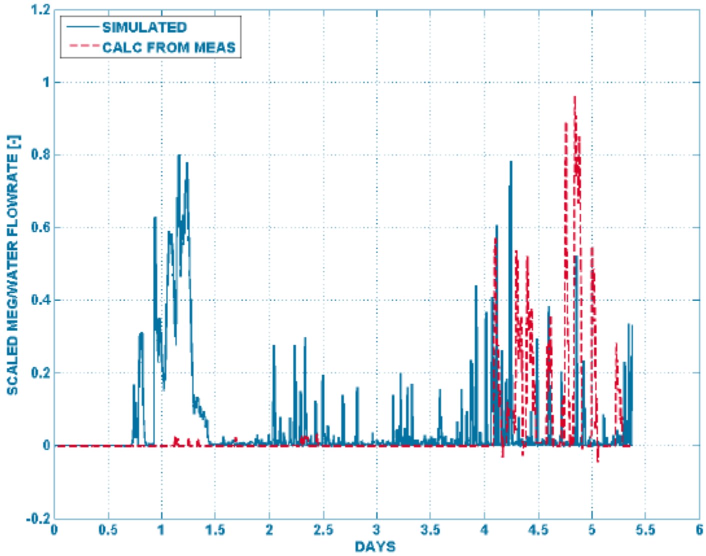


Figure2.19: MEG/water flow rates start-up after a long shut-down. [12, p.10].

A more obvious difference can be seen in the MEG/water rate figure. The gap between MEG/water surges arriving the shore is greater in simulation and measurement results. In the simulation, liquid accumulation does not last long, and the distribution is decentralized. In real life, liquid accumulation appears to be concentrated and last longer [12, p.10].

Therefore, in this case, the tuned OLGA model is not the best tool for predicting the accumulation of liquid in the pipeline. If it is to be used, it must be considered that it predicts earlier than the liquid accumulation occurs.

2.5 Previous laboratory experiments

2.5.1 IFE experiments

2.5.1.1 The test facility and fluids

The Institute for Energy Technology (IFE) completed a series of surge wave studies in gas-liquid two-phase flow in 2004, both by lab experiments and numerical simulations. The test section has an inner diameter of 0.1 meters and a length of 25 meters. The test tube is divided into two parts: the PVC pipe and the steel pipe. a transparent PVC pipe is to better observe fluid flow phenomena. In order to record traces of holdup and pressure gradients, many gamma densitometers and differential pressure sensors are distributed along the test section [1, p.10].

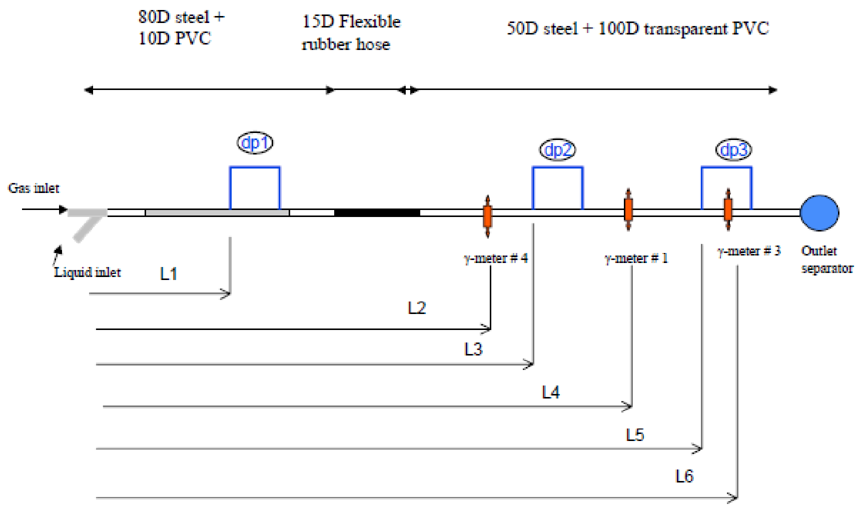


Figure2.20: Distribution of gamma densitometers and differential pressure transducers along the test section [1, p.12].

Three different gas-liquid fluid combinations have been used in experiment works: SF6-water, SF6-ExxsolD80 and SF6-Marcol. The reason why SF6 is used as a gas phase is that its molecular mass is five times that of air, which means that at moderate pressure, SF6 has a higher gas density and makes the flow phenomena observed through the transparent pipes are similar to those found in the gas-condensate pipes. [1, p.12]. For the liquid phase, water is the ordinary tap water, and its density is not affected by the high gas density. [1, p.13]. The ExxsolD80 is a transparent, light, solvent oil. SF6-saturated ExxsolD80 has a density that is higher than ExxsolD80 at atmospheric conditions. The Marcol oil is a mixture of the two oils Marcol 82 and Marcol 52. Marcol is a medical white oil, without color and odor. A mixture ratio of 3:2 between the 82 and 52 oils should give a mixture lower viscosity. [1, p.14]. The gas and liquid are separated before into the test pipe section, “mixed” in the pipe entrance, and flow through the pipe as the layered fluid [1, p.11].

2.5.1.2 Propagation of long liquid surges

For long liquid surges, the simulations are performed under the conditions of a given gas flow rate and where the pipe wall is initially dry. The fluid viscosity, surface tension, gas density and pipe inclination are all parameters that can be varied. Using different gas-liquid combinations to complete the experiments is to gain basic understanding on the propagation of long liquid surges under highly controlled inlet conditions [1, p.16].

The simulations of long liquid surges have been done in the pipe geometry of Figure 2.20. The following procedures are used to implement surges:

- To dry wall of pipe, the liquid in the pipeline needs to be blown out

every 4-5 minutes

- Firstly, adjusting the gas flow to a predetermined value, and then starting the liquid pump so that the liquid enters the test section, producing a positive surge.

- Turn off the pump, to initiate and observe negative surge, until the

tail of the surges disappears completely, and the pipeline returns to a single phase of gas, and the

experiment ends [1, p.16].

The data logger and the video camera are used to record the experimental process. The following figure shows the schematic layout of long liquid surges.

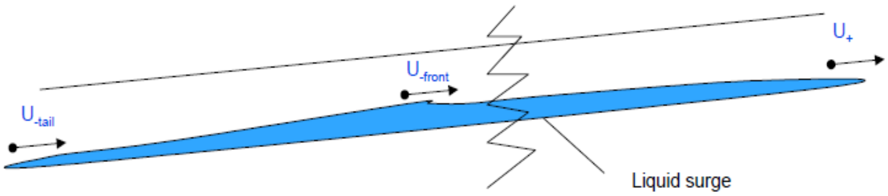


Figure2.21: Schematic layout of long liquid surges [1, p.17].

The following results can be obtained:

- The positive surge usually has a propagation velocity indicated U+.

The front velocity of water is faster than that of oil. U+ increases as the inclination of the pipe increases and the surface liquid velocity increases [1, p.18].

- The negative surge has a front and a tail, propagating with

velocities denoted U-front and U-tail. U-tail is generally lower than U-front and is independent of the inclination of the pipeline. The negative surge velocity is more changeable to gas flow than liquid flow [1, p.21].

If giving a shock at the tail of the negative surge, since the gas flow rate at this time is the minimum flow rate for the liquid to be blown out of the pipeline, the interfacial force of the gas and liquid phases is close to the gravity force, and the resulting liquid surges is shown in the following figure [1, p.24].

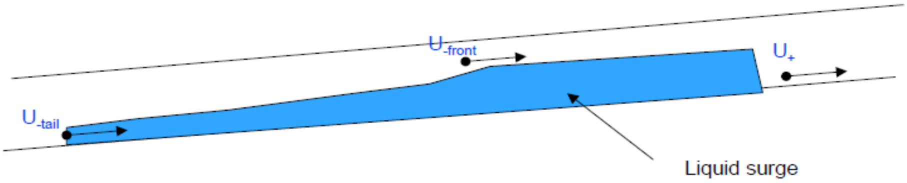


Figure2.22: Schematic outline of the liquid surges in experiments with an end shock [1, p.25].

2.5.1.3 liquid surges of finite length pipe by dip

In the finite length pipe, surge waves can be observed through the dip geometry, because when shut-down, liquids tend to accumulate at low points. When a sudden start of the gas compressor, the gas drives the liquid at the low point of the pipeline, generating surge waves phenomenon [1, p.27].

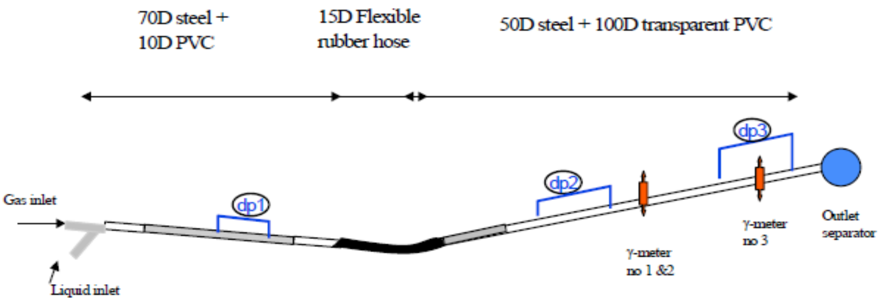


Figure2.23: Schematic layout of dip generated liquid film segments of finite length [1, p.28].

The pipeline layout is shown in Figure2.23. The test procedure applied was as follows:

•First use high-rate gas to blow all the liquid out of the pipe, and then running the large dosage pump to make the liquid accumulate at the dip.

•Restart the gas pump and reach the preset flow rate in 3 or 4 seconds.

•Use data logger and the video camera to observe the liquid flow phenomenon of the pipe dip downstream [1, p.27].

Dip generated liquid surges outline as seen in Figure2.24.

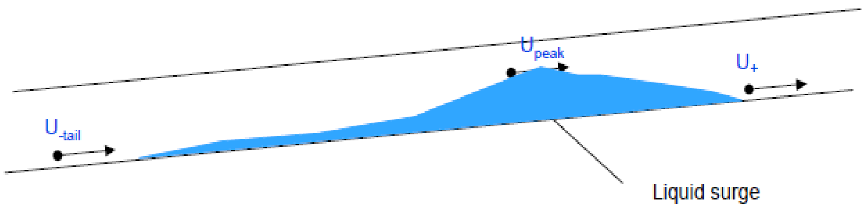


Figure2.24: Schematic outline of the shape of the dip-generated liquid surges [1, p.29].

Unlike long liquid surges, U_{peak} appeared here, which means that the liquid's holdup had a significant upward fluctuation. The holdup profile is shown in the figure below.

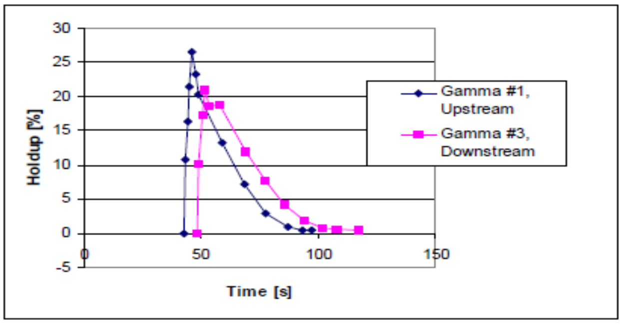


Figure2.25: Holdup profile of the dip-generated liquid surges [1, p.30].

The experiment of dip generated surges of finite length gives the following conclusions:

•U_{peak} replaced the velocity of front. Although the speed values are not much different, U_{peak} brings a more obvious holdup change, and the velocity of tail is much lower.

- Water still moves faster than Marcol.

- An increase in the accumulation of liquid at a low point brings about an increase in U_{peak} and peak holdup, while the pipe inclination is counterproductive to peak holdup.

2.5.1.4 Pump generated liquid surges

With the dip generated surges experiment, surge waves can be observed throughout the entire pipe section, which means that surge waves do not reach a stable state in a finite length pipe. Therefore, in a straight pipe, a limited length of liquid film was introduced by running the liquid pump for a short period of time, however, the gas compressor was always operated at a constant speed to observe the propagation of surge waves in the pipe [1, p.32].

Using this method to experiment, the final conclusions are [1, p.33]:

•First, there is no systematic difference in the front and tail of velocity compared to previous surges.

•Second, there was no significant change in the appearance and duration of the peak wave and the holdup curves.

2.5.1.5 Two surges in sequence

This part is to investigate whether the existence of the liquid film will affect the velocity of positive surge. The experimental procedure and geometric configuration are almost the same as long liquid surges, except that the pump was temporarily closed for a period of time in order to generate two consecutive waves [1, p.35].

After a limited number of experiments, it can be found that the front velocity of the latter wave is indeed slightly lower than the previous wave. This difference is systematic, but it also contains measurement uncertainty. In fact, liquid film does not affect the propagation velocity of positive surge [1, p.36].

2.5.2 Laboratory experiments at NTNU

Experiments conducted at NTNU are to study whether gas-liquid stratified flows can produce surge waves after gas choking and ramp-up again in the pipe with a dip. The gas used in the experiment was air and the liquid were water.

2.5.2.1 Experiment facility at NTNU

In order to better observe the propagation of surge waves in the pipeline, a pipeline longer than the previous IFE experiment would be used. The length of the pipeline is 57.84 meters and the inner diameter is 60mm. Experiments conducted on a combination of S-riser and horizontal pipeline [3, p.32].

The S-riser is to create a dip. S-riser nozzle was connected with a flexible pipe to make the pipe with a length of 1 meter and a downward inclination of 2.3 degrees, after a 0.5-meter horizontal hose, to achieve the dip, the hose (4.6 meters) rose upward by 11 cm to form a 1.4-degree angle and then connected to the horizontal pipe. The S-riser connection and liquid accumulation at the dip could be seen in following figure [3, p.34].

Figure2.26(a): S-riser nozzle was connected with a flexible pipe for a dip [3, p.35].

Figure2.26(b): Liquid accumulation at the dip [3, p.35].

Because of the limitations of the laboratory site, a straight horizontal pipeline cannot be achieved. Two 180-degree turns are used, and the flow regime would not be affected by the turns. The roughness of all pipes is 0.05mm. A schematic outline of the test section pipes is shown in Figure 2.27.

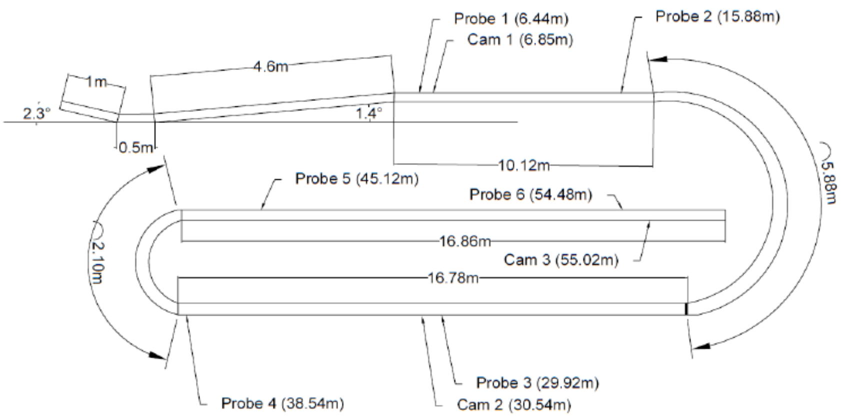


Figure2.27: Schematic outline of pipe geometry [3, p.36].

As shown above, 6 probes were installed to measure the value of the holdup of surge waves in the horizontal pipe section. The probes are positioned at 6,44 m, 15,88 m, 29,92 m, 38,54 m, 45,12 m and 54,02 m downstream the inlet nozzle [3, p.37]. The method to calculate the wave velocity between two probes is to consider the average value, that is, the distance between two probes divided by the time interval between the two peaks [3, p.39]. Three cameras are used to record the waves at each of the long sides of the flowline, at 6, 85 m, 30, 54 m and 526 m downstream the inlet nozzle [3, p.40].

2.5.2.2 Experiments procedure

Eight cases were performed in the experiments. Gas flow rate and water flow rate are shown in the following table [3, p.40].

Table3.1: the air and water flow rate settings in the experiments [3, p.40]

	Initial air flow rate		Initial air valve opening [% of full opening]	Water flow rate	
Case:	U_{sg} [m/s]	$\dot{m}$ [kg/s]		U_{sl} [m/s]	$\dot{m}$ [kg/s]
1	13,4	0,045	27	0,0113	0,032
2	10,9	0,037	25	0,0113	0,032
3	8,5	0,029	23	0,0113	0,032
4	7,6	0,026	22	0,0113	0,032
5	13,4	0,045	27	0,0264	0,075
6	10,9	0,037	25	0,0264	0,075
7	8,5	0,029	23	0,0264	0,075
8	7,4	0,025	22	0,0264	0,075

•When the steady stratified flow was flowing in the pipe, adjust the air valve opening to make Usg = 3,9 m/s ($\dot{m}$ = 0,013 kg/s),last for 10 seconds, and re-increase the air flow to the previous level.

•Data logger and cameras are used to record experimental results and phenomena [3, p.41].

2.5.2.3 Experimental results

With experimental setting of air flow rate changes, a relatively long surge wave can be initiated throughout the pipeline at a given water flow rate. The following figure shows the development of the surge wave in case 2 with U_{sg} = 10,9 m/s and U_{sl} = 0,0113 m/s. The wave front can be seen at the top of the picture. The wave peak is obviously in the middle picture. The lowest picture shows that after the surge wave, the flow regime in the pipeline returns to the stratified flow [3, p.42].

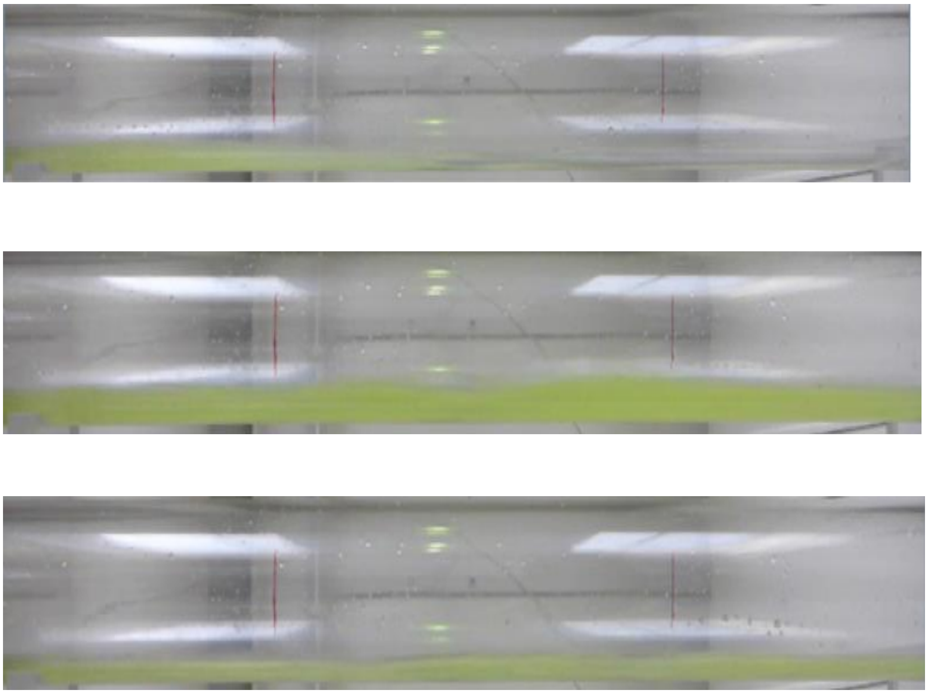


Figure2.28: surge wave development of Usg = 10.9m/s, Usl = 0.0113m/s. [3, p.43].

Through the holdup plot, obvious wave peak value can be found, the wave peak amplitude dropped rapidly between probe 1 and 3, after the probe 3, different cases have different performances, some cases increased a little, some cases slightly decreased or stopped falling. The reason for such changes may be that the part of the pipe where the probe 3 was located was not completely horizontal. The wave peak amplitude increased with the increase of Usl and decreased with the increase of Usg. Figure 2.29 shows the profile plots of the wave peak holdup from probe 1 to 6 for all the eight analyzed cases [3, p.45].

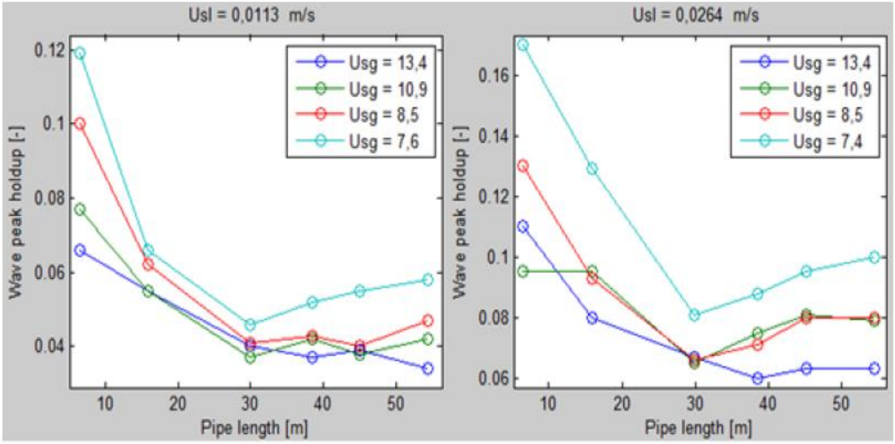


Figure2.29: The wave peak holdup for 8 analyzed cases. [3, p.45].

In the holdup trend plot, still for example of case 2, it can be seen that the wave shows a systematic change in the time of passing each probe, and the passing time gradually increased, that is, although the wave peak slowly decreased, the wavelength increases relatively. Therefore, the surge wave initiated in the experiments have the ability to propagate longer distances. Assuming that the pipeline is long enough, the surge wave needs to travel longer distances and experience more time to reach a steady state. This is similar to the characteristics of the surge wave observed in the field [3, p.44].

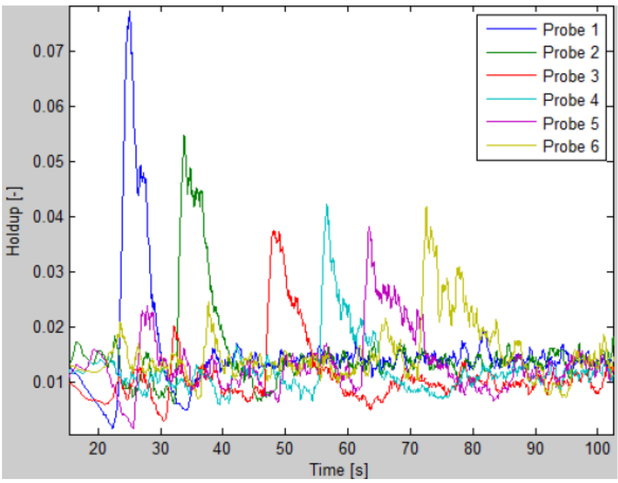


Figure2.30: the experiment results of holdup trend plot of case 2 [3, p.45].

When referring to wave velocity, the velocity clearly increases with increasing Usg and increasing Usl, and the wave velocity decreases slightly along the pipeline [3, p.46].

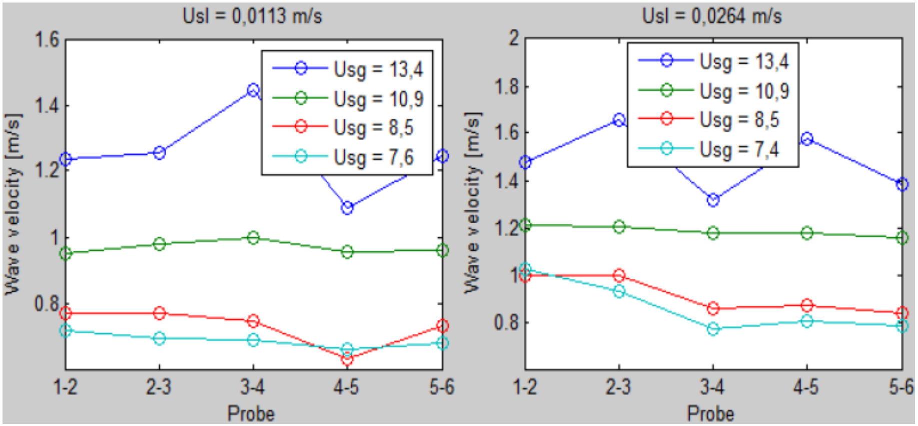


Figure2.31: The wave velocity plot for 8 analyzed cases. [3, p.45].

In the experiments performed by NTNU, three-phase fluids were not studied. One was due to the limitations of experimental equipment, and the other was because the oils available in the laboratory had a large viscosity and could not form a stratified flow.

In the next section, based on the settings in the experiments, the previous OLGA and Ledaflow simulations are compared with the simulations conducted by the latest version of software, and a study of the effects of water-cut on surge waves in 3-phase fluids will be attempted.

3. Numerical Simulation

3.1 Simulation programs

The numerical simulations of surge wave are the focus of this Master thesis. The latest versions of OLGA and LedaFlow would be applied. The simulations are mainly divided into three parts. The first is to reproduce the previous experiments in the simulation programs, adjust the options and parameters in the software. and the second is to simulate the surge waves in the long distance, large diameter, and complex terrain pipelines to observe the propagation of waves. The third is to use software simulations based on field data and evaluate the results. The simulations were mainly carried out in gas-liquid two-phase flow and would also try to research the influence of water content in the 3-phase flow on the wave propagation.

3.1.1. OLGA

OLGA is a modelling tool for transportation of oil, natural gas and water in the same pipeline, so-called multiphase transportation. The name is short for "oil and gas simulator"[14]. The earliest development of OLGA can be traced back to 1979, Dr. Bendiksen, who employed by the Institute for Energy Technology (IFE) wrote the code for the first version of OLGA. Since then, IFE and SINTEF have jointly developed this software [15]. OLGA has been commercially available since the SPT Group started marketing it in 1990 [16]. Now the technology is regarded as a central success for Norwegian petroleum research [12].

OLGA is a three-phase fluid simulation program, five mass equations are applied to gas, water and oil in the continuous phase, as well as bubbles and droplets. Three momentum equations are included, one for gas and droplets, one for continuous oil zone and one for continuous water zone. Slip relation exists in oil and water, or in the liquid droplets in the gas field. One energy equation is for the mixture, which means that all phases are at the same temperature, one equation is solved for pressure [17, p.26-27]. The equations used in the gas-liquid two-phase flow model are as follows [18, p.2-7].

Mass conservation equations:

gas phase:

$$\frac{\partial}{\partial t}\left(V_g \rho_g\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(AV_g \rho_g v_g\right) + \psi_g + G_g \tag{1}$$

the liquid at the wall:

$$\frac{\partial}{\partial t}\left(V_L \rho_L\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(AV_L \rho_L v_L\right) - \psi_g \frac{V_L}{V_L + V_D} - \psi_e + \psi_d + G_L \tag{2}$$

liquid droplets:

$$\frac{\partial}{\partial t}\left(V_D \rho_L\right) = -\frac{1}{A}\frac{\partial}{\partial z}\left(AV_D \rho_L v_D\right) - \psi_g \frac{V_D}{V_L + V_D} - \psi_e + \psi_d + G_D \tag{3}$$

Where:

- V_g,V_L,V_D = gas, liquid-film and liquid droplet volume fraction
- ρ = density
- v = velocity
- p = pressure
- A = pipe cross section area
- ψ_e, ψ_d = entrainment deposition rats
- G_f = possible mass source of phase f. f = g (gas), L (liquid), i (interface), D (droplets)

Momentum conservation equations:

Combined equation for gas and liquid droplets:

$$\frac{\partial}{\partial t}\left(V_g\rho_g v_g + V_D\rho_L v_D\right) = -(V_g + V_D)\left(\frac{\partial p}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}\left(AV_g\rho_g v_g^2 + AV_D\rho_D v_D^2\right)$$
$$-\lambda_g \frac{1}{2}\rho_g \left|v_g\right| v_g \frac{S_g}{4A} - \lambda_i \frac{1}{2}\rho_g \left|v_r\right| v_r \frac{S_i}{4A} + \left(V_g\rho_g + V_D\rho_L\right) g\cos\alpha$$
$$+\psi_g \frac{V_L}{V_L + V_D} v_a + \psi_e v_i - \psi_d v_D$$

(4)

For the liquid at the wall:

$$\frac{\partial}{\partial t}(V_L\rho_L v_L) = -V_L\left(\frac{\partial p}{\partial z}\right) - \frac{1}{A}\frac{\partial}{\partial z}\left(AV_L\rho_L v_L^2\right) - \lambda_L \frac{1}{2}\rho_L \left|v_L\right| v_L \frac{S_L}{4A}$$
$$+\lambda_i \frac{1}{2}\rho_g \left|v_r\right| v_r \frac{S_i}{4A} + V_L\rho_L g\cos\alpha - \psi_g \frac{V_L}{V_L + V_D} v_a - \psi_e v_i + \psi_d v_D$$
$$-V_L d(\rho_L - \rho_g) g \frac{\partial V_L}{\partial z}\sin\alpha$$

(5)

Where:

- A = pipe inclination angle
- S_g, S_L, S_i = wetted perimeters of the gas, liquid and interface
- G_f = internal source, assumed to enter at a 90-degree angle to the pipe wall and not carry net momentum

Mixture energy conservation equation:

$$\frac{\partial}{\partial t}\left[m_g\left(E_g + \frac{1}{2}v_g^2 + gh\right) + m_L\left(E_L + \frac{1}{2}v_L^2 + gh\right) + m_D\left(E_D + \frac{1}{2}v_D^2 + gh\right)\right] =$$
$$-\frac{\partial}{\partial z}\left[m_g v_g\left(H_g + \frac{1}{2}v_g^2 + gh\right) + m_L v_L\left(H_L + \frac{1}{2}v_L^2 + gh\right) + m_D v_D\left(H_D + \frac{1}{2}v_D^2 + gh\right)\right] + H_S + U$$

(6)

Where:

- E = internal energy per unit mass
- h = elevation
- H_S = enthalpy from mass sources
- U = heat transfer from pipe walls

Pressure equation:

$$\left[\frac{V_g}{\rho_g}\left(\frac{\partial \rho_g}{\partial p}\right)_{T,R_S}+\frac{1-V_g}{\rho_L}\left(\frac{\partial \rho_L}{\partial p}\right)_{T,R_S}\right]\frac{\partial p}{\partial t}=-\frac{1}{A\rho_g}\frac{\partial\left(AV_g\rho_g v_g\right)}{\partial z}$$
$$-\frac{1}{A\rho_L}\frac{\partial\left(AV_L\rho_L v_L\right)}{\partial z}-\frac{1}{A\rho_L}\frac{\partial\left(AV_D\rho_L v_D\right)}{\partial z}+\psi_g\left(\frac{1}{\rho_g}-\frac{1}{\rho_L}\right)$$
$$+G_g\frac{1}{\rho_g}+G_L\frac{1}{\rho_L}+G_D\frac{1}{\rho_L} \tag{7}$$

closure laws

In the OLGA, the closed rules are used to solve the equations in the gas-liquid stratified flow. The main considerations are wall friction, interphase friction, gas bubbles in liquid film, liquid/liquid dispersion and droplet entrainment/deposition [18, p.9].

3.1.2 LedaFlow

LedaFlow is a new transient multiphase flow simulator developed by SINTEF, ConocoPhillips, and TOTAL, which have with both one- and multi- dimensional (Q3D) modeling capabilities. The distribution of phases is shown in the figure below. g, o, w respectively represents gas, oil and water. d means dispersed phase, dwg means that water is dispersed in gas, c refers to the continuous phase. There are actually 9 phases in the 3-phase fluid.

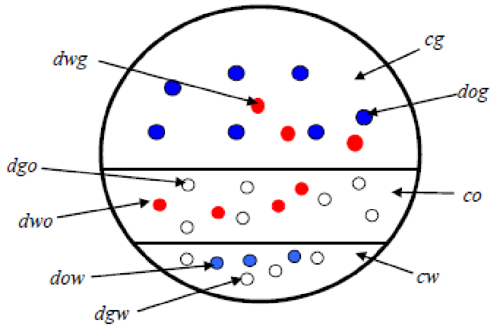


Figure3.1 Distribution of phase plot which used in LedaFlow [17, p.27]

The closed models in OLGA is based on an empirical model, whereas the 1D model in LedaFlow relies on a mechanistic model. Therefore, for each field (continuous, bubble and droplet) in the multiphase flow, a mass, momentum, and energy conservation equations are included [19, p.1]. The general formulation of the conservation equations applied in LedaFlow are seen in equations 8 – 10 below [3, p.53-54].

Mass conservation equationss:

$$\frac{\partial \alpha_k \rho_k}{\partial t} + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k) = \sum_{i \neq k} \Gamma_{ki} + \Gamma_{kext} \tag{8}$$

Momentum conservation equations:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k u_k) + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k u_k) = -\frac{\partial \alpha_k P_k}{\partial x} - \alpha_k \rho_k g \sin\theta + \frac{\partial \alpha_k \tau_k}{\partial x}$$
$$+ P_{\text{int}} \frac{\partial \alpha_k}{\partial x} + \sum_{i \neq k} F_{ki} - F_{kw} + \sum_{i \neq k} \Gamma_{ki} u_{ki} + \Gamma_{kext} u_{kext} \tag{9}$$

Energy conservation equations:

$$\frac{\partial}{\partial t}(\alpha_k \rho_k h_k) + \frac{\partial}{\partial x}(\alpha_k \rho_k u_k h_k) = \frac{\partial}{\partial x}(\alpha_k \kappa_k \frac{\partial}{\partial x} T) + \alpha_k \frac{DP}{Dt} + Q_{kw} + \sum_{i \neq k} Q_{ki} + \Gamma_{kext} h_{kext} \tag{10}$$

Where:

- k = field index
- u = average field velocity
- t = time
- x = coordinate along the pipe
- α = field volume fraction
- ρ = field density
- Γ_{kext} = net external mass source (system mass extraction and injection)
- Γ_{ki} = net mass flow rate obtained by field k from field i
- τ_k = shear stress of field k in axial direction
- P_k = field pressure
- P_{int} = pressure at large scale interface (only for stratified flow)
- g = gravity
- θ = pipe inclination angle
- F_{ki} = interfacial friction between field k and other fields
- F_{kw} = wall friction
- u_{kext} = velocity of external mass source
- h_k = enthalpy of field k
- κ_k = effective thermal conductivity of field k
- T_k = temperature of field k
- P = system pressure (average pressure $P = \sum \alpha_k P_k$)
- Q_{ki} = interfacial heat transfer rate of field k with other fields
- Q_{kw} = heat transfer rate of field k at pipe wall
- h_{kext} = enthalpy of external mass source

3.2 Reproduce and compare previous simulation

In the previous studies on surge waves, Steinar Ingebrigtsen Grødahl has completed some experiments to generate the surge waves and observe the propagation processing in the laboratory, and he also used OLGA7.1 and LedaFlow1.4.242.69 to simulate the experimental settings. In his simulation results, OLGA7.1 responded well to the experimental results, but LedaFlow 1.4.242.69 performed much poorer.

In this part, it used the latest version programs, the OLGA2016.2.1 and LedaFlow2.3.254.029, to reproduce the surge wave experiments and compared results with the experimental results and previous simulation results. The goal was to better observe the surge wave by the means of numerical simulation.

3.2.1 OLGA simulation

The simulations have been performed in OLGA 2016.2.1. All parameter settings remained exactly the same as previous experiments.

3.2.1.1 Simulation setup and boundary conditions

A basic OLGA case was used, and the pipeline geometry was set up with the dimensions shown in Table3.1. And the flow path plot seen in Figure3.2. Two mass sources, one for air and one for water, were set on the first section on pipe one. [3, p.56].

Table3.1: The pipeline geometry settings in OLGA [3, p.56]

Pipe	x[m]	y [m]	Length [m]	Elevation [m]	Diameter [m]
Start Point	0	0			
Pipe-1	0,9992	-0,04	1	-0,04	0,06

Pipe-2	1,4992	-0,04	0,5	0	0,06
Pipe-3	6,09788	0,07	4,6	0,11	0,06
Pipe-4	57,8379	0,07	51,74	0	0,06

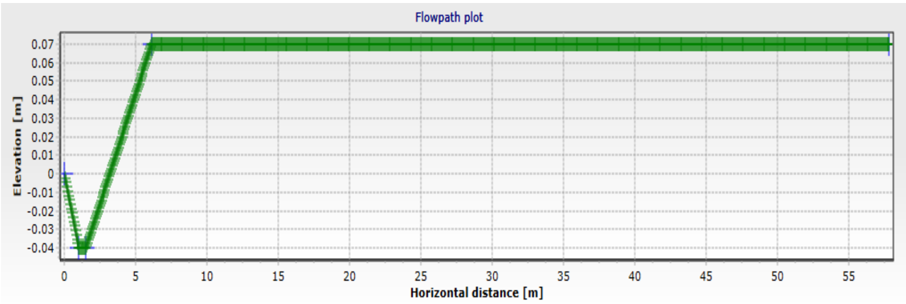


Figure3.2: Flow path plot of pipeline

The following assumptions and boundary conditions were applied: [3, p.57].

•No heat transfer, adiabatic, all temperatures set to 20° C

•Outlet node pressure boundary set to 1 atm

•A straight pipeline without any turns was assumed

•Pipeline roughness 0.05 mm

•The air-water PVT-file obtained from Zhilin Yang was applied [19]

•Max dt = 1 s, Min dt = 0,00001 s

•Slugvoid: Sintef,

•Mass equation scheme: 1 st. order

•Flowmodel: OLGA

According to the previous experimental results, the simulation directly used mesh=1D and restart setting. The purpose was to observe a clearer holdup fluctuation and maintain the steady-state holdup keep consistent between before wave and after wave. the flow rates for water and gas showed in Table 3.2, using the case 2 as an example, which means the Usg = 10.9m/s, and the Usl = 0.0113m/s. [3, p.57].

Table3.2: Flowrate settings in the OLGA simulation [3, p.57].

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.037	0.032
10	0.037	0.032
11	0.013	0.032
22	0.013	0.032
23	0.037	0.032
Integration		130 (s)

3.2.1.2 Results and Comparations

First of all, no matter in which version, the same settings have created the same flow regime. The flow regime in the horizontal pipeline kept the stratified flow.

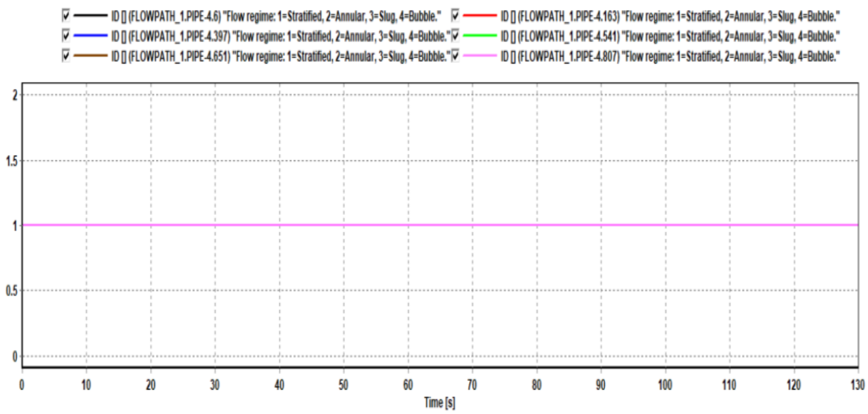


Figure3.3: Flow regime ID plot in horizontal pipeline by the OLGA2016.2.1

The results of holdup trend by OLGA2016.2.1 can be seen in Figure3.4

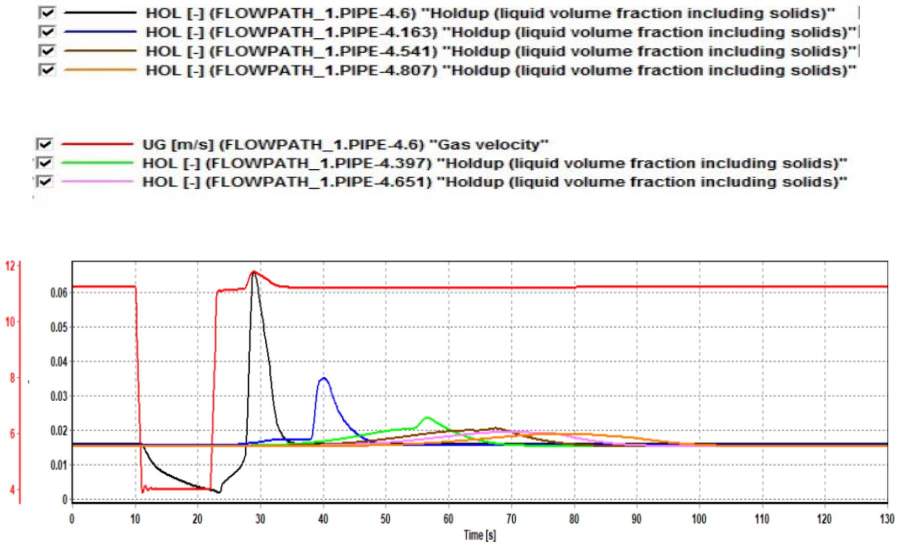


Figure3.4: Holdup trend plot in horizontal pipeline, when Usg = 10.9 m/s, Usl = 0.0113m/s.

OLGA2016.2.1 can simulate surge waves, but it is easy to find that, the apparent holdup fluctuations occurred near the entrance of the horizontal pipeline, the flowing of the surge wave was clearly observable before the 16 meters. After this distance, the attenuation of the surge wave was intense. At the last three observation points, the maximum value of holdup does not exceed 0.02. Obviously, compared with the experimental data and the previous OLGA simulation results in OLGA7.1, this simulation has differences on development of holdup, and Figure3.5 to Figure3.6 show the previous results.

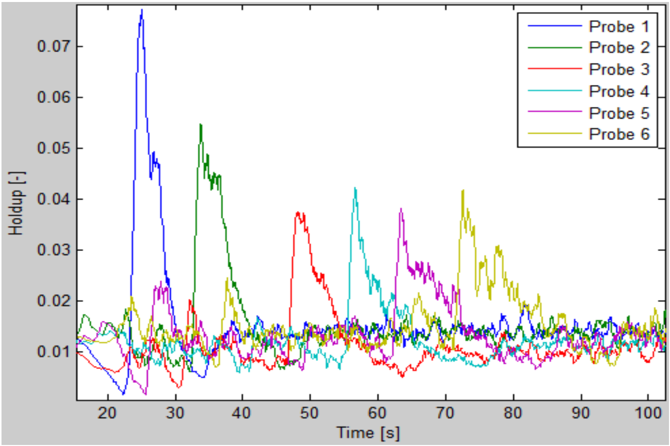


Figure3.5: Holdup trend plot of the surge wave propagation from probe 1 to probe 6 (experimental results) [3, p.84]

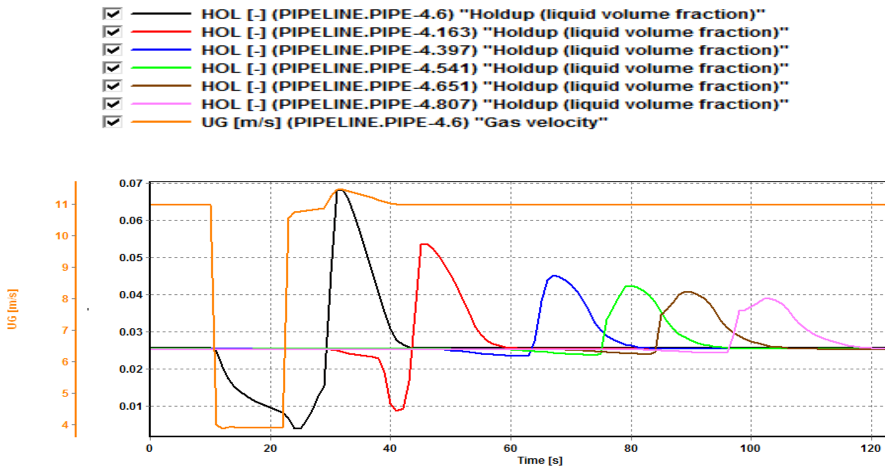


Figure3.6: OLGA7.1 simulation holdup trend plot of the wave. The gas velocity is plotted to visualize how the wave was initialized. [3, p.85]

The significant difference in simulation results was likely to be caused by a change in the physical computing model or calculation method after the upgrade of the system software itself. In order to obtain a more comprehensive analysis, the OLGA HD model of OLGA 2016 and the OLGA model of OLGA 7.3.5 were next introduced to simulate the same experimental conditions. Different colorful lines represent different probes.

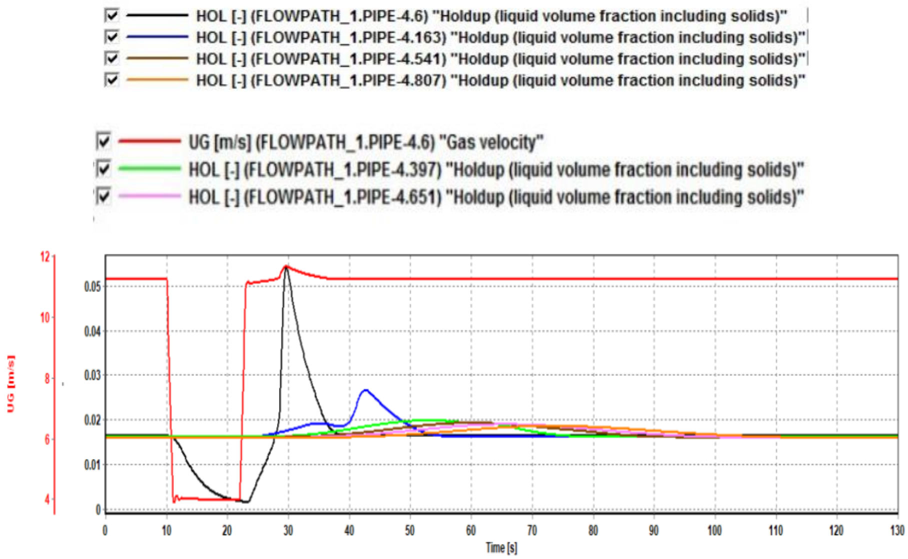


Figure3.7: OLGA HD model of OLGA 2016.2.1simulation holdup trend plot of the wave. The gas velocity is plotted to visualize how the wave was initialized.

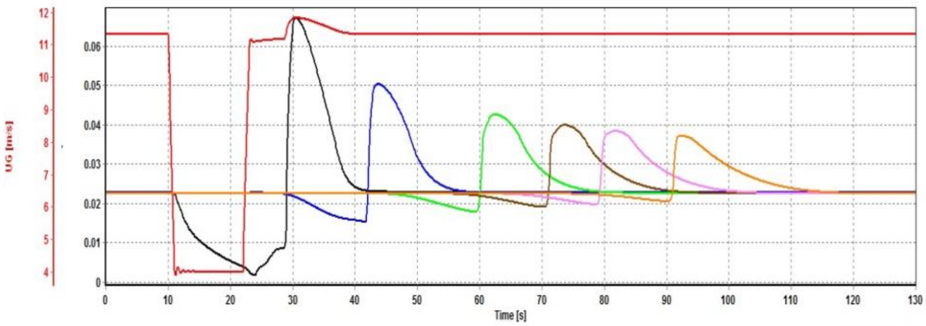


Figure3.8: OLGA model of OLGA 7.3.5 simulation holdup trend plot of the wave. The gas velocity is plotted to visualize how the wave was initialized.

Through the comparison among different versions of the OLGA programs, the conclusion is that both OLGA7.1 and OLGA7.3.5 can respond to the same holdup trend plot as the experimental results under the parameter settings, which means they showed surge wave propagations in the horizontal pipeline well.

However, OLGA2016.2.1 did not perform well in this simulation. Whether it was OLGA Flow model or OLGA HD Flow Model, there was only one or two obvious holdup changes just after entering the horizontal pipeline, the drop of holdup value from the first observation point to the second observation point was dramatic and the simulation result of HD Flow model was even worse.

The following comparison plots of the holdup peak value and probe wave velocities clearly showed the difference among each OLGA version and the experimental results. The Usg=10.9m/s corresponds to the air flow in Table 3.2 is 0.037kg/s, Usl=0.0113m/s corresponds to the flow of water is 0.032kg/s. It is not difficult to find that OLGA7.3.5 was the best match with the actual experimental data in the holdup peak value chart. In the wave velocity comparison chart, the all numerical simulation velocities were less than the actual velocity, but the tendencies were the same. The wave speed between probes in the experiment was kept at about 1m/s. The gap between the results of OLGA2016 and experimental data was the smallest, and the variation of the wave velocity was between 0.6m/s and 0.76m/s.

However, OLGA 2016 is the latest version which NTNU can provide to make numerical simulations for this paper's research. So, although using it to reproduce the previous experiment, the results were not optimal, it was still chosen to run the following simulations.

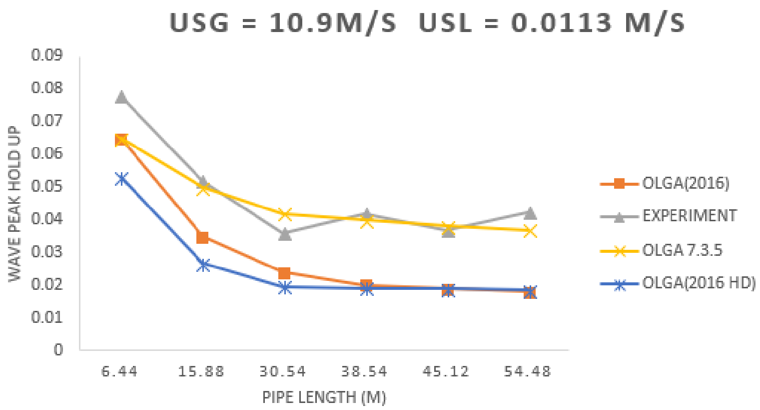


Figure3.9: The wave peak holdup comparation chart among OLGA programs and experiments

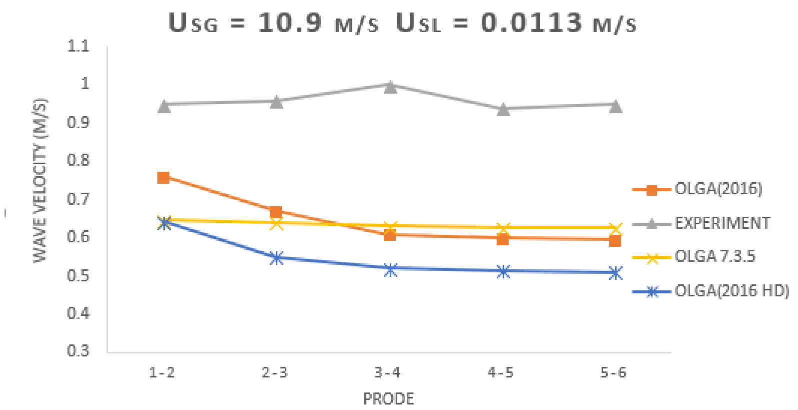


Figure3.10: The wave velocities comparation chart among OLGA programs and experiments

3.2.1.3 Mesh size Effect

As we known, mesh is important for numerical simulation. An appropriate mesh can help reduce the numerical diffusion in OLGA. A too fine mesh can potentially result in instabilities or cause the simulation to crash [3, p.57].

For this comparison, the gas and liquid flow rates in Table3.2 were still used. Figure3.11 below shows the plot of a wave at probe 1, 3 and 6 with Δx = 0,5D at the top, Δx = 1D in the middle and Δx = 10D at the bottom.

When the set mesh is larger, the numerical diffusion is greater obviously. From Δx = 0.5D to Δx = 1D, the change in peak amplitude was insignificant, but the holdup curve of Δx = 0.5D was steeper. When Δx = 10D, the peak of holdup in probe1 was only half of Δx = 0.5D. Obviously, in OLGA, this mesh setting was not suitable for experimental simulation.

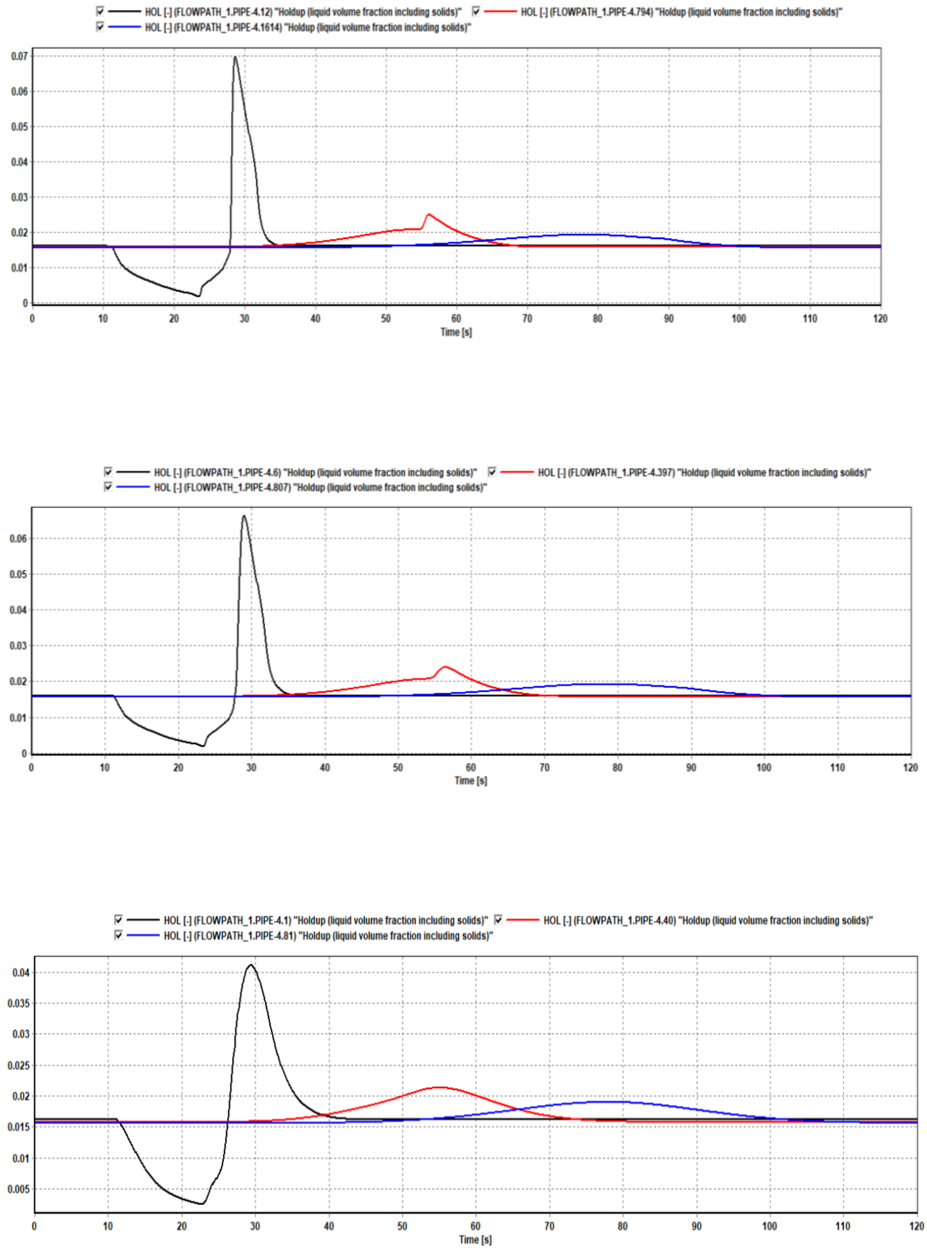
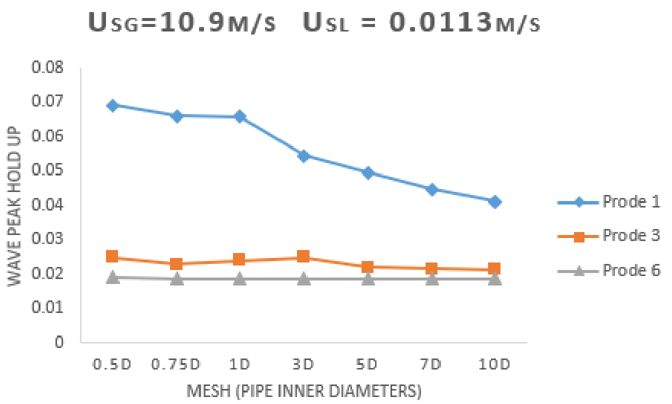


Figure3.11: The influence of different meshes on a wave. Δx = 0,5 pipe inner diameters in the plot at the top, Δx = 1 in the middle and Δx = 10 at the lowest plot.

In Figure3.12, the effects of the mesh size on the wave peak holdup and wave velocity were shown. In fact, the biggest impact was on probe1, and the changes in probe 3 and probe 6 are minor. This means that as the horizontal distance increases, the effect of numerical diffusion becomes less and less.

When Δx<1D, the holdup peak value and wave velocity are maintained at a stable value even in probe1. However, when Δx>1D, a significant drop occurred in probe1. This change trend can be seen both for holdup peak value and wave velocity charts.

In fact, the smaller the mesh size was, the smaller the numerical diffusion in OLGA would be. However, there were still time costs to be considered, when Δx=0.5D, the same case took 1 hour to complete. Therefore, mesh=1D was indeed the most suitable choice, either in OLGA7.1 or in OLGA 2016.2.1.



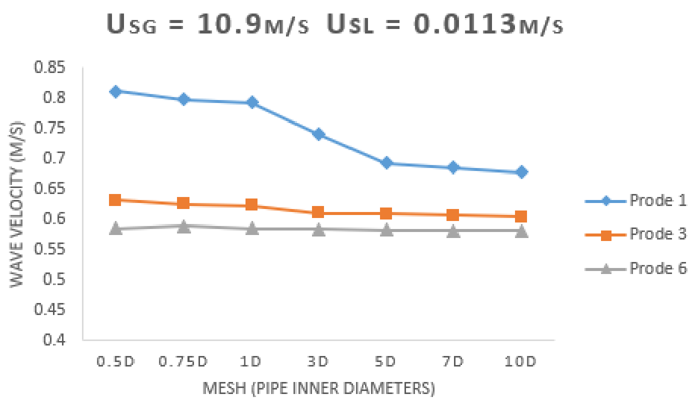


Figure3.12: Wave peak holdup and velocity at different mesh size, delta x = 0,5D – 10D

3.2.1.4 OLGA mass equation discretization effect

In OLGA's calculation options, there are first-order and second-order choices regarding the discretization scale of the mass equation. If a second-order calculation model was chosen, under the same case and Δx=1D setting, in the following figure, it can see that the second-order mass equation discretization creates a slight sharper front and slightly higher wave peak holdup than first order discretization [3, p.60]. And after the peak of the wave, the holdup changes more steeply, using the first-order, the tendency line is a smooth curve, while for the second-order, it was a similar straight line with a large slope.

Although the second-order calculation model can reduce the numerical diffusion to a certain extent, the peak of the wave in Δx=1D can even approximate the peak of Δx=0.5D in the first-order, the first-order is more robust, and it is the recommended default setting by OLGA to be used for most situations. [3, p.61]

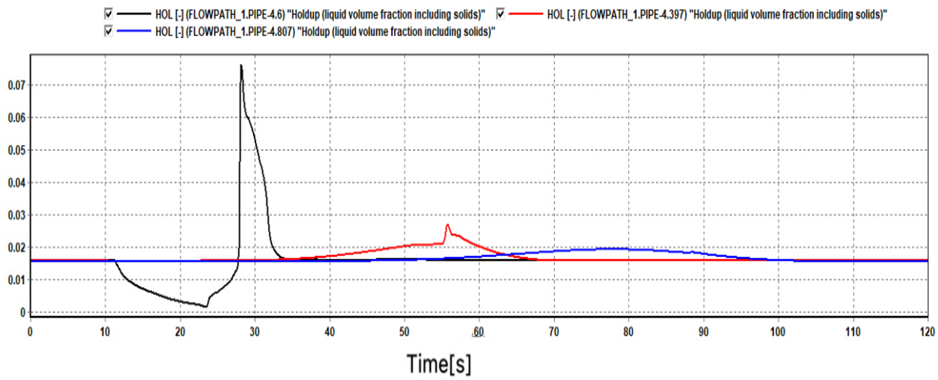


Figure 3.13: Second order mass equation discretization applied on the wave shown when Δx = 1D.

3.2.1.5 OLGA tuning setting on interfacial friction

The TUNING in OLGA makes it possible to tune the fluid properties, friction, phase mass transfer and entrainment of liquid droplets into the gas phase. It can be used for adjusting the OLGA model to specific sets of measured data or for sensitivity studies [16].

In this part, it focused on tuning coefficient for interfacial friction between liquid and gas. It studied the effect of the phase friction force of gas-liquid on holdup values, the same flow setting, geometric configuration and boundary conditions, and mesh=1D have be used. Figures showed that the holdup of the probe1,3,6 changes over time.

The change in the tuning coefficient for interfacial friction between liquid and gas is from 0.4 to 5. The smaller the value of the tuning coefficient, the smaller the friction between the two phases, and vice versa.

From the figures below, they can be found that whether increasing or decreasing the value of the tuning coefficient, the effect on holdup was negative. However, as the tuning coefficient increased, the time for the holdup to fluctuate became earlier.

When the coefficient of friction between the phases was equal to 0.4, the effect of the gas flow choking and ramping up again on the flow of the liquid decreased, so that the value of holdup decreased. The reason for this may be that although the friction force was reduced, the increase in gas flow rate again cannot drive enough liquid to achieve the large variation of holdup. Compared to the default value of tuning which is equal to 1, the magnitude of the decrease is not big. The whole curve became smoother, that is, the holdup fluctuation took longer duration.

When the coefficient of phase friction has increased to 10, this effect was significant for the peak of the wave. When using the same case for simulation, the holdup peak at probe1 has dropped to 0.035, indicating the frictional effect of the holdup fluctuation was negative. The time range of fluctuations was also more concentrated. It is not difficult to find from the plot that the curve became relatively narrow.

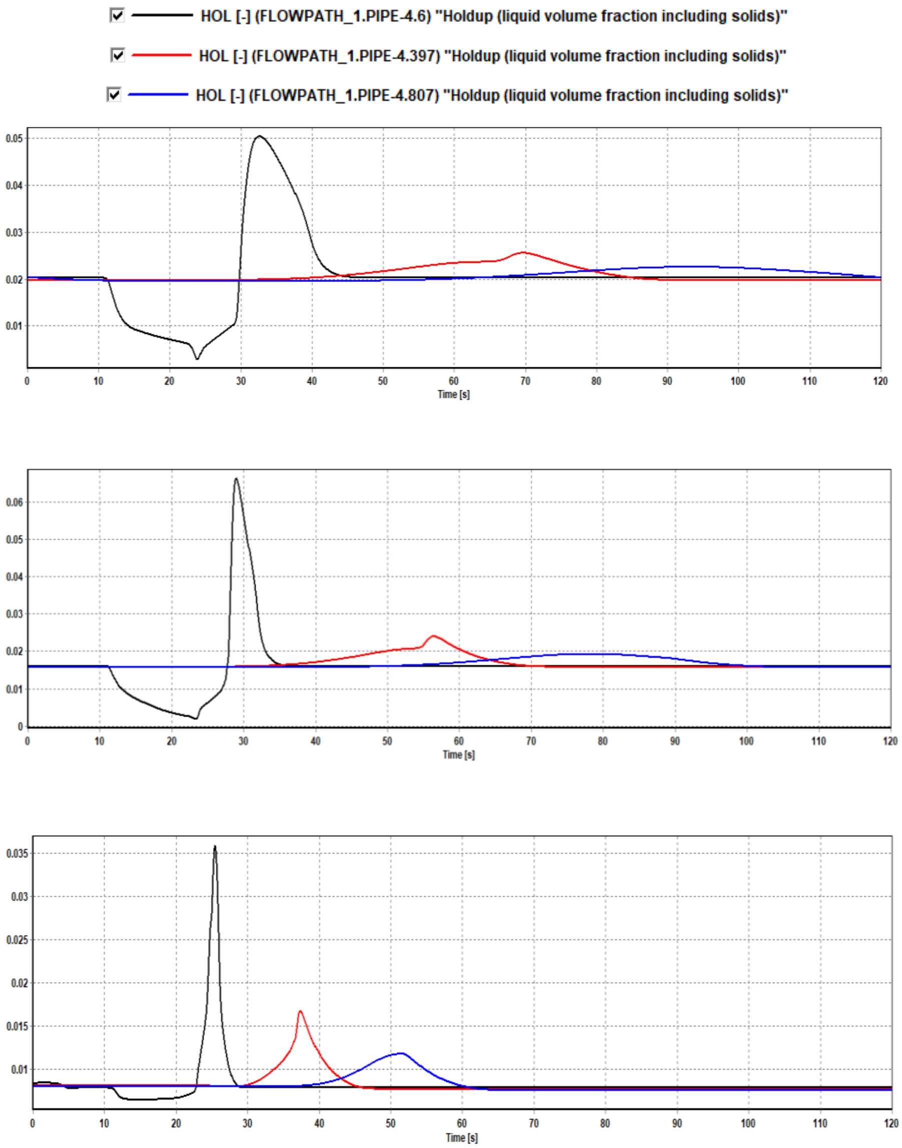


Figure 3.14: The influence of different interfacial friction on a wave. Tuning value = 0,4 at the top, Tuning value = 1 in the middle and Tuning value = 10 at the lowest plot.

3.2.2 LedaFlow simulation

The LedaFlow simulations have been performed in the version 2.3.254.029. All parameter settings remained exactly the same as previous experiments.

3.2.2.1 Simulation setup and boundary conditions

The lab pipeline geometry was set up, see Table3.3 below. Two mass sources, one for air and one for water, were placed in section one.

Table3.3: The LedaFlow setup geometry [3, p.61]

x [m]	y [m]	z [m]	Diameter [mm]	T_{out} [K]
0,00	0	0	60	293
1,00	0	-0,04	60	293
1,50	0	-0,04	60	293
6,10	0	0,11	60	293
57,84	0	0,11	60	293

The following assumptions and boundary conditions were applied [3, p.62]:

•A three-phase case is selected but all parameters of the oil are set to zero.

•The air-water PVT-file obtained from Zhilin Yang [19] was applied.

•Pipeline roughness was equal to 0.05 mm.

• No temperature calculations were applied, for the simulation, temperature kept 293K

•The outlet pressure was set to 1 atm at the outlet node.

•The CFL time step was set to 0,1.

•Max dt = 1 sec.

The gas and liquid flow rate settings were the same as in Table4.2. According to the previous simulation, Δx =10D was used as the mesh scale. Fortunately, in the new version, there is no increase or decrease in the steady-state value of holdup before and after the wave fluctuation, Therefore, in this version, for the simulation of LedaFlow, it was not necessary to consider the setting of restart.

3.2.2.2 Results and Comparations

About the flow regimes, in the case of Usg =10.9m/s, Usl = 0.0113m/s, the results of the LedaFlow simulation were consistent with the experimental and OLGA results. Flow regime indices in LedaFlow are that 1 stands for stratified wavy flow,2 means annular flow and 3 is the slug flow [20].

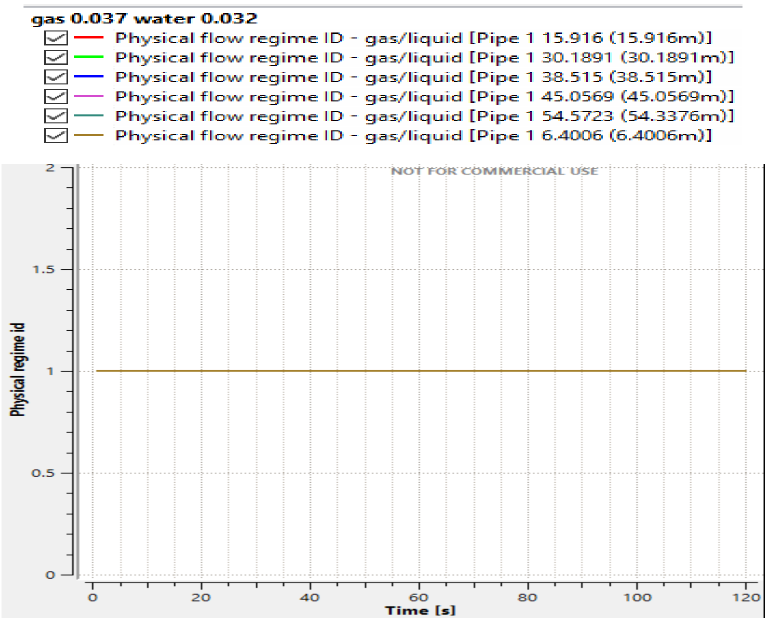


Figure3.15: Flow regime ID plot in horizontal pipeline by the Ledaflow2.3.254.029

In the holdup plots, the new version of LedaFlow (Figure 3.17) responds better under such conditions. There was no obvious difference comparing with the experimental data (seen in Figure3.5) and previous simulations (seen in Figure 3.16below).

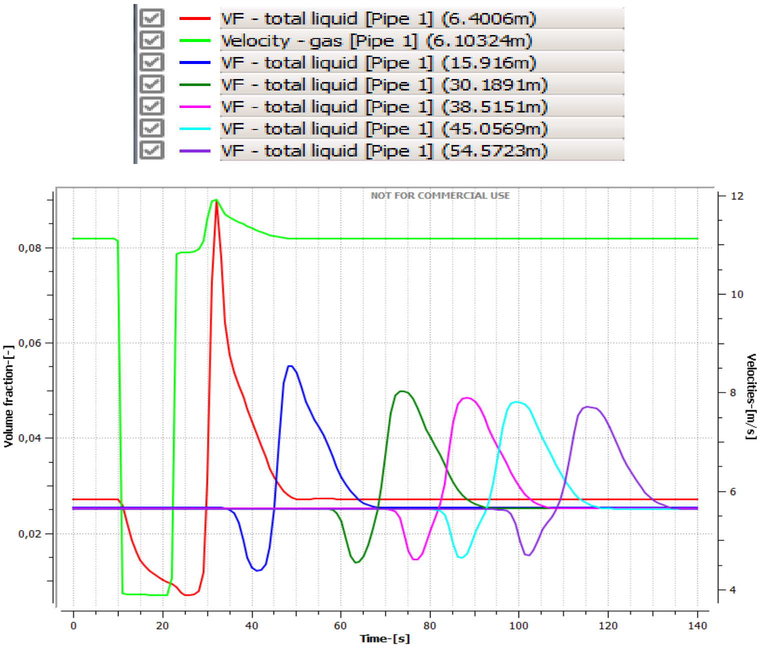
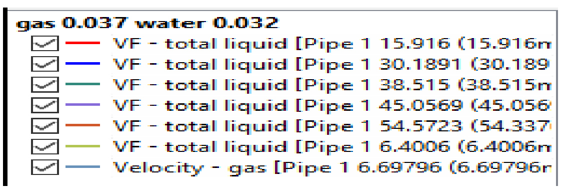


Figure 3.16: LedaFlow simulation holdup trend plot of the wave. The gas velocity is plotted to visualize how the wave was initialized. (LedaFlow v1.4.242.619). [3, p.86]



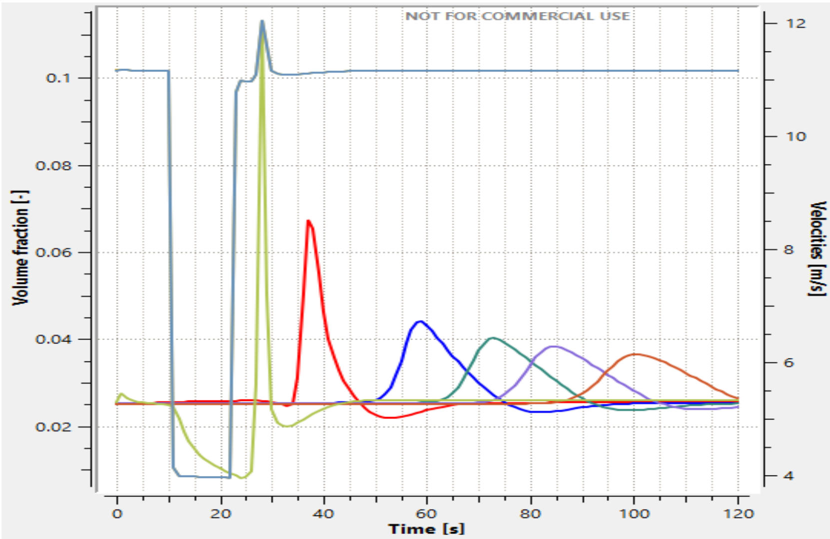
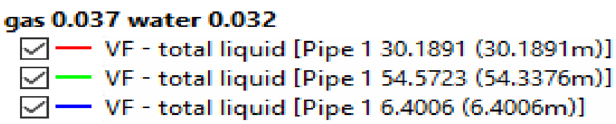


Figure3.17: LedaFlow simulation holdup trend plot of the wave. The gas velocity is plotted to visualize how the wave was initialized. (LedaFlow v2.3.254.029)

3.2.2.3 Mesh size effect

It can be learned from previous research that in Ledaflow, compared with OLGA, the coarser mesh was needed to complete the calculation in the simulation. From Figure3.18, when $\Delta x = 5D$, unstable status still appeared in the results. When Δx was 10D or14D, the simulation results were close to the experimental results, but when Δx was approaching 14D, the holdup of probe3 decreased obviously comparing the that of Δx =10D. This is why 10D was used to complete the simulation.

When Δx =30D, the change of holdup in probe1 was drastic, which also proved that the initiation of the wave was more mesh dependent than the wave propagation further down the pipeline [3, p.62].



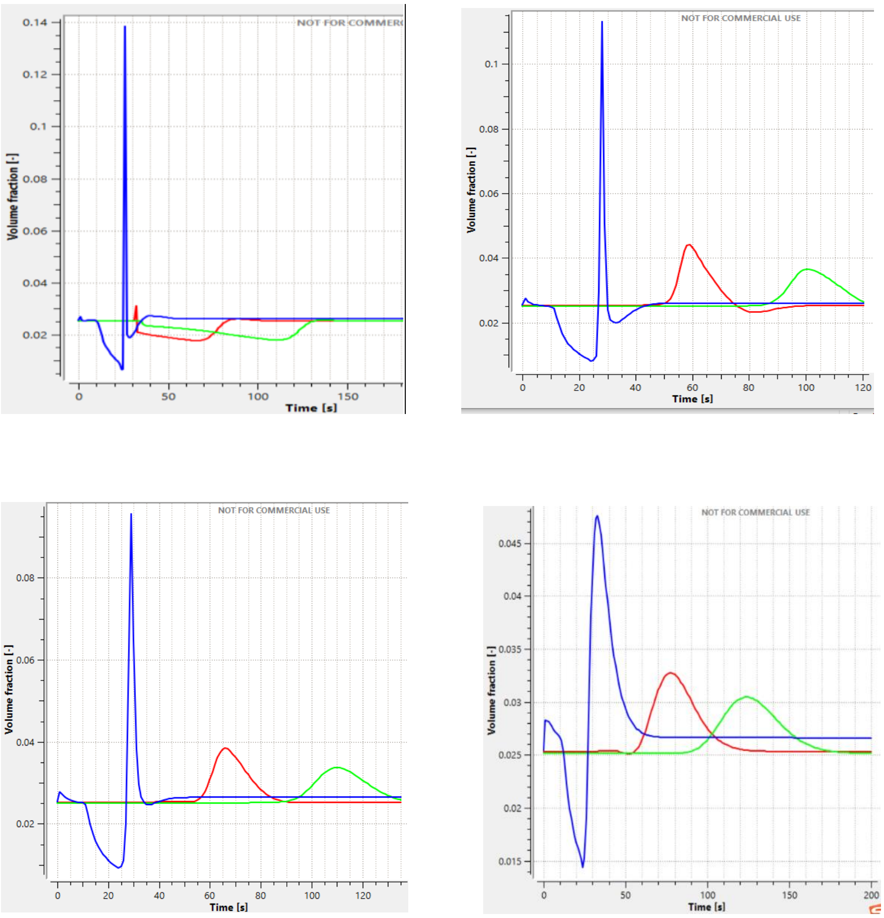
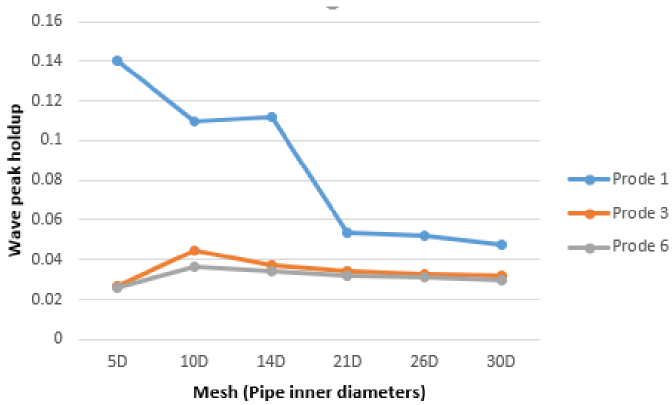


Figure3.18: the Δx = 5D in the top left plot and 10D in the top right plot. Δx = 14D is the bottom left one, the bottom right plot belongs to 30D.

The change of the wave velocities was also mainly reflected in probe1. From 5D to 21D, the wave velocity showed a straight decline, and then it stayed stable at around 0,45 m/s. The specific difference can be shown by the following figures.



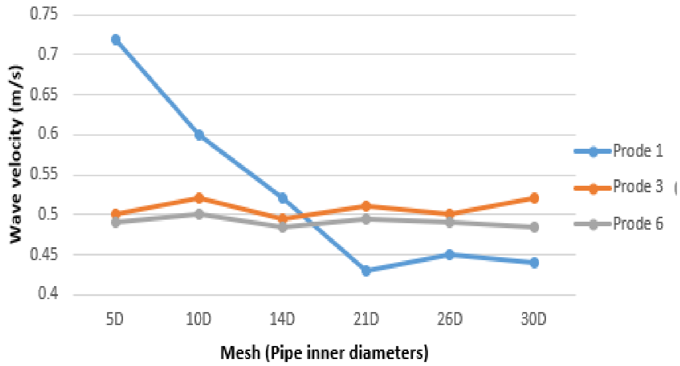


Figure3.19: The mesh effect on peak value and velocity in LedaFlow v.2.3.254.029

3.2.2.4 High order discretization

In LedaFlow, simulation can be performed in high-order discretization. If higher order methods are used, numerical diffusion will be minimized at the expense of simulation speed and robustness [20]. The LedaFlow results are therefore presented with higher order discretization in time and space and slug capturing activated.

The following figure shows the simulated results of high-order calculation when Δx =10D. Obviously, this result did not respond well to the experimental data, which means that the simulation of surge waves using the high-order options under this condition was not applicable.

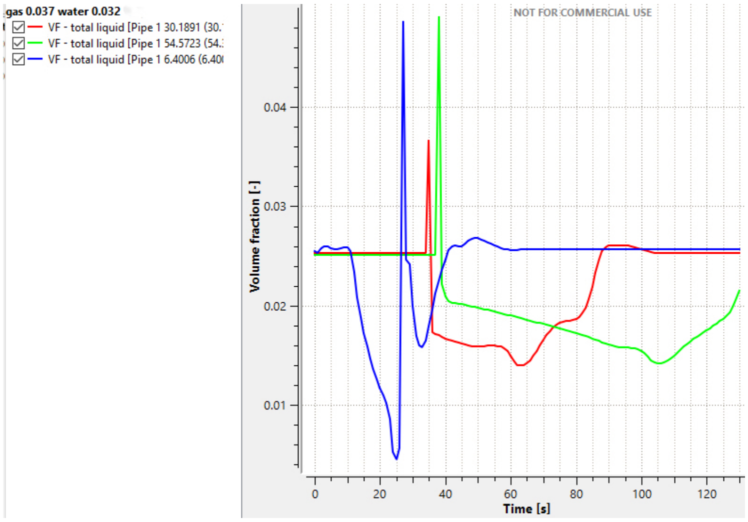


Figure3.20: Higher order discretization holdup trend plot. Δx = 10D

3.2.3 Software comparation

The simulated results of the experimental data in all new versions program (8 different cases) would be shown in the Appendix. From the follow figures, it can be clearly seen that for OLGA 2016.2.1, when the gas flow rate is 0.029 kg/s and the water flow rate is 0.032 kg/s, in addition to the wave peak of probe1 and 2, the simulation results were in the best agreement with the experimental data among all cases.

OLGA 2016.2.1

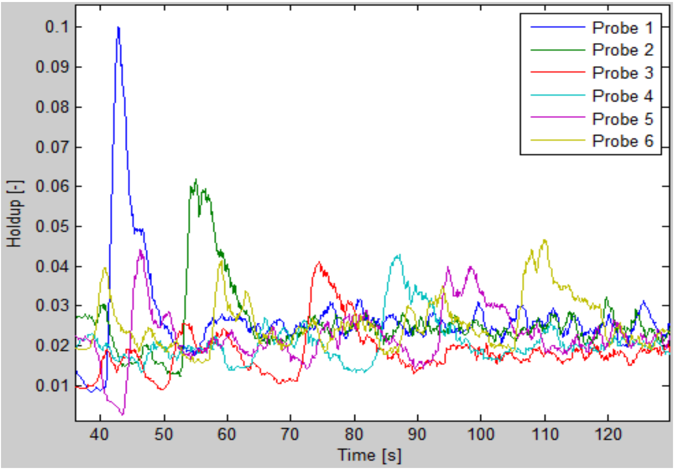


Figure3.21: Holdup trend plot of the surge wave propagation from probe 1 to probe 6, case of gas flowrate is 0.029kg/s, water flowrate was 0.032kg/s. [3, p.89]

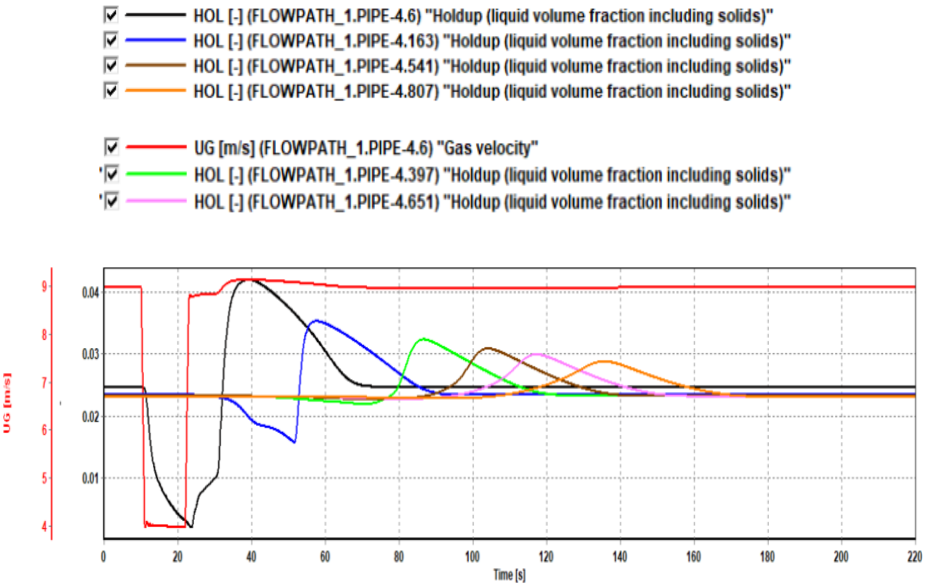


Figure3.22: OLGA simulation holdup trend plot of the wave, case of gas flowrate is 0.029kg/s, water flowrate was 0.032kg/s.

In the condition that the flow rate of water was 0.075 kg/s, all holdup fluctuation plots were not ideal. When the gas flow rate was large (0.045kg/s or 0.037kg/s), twice changes in holdup fluctuations occurred at probe1, which was an unstable state. The reason is that the larger the gas flow rate choking and ramping up again, the easier it was to cause the holdup to oscillate.

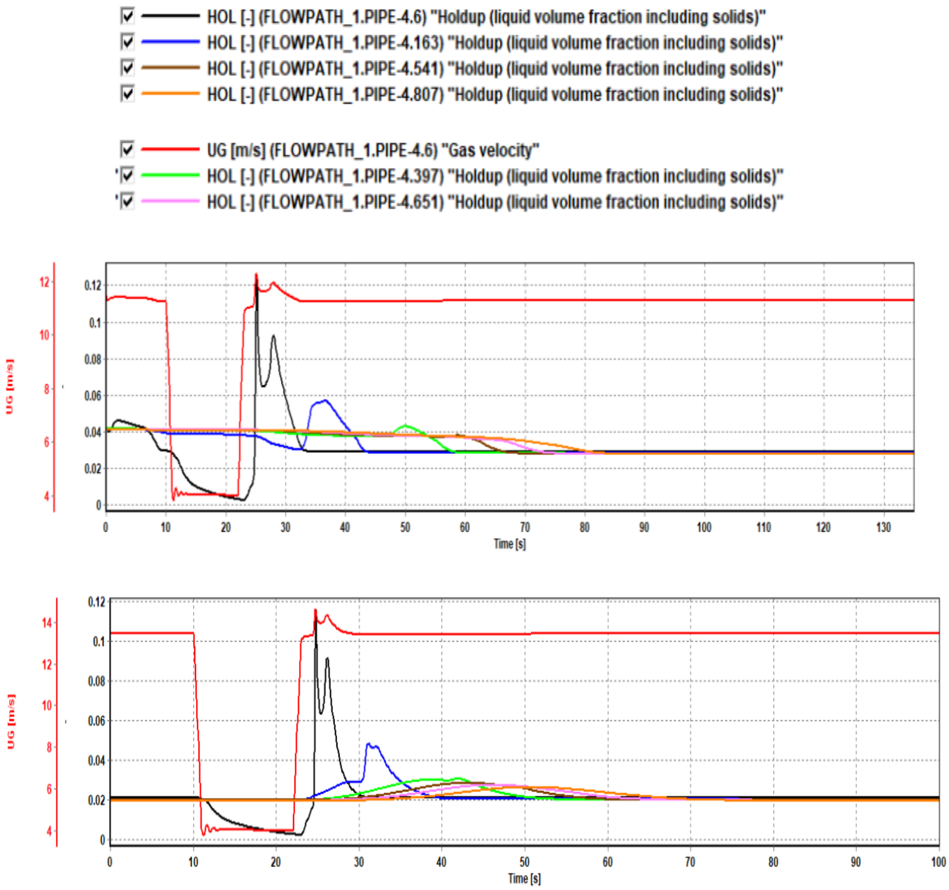


Figure3.23: OLGA simulation holdup trend plot of the wave. The gas velocity is plotted to visualize how the wave was initialized. The first one is the gas flow rate is 0.037kg/s, the second is the 0.045kg/s. both water flow rate is 0.075kg/s

When the gas flow rate stetted less than 0.03 kg/s, through the flow regime plots, the slug flow occurred when the gas flow rate choked. For 0.029kg/s. slug flow lasted short, the calculation model was from slug flow to stratified flow model only 1 second, so in the holdup plot, at the front of the horizontal pipeline, the positions of probe1 and probe2 appeared irregular fluctuations, but in the following pipe sections, the surge wave still had a good spread, although the magnitude of the fluctuation is not obvious.

When the gas flow rate is 0.025 kg/s, the slug flow took longer and appeared twice. Therefore, in the holdup plot, the propagation of the surge wave was quite inconspicuous.

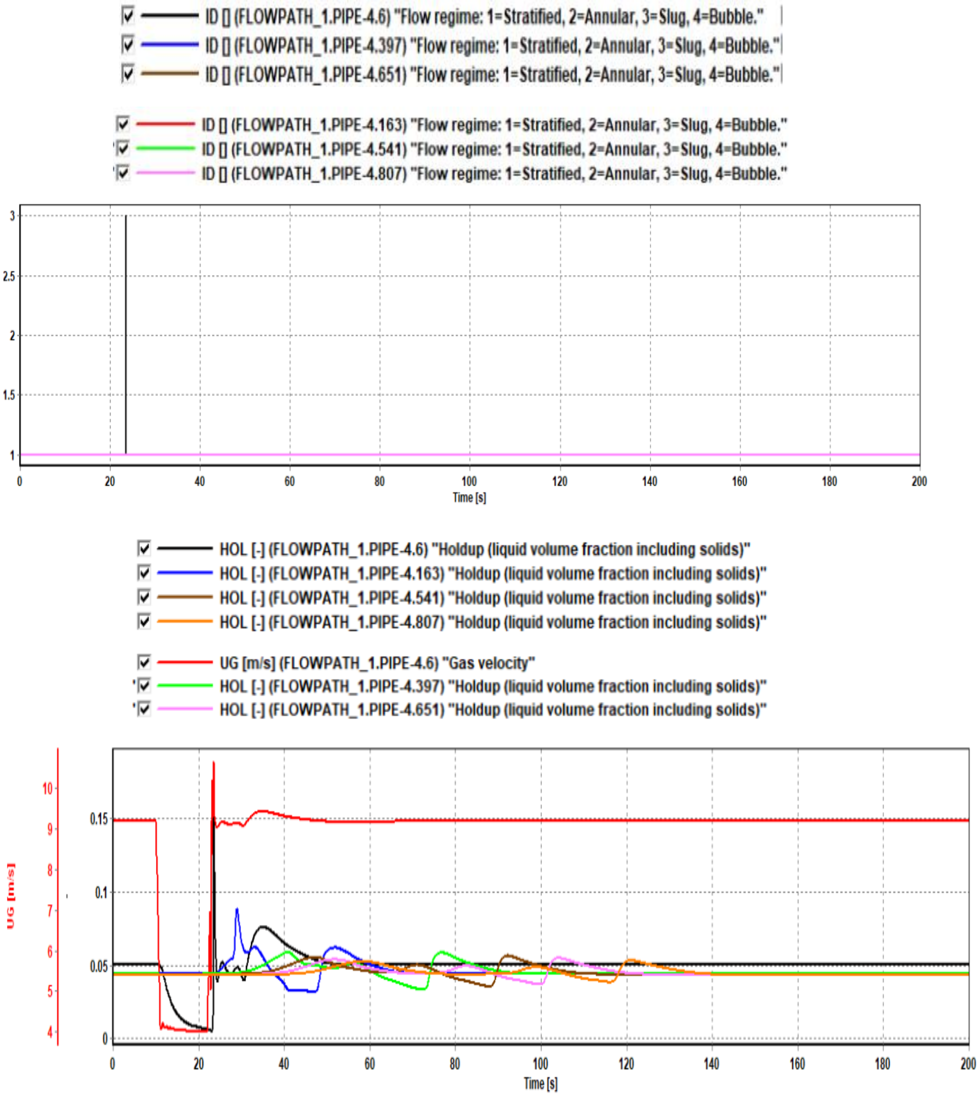


Figure3.24: OLGA simulation in flow regime ID plot and holdup trend plot when gas flowrate is 0.029 kg/s and water flowrate is 0.075kg/s.

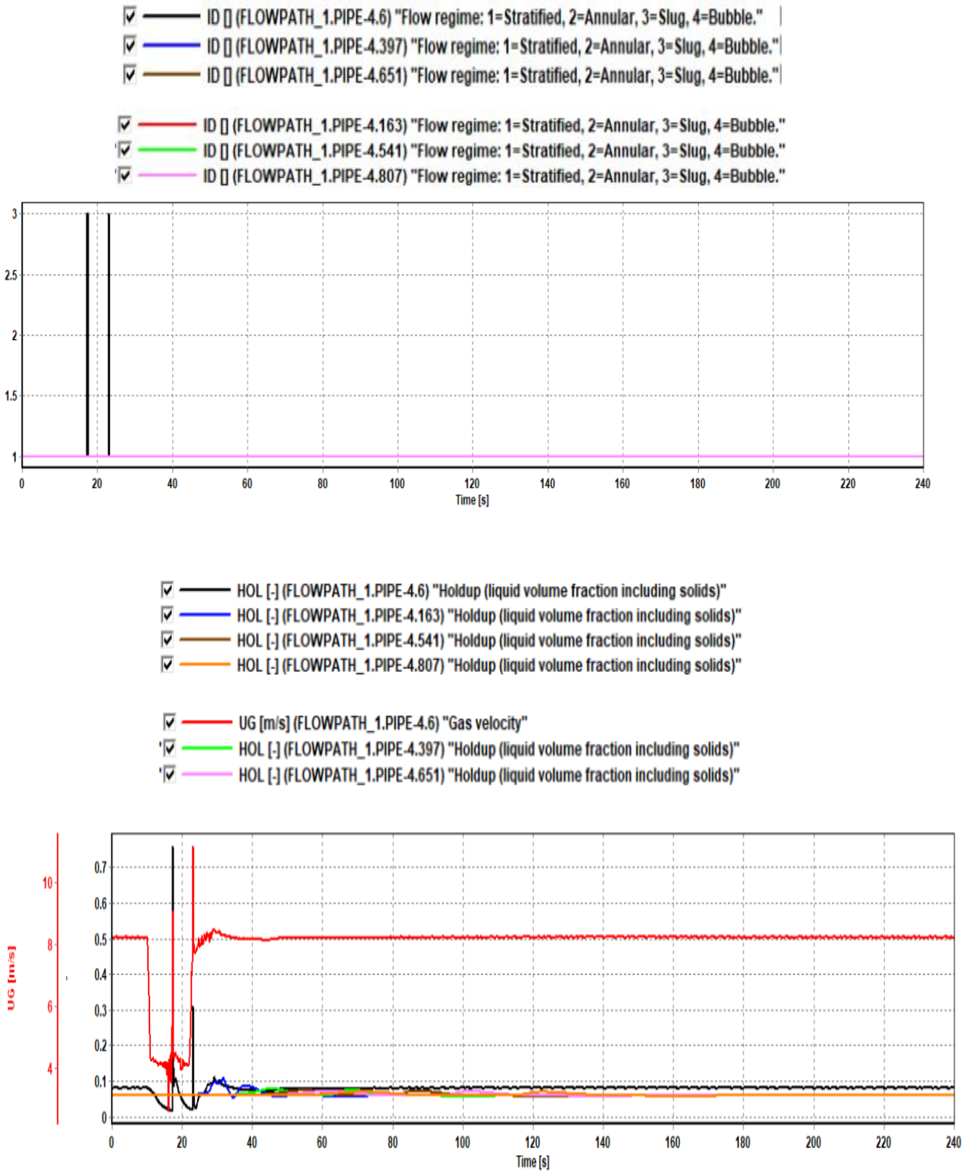


Figure3.25: The new OLGA simulation in flow regime ID plot and holdup trend plot when gas flowrate is 0.025 kg/s and water flowrate is 0.075kg/s.

LedaFlow v2.3.254.029

From previous studies, we can know that compared with OLGA, LedaFlow could not achieve good results in the simulation of experimental cases. In fact, even if the software version has been upgraded, LedaFlow can only obtain better simulation results for the two cases, namely the flow rate of water is 0.032kg/s, the flow rate of gas is 0.037kg/s and 0.045kg/s.

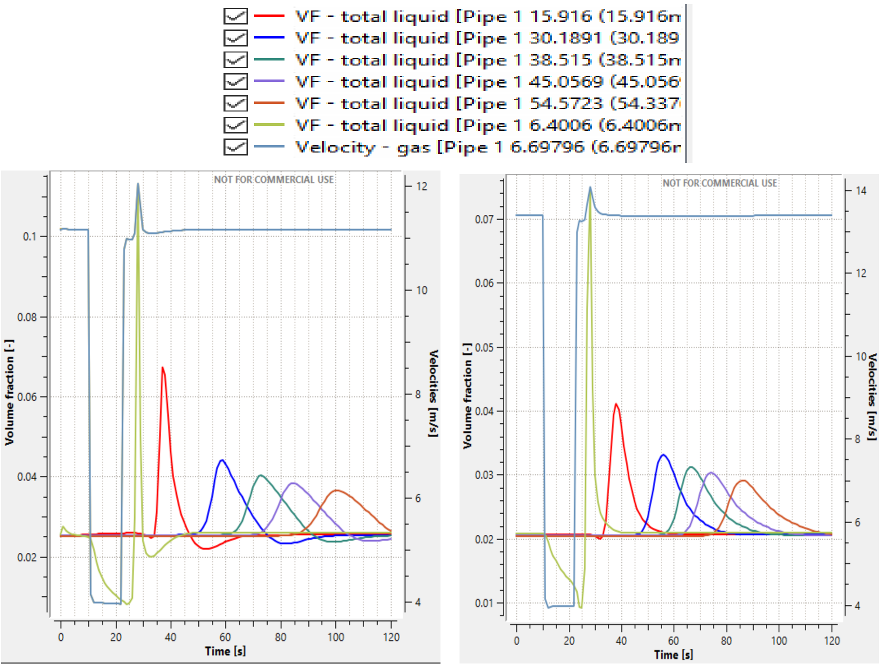


Figure3.26: LedaFlow simulation in holdup plot when water flowrate is 0.032kg/s. the left one is gas flowrate is 0.037kg/s, the right is 0.045kg/s. The gas velocity is plotted to visualize how the wave was initialized.

In the other six cases, the slug flow appeared in the flow regimes, which was the main reason that the surge wave could not be observed in the simulation results. Taking the flow rate of water was 0.032 kg/s and the gas flow rate as 0.029 kg/s as an example, it can be seen in the figures below that probe3,4,5 and 6 had successive slug flow, although the duration was short, but this state was enough to have a significant effect on the holdup plot.

Firstly, the peak value of the wave was much larger than the measured value of the experiments. Secondly, the duration of each wave was short, and the wavelength was not long enough. A systematically fall in amplitude is not seen either.

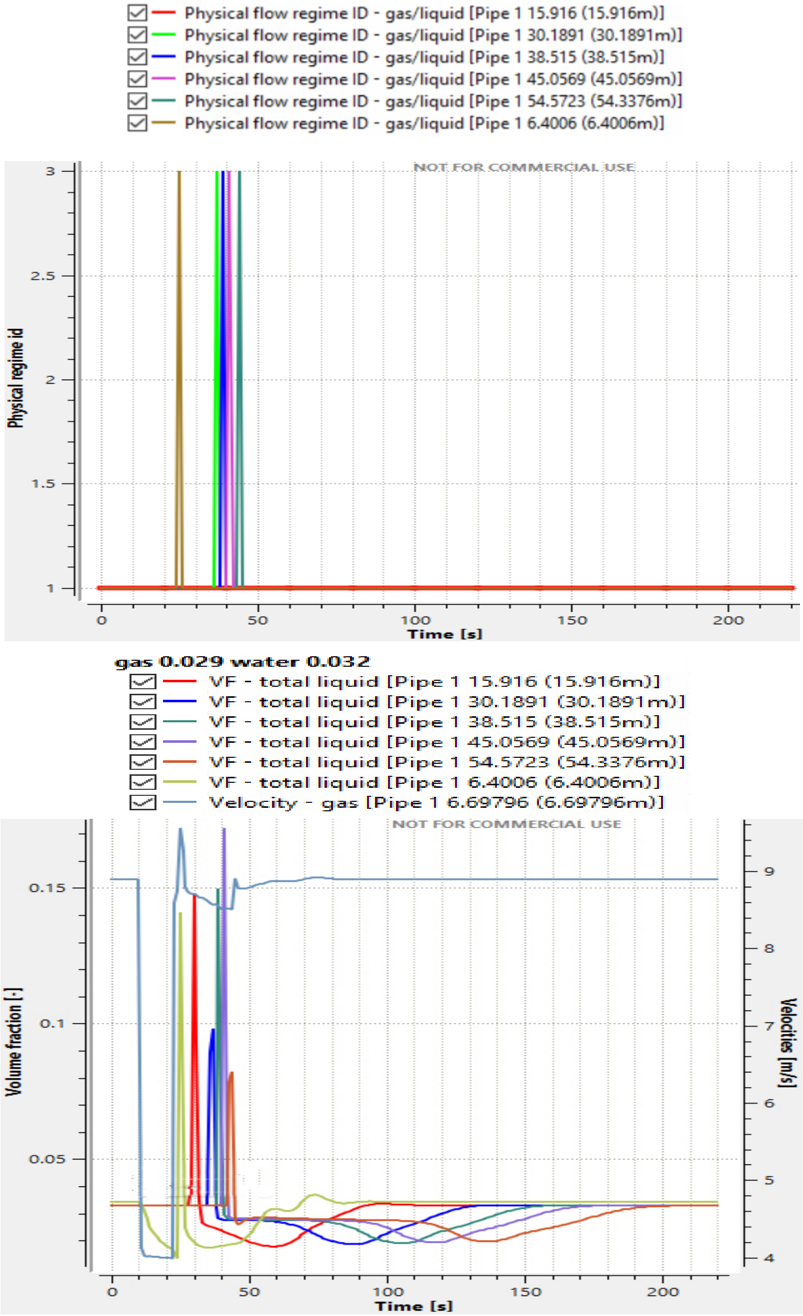
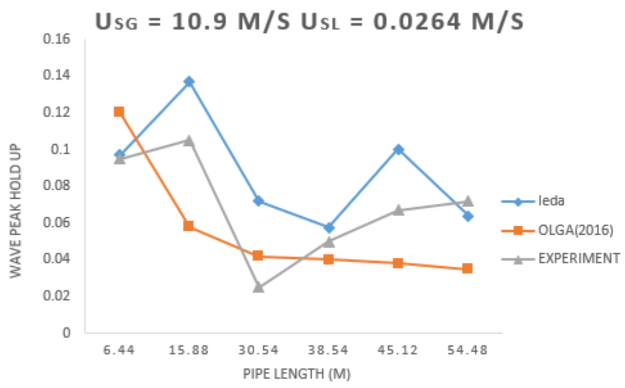


Figure3.27: LedaFlow simulation in flow regime and holdup plot when water flowrate is 0.032kg/s and gas flowrate is 0.029kg/s. The gas velocity is plotted to visualize how the wave was initialized

From the above results, when compared with the previous experiments and the results of the old software simulation, the OLGA2016.2.1 performance on average was better than the LedaFlow in the new version.

The disadvantage of OLGA was mainly behind of the horizontal pipeline, which can't simulate the obvious surge wave trend plots, but it still showed a good performance for probe1. Even if the slug wave appeared, the time was shorter, and the simulation results of the 8 cases were compared with the previous software, the differences were acceptable. For LedaFlow, the main difference was in the flow regime. This problem leaded to the propagations of the surge wave were not obvious in the pipeline. Since only very few cases have good results in it, it is not significant for experimental studies to be comparable and referential.

The figures below showed the comparisons between the latest version of OLGA, LedaFlow and real experimental data when the flow rate of water is 0.075 kg/s (Usl = 0.0264m/s) and the flow rate of gas is 0.037 kg/s (Usg = 10.9m/s). The main contrasts were the peak value and probe and wave speed between probes. The differences between simulation results and experimental data were clearly visible, because OLGA has a more stable performance in terms of simulation, so in the next study, OLGA simulation would be the main.



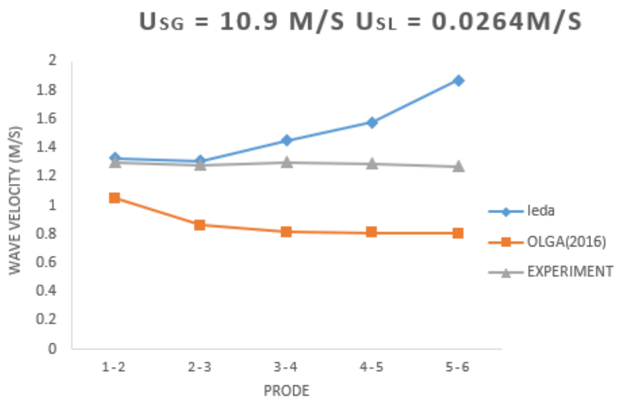


Figure3.28: The lab observations of the wave peak value and wave propagation velocity between each probe compared to the OLGA and LedaFlow simulations when water flowrate is 0.075kg/s, gas flowrate is 0.037kg/s.

3.3 Up and down pipe simulation

In the actual gas filed production, such as extracting gas from the subsea, the geometries in terrain are complicated. In the previous experiments, there was only one dip in pipeline, so more than one rising and falling pipe need to be set in simulations and study the variations of wave velocity in the pipes. In fact, only if the wave propagation velocities are not equal in the pipes which have the slight inclinations, it is possible to observe the surge wave in the horizontal pipe.

3.3.1 Modifying Geometry Settings in Previous Experiments

The numerical simulations have been carried out in OLGA 2016.2.1. The geometric configurations and dimensions of the pipes are shown in the following table. Similarly, two mass sources, one for air and one for water, all were set on section one of the pipe one.

Table3.4: The geometry settings in up and down pipe

Pipe	x(m)	y(m)	Length (m)	Elevation (m)	Diameter (m)
Start point	0	0	-	-	-
Pipe-1	0.9992	-0.04	1	-0.04	0.06
Pipe-2	1.4992	-0.04	0.5	0	0.06
Pipe-3	6.09788	0.07	4.6	0.11	0.06
Pipe-4	11.0967	-0.04	5	-0.11	0.06
Pipe-5	34.0928	0.38	23	0.42	0.06
Pipe-6	49.087	-0.04	15	-0.42	0.06
Pipe-7	57.087	-0.04	8	0	0.06

The flow path plot is shown following in Figure3.29, two dips were set. The max angle was in pipe-1(2.3-degree), the min angle was in pipe-5(1.05-degree). Other assumptions and boundary conditions were the same as the previous experiments applied. The mesh =1D, and the flow rates for water and gas also used the data in Table3.2.

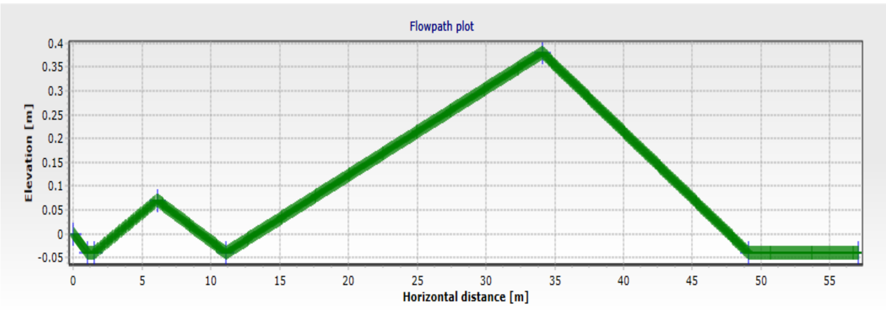


Figure3.29: Flow path plot of up and down pipes

Due to the change in the geometry settings, a slug flow occurred in pipe-3, but only 0.5 seconds, and then quickly restored the stratified flow model. The flow regime of each pipe is shown in the figure below.

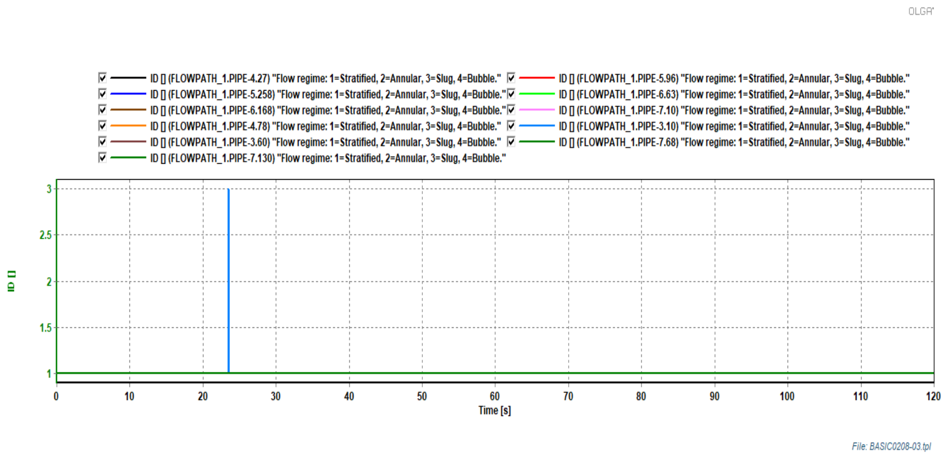
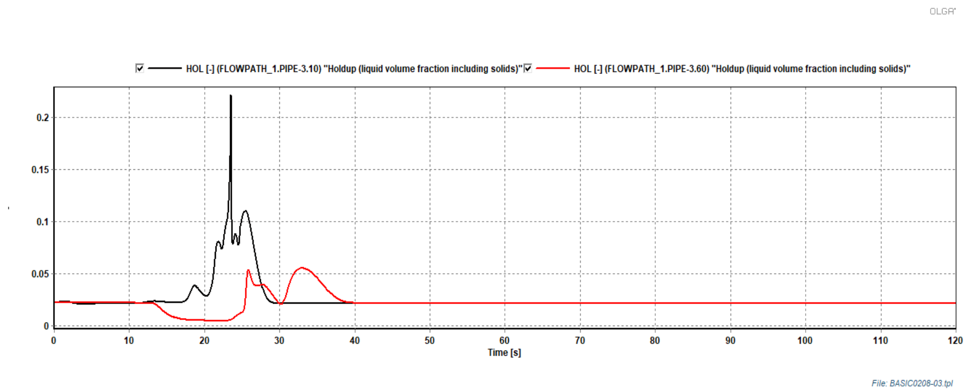
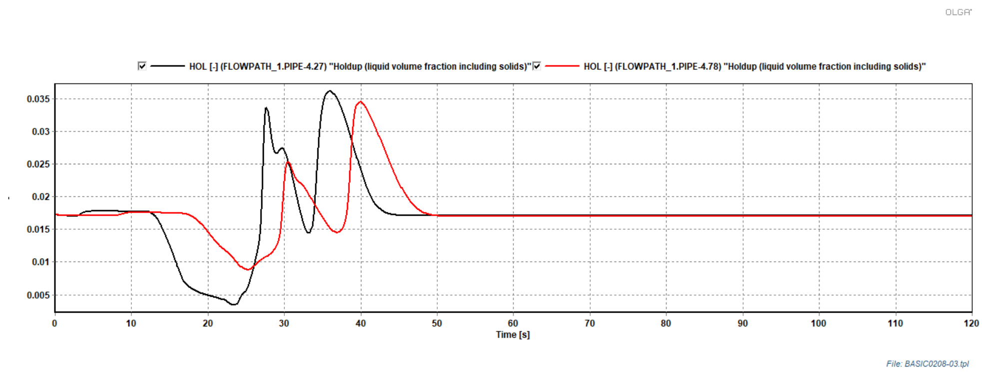
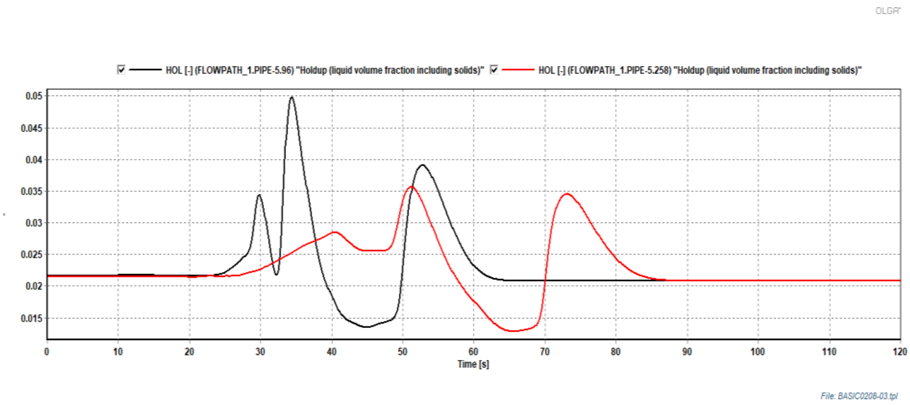


Figure3.30: Flow regime ID plot in the up and down pipes

The holdup developments in different pipes can be seen in Figure3.31. We can use these plots to calculate the wave velocities under this geometry settings.







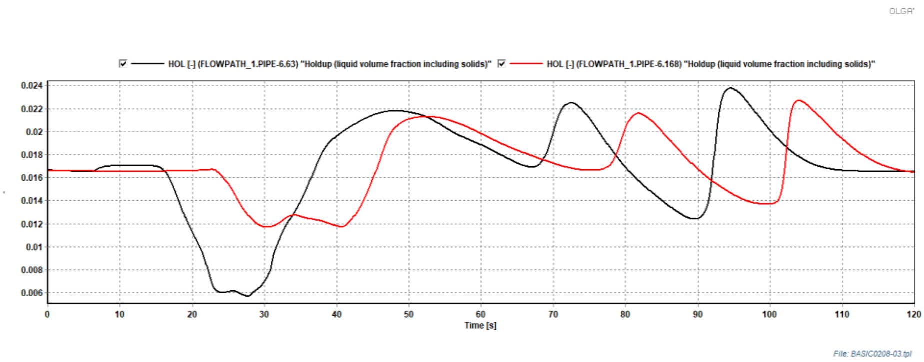


Figure3.31: Holdup trend plots in up and down pipes, from the pipe3 to pipe6.

In all pipes which have small inclination, surge waves can be observed. In each pipe, the apparent fluctuations of the holdup more than once, which means that in addition to the surge waves generated at the entrance due to gas choking and ramp up again, waves were also generated during the flow.

The peak values of the holdup in the up pipes (pipe-3 and pipe-5) were higher than that of the down pipe (pipe-4 and pipe-6). However, when it comes to wave velocities, they showed opposite effect, shown in Table3.5, the wave velocities of the down pipes were greater than that of the up pipe, the reason is that the gravity has the positive influence on the velocities in down pipe.

Table3.5: wave velocities belong to the up and down pipes

Pipe	Velocity (m/s)
Pipe-3	0.465
Pipe-4	0.723
Pipe-5	0.481
Pipe-6	0.677

As can be seen from the profile plot below, at the same time, holdup fluctuations occurred at different locations in the pipeline. When T=17s (black line), there were waves in pipe-3, pipe-5 and pipe-7, the wave formed by the inlet gas changes and the liquid flowing in this geometry pipeline. According to the red and blue lines, the waves propagated forward respectively and not merged, still three holdup changes in the pipeline. When T=77s, only one wave propagated in pipe-5(purple line), the reason is that the wave formed by the liquid flowing has disappeared during the propagation.

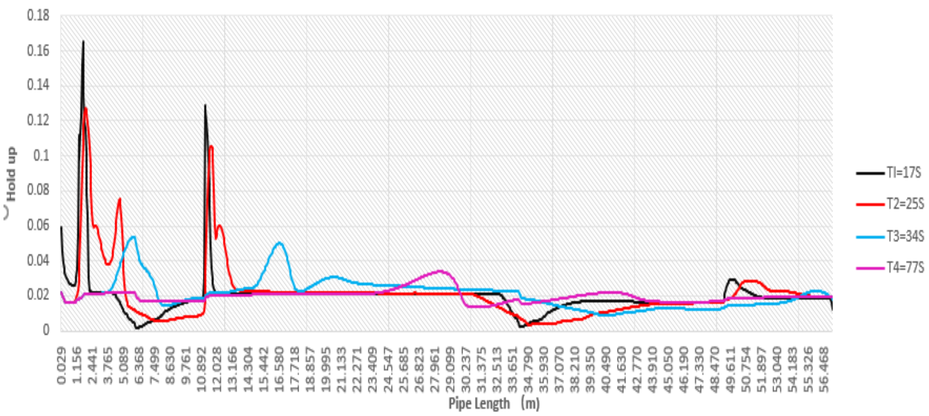


Figure3.32: Holdup profile plot at different time in up and down pipes

In the horizontal pipe, since the new configurations in geometry of pipes, the holdup changes of each point became complicated, and there was no longer only one obvious fluctuation compared with the simulation in 3.2.1(Figure3.4), during the integration time, there were 4 significant changes in holdup at each observation point. Although the maximum value of holdup in the horizontal pipe was half of the holdup in the previous experiment simulation, the wave propagation lasted for the whole time, even at the end of simulation, the holdup values did not tend to be stable. This is also a characteristic of the surge wave propagation. The fluctuation range of the holdup is not large, but the duration is long. The holdup trend in horizontal pipe (pipe-7) showed in Figure3.33.

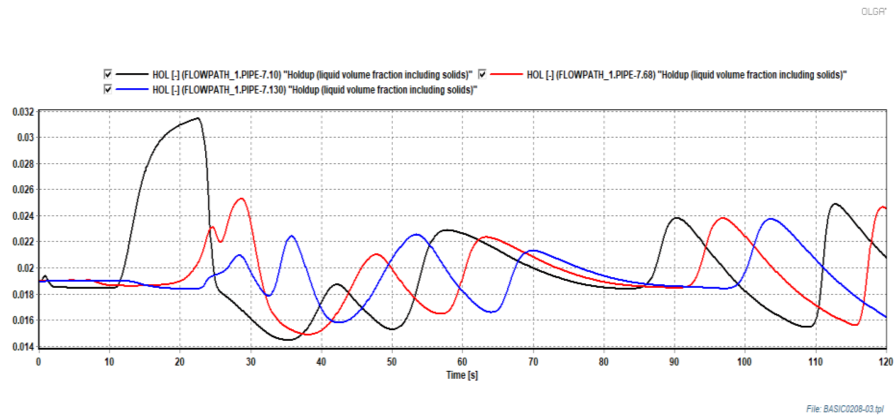


Figure3.33: Hold up trend plot in horizontal pipe under the new geometry settings

From the above simulations, the effect of changes in the geometric configuration on the liquid flowing is obvious. More undulating pipes would create more turbulences in the liquid flowing, which could change the flow regime (from stratified flow to slug flow). Of course, as long as the mass flow rate of the gas is large enough and the mass flow rate of the liquid is small, which can satisfy the stratified flow in the undulating pipes. In addition, the surge waves in the horizontal pipe were also more pronounced. Most notably, the holdup of one point fluctuated more than once and lasted for a long time.

3.3.2 Large-scale pipeline simulation

In the gas fields, the length of the pipeline for transporting gas is very long and the diameter is large, for example from Mikkel to Midgard, the connection pipe is 37 km and 18-inch diameter [4, p.2]. Liquid inventory management is an important subject in a subsea wet gas pipeline system mainly due to long distance, large diameter and three-phase fluid (gas, water/MEG, and condensate) effects [22, p.1]. In this section, the simulations of the large-scale pipeline would be used to make them closer to the actual production conditions.

3.3.2.1 The same length on up and down pipes

In this section, the biggest feature of the geometric configuration of the pipeline is that the up and down pipes had the same length. There were also two dips. The down pipe at the entrance (pipe-1) did not set very long, the purpose is to get more obvious holdup changes in the flowing pipes, as we know, the holdup fluctuations become small and slow as the length of the pipeline increases. Compared with the previous experiment settings, the horizontal pipe section at the first dip was removed, in order to better observe the wave velocity changes and holdup changes in the next up pipe.

In the geometrical settings, there were not only necessary to maintain the equal length of the up and down pipes, but also to maintain the inclination angle of the pipes between 1° and 2°. In addition, the diameter of the pipeline must be increased accordingly. The geometric configurations and dimensions of the pipes are shown in the following table. Similarly, two mass sources, one for air and one for water, all were set on section one of the pipe-1.

Table3.6: Geometry settings of large-scale pipes which have the same length

Pipe	x(m)	y(m)	Length (m)	Elevation (m)	Diameter (m)
Start point	0	0	-	-	-
Pipe-1	24.9968	-0.4	25	-0.4	0.3
Pipe-2	224.957	3.6	200	4	0.3
Pipe-3	424.917	-0.4	200	-4	0.3
Pipe-4	624.877	3.6	200	4	0.3
Pipe-5	824.837	-0.4	200	-4	0.3

Pipe-6	1324.84	-0.4	500	0	0.3

The flow path plot as following in Figure4.35. The max angle is in pipe-2(1.14°),the min angle is in pipe-1(0.92°).

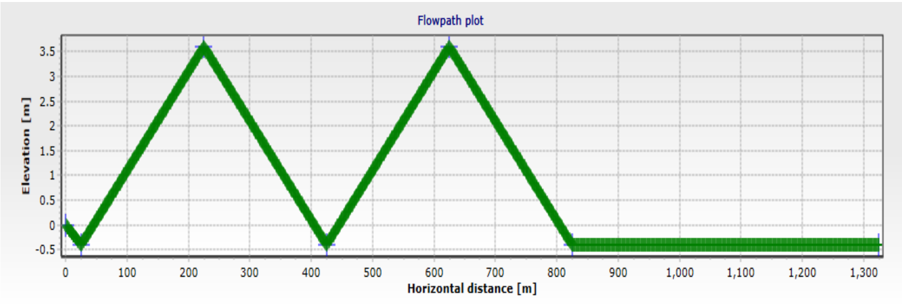


Figure3.34: Flow path plot of large-scale pipes which have the same length

The following assumptions and boundary conditions were applied in this simulation:

• Adiabatic model without any temperature calculations and all temperatures were set to 20° C.

•Outlet node pressure boundary set to 1 atm.

•A constant pipeline roughness of 0,05 mm was assumed for the entire pipeline.

•An air-water PVT-file obtained from Zhilin Yang [19]

•Max dt = 1 sec., Min dt = 0,00001 sec.

•Slugvoid Sintef.

•1 st. order mass equation discretization

•OLGA Flowmodel

Since the diameter of the pipe increased, Mesh = 3.3D was used as the calculated grid. The flow rates applied to initiate the wave seen in Table3.6. When setting the flow rates, they were necessary to ensure that the flow regime in all the pipes are stratified flows. The simulation integration is 8 minutes. The air flow is choked after 60 seconds and is maintained for 60 seconds.

Table3.6: Flow rate settings and integration time

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	3.7	3.2
60	3.7	3.2
61	1.3	3.2
120	1.3	3.2
121	3.7	3.2
Integration		480 (s)

In pipe-2, there was still slug flow for 2.5s (from 117.8s to 120.3s), while in other pipes, the flow regime during the integration time maintained the stratified flow, indicating that the flow rate settings for air and water were reasonable. Flow regime chart as shown in Figure3.35, holdup trend plots in different pipes (from pipe-2 to pipe-5) were showed in Figure3.36.

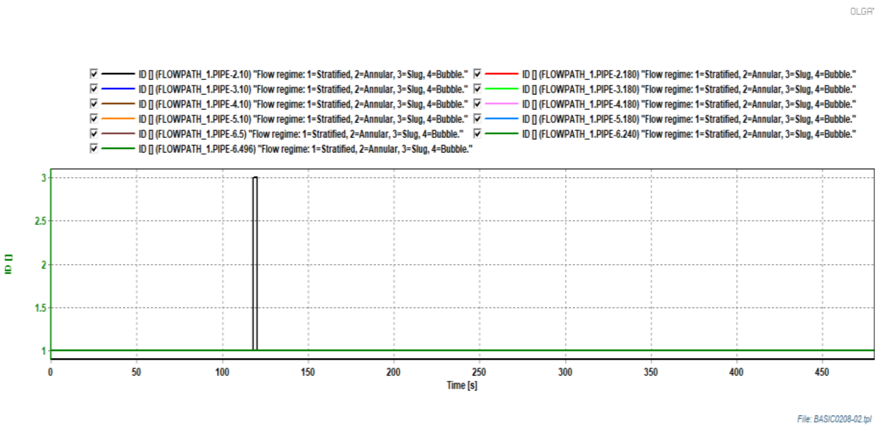


Figure3.35: Flow regimes ID plot of large-scale pipes which have the same length.

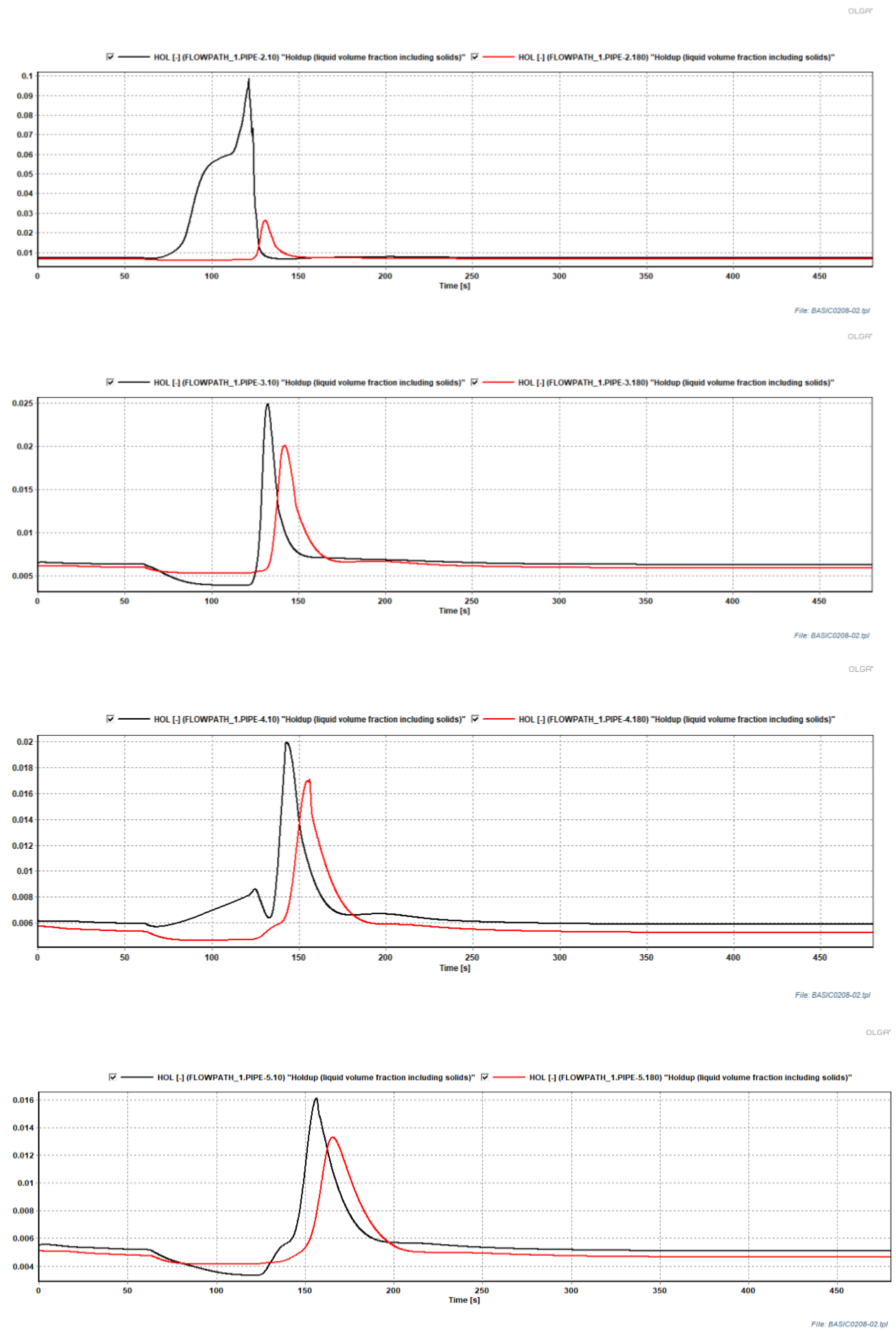


Figure3.36: Holdup trend plots in pipes, the first one is pipe-2, the second one is pipe-3,the third one is pipe-4 and the last one belongs to pipe-5.

It can be seen that in large-scale pipes (length is 200m, diameter is

0.3m), the holdup of the up and down pipes fluctuated only once, which means in this case, there was no wave due to the water flowing. Pipe-2 was most affected by the wave due to the gas choking and ramp-up again, and holdup fluctuations at the first observation point lasted the longest time. As the distance increases, the maximum value of holdup in the pipeline gradually decreased.

By calculating the wave velocity (Table3.7), wave velocity in pipe-2 was greater than that of pipe-3, which may be due to the short slug flow in pipe-2, and the shorter length of pipe-1, the gas at the inlet changes in the flow rate had greater influence on pipe-2. In the following pipes, the wave velocity of the down pipe (pipe-3, pipe-5) was significantly larger than that of the up pipe (pipe-4), also because gravity has a positive acceleration on the up pipes.

Table3.7: Wave velocity of pipe-2 to pipe-5

Pipe	Velocity (m/s)
Pipe-2	19.10
Pipe-3	17.17
Pipe-4	14.40
Pipe-5	19.32

From the profile plot (Figure3.37), according to the settings, at 60 s the gas flow rate was reduced from 3.7 kg/s to 1.3 kg/s. At 72 s (black line), the effect of the reduced gas flow rate started to propagate to pipe-2, thus the holdup in pipe-1 gradually decreased, a holdup increase occurred in pipe-2, since a low spot was between pipe-1 and pipe-2, the liquid started to accumulate.

At 94s (red line), the holdup in pipe-2 exceeded pipe-1, and until 122s (blue line), the holdup reached the maximum at 32.5m in pipe-2, the value was 0.1064. Afterwards, as the gas flow rate increased, the liquid gathered at the lowest point moved forward. Therefore, in the fellow flowing, the value of holdup decreased, but it propagated forward in the form of the surge wave. At 132s (purple line), the holdup's fluctuation in pipe-2 was already small, and the wave was passed to pipe-3.

Because after 121s, the gas flow rate restored and did not change, the surge wave propagated forward with no drastic fluctuations. However, we did not observe the merge of surge waves in the profile, and as the surge wave propagated, the peak of the holdup has a systematic decreasing.

At 168s (yellow line), the wave reached pipe-6 (horizontal pipe) with a peak value of 0.013, After 200s, holdup fluctuations ended in the entire pipe. In the figure below, the green line represents the geometry of the pipe, through which it can better observe the position of the wave peak.

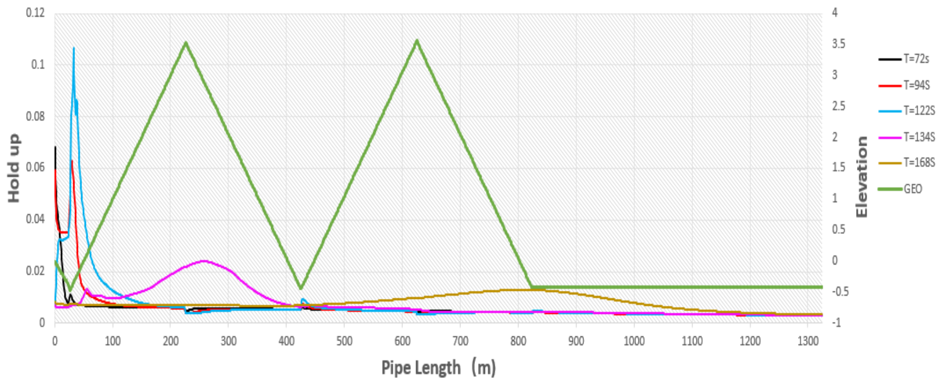


Figure3.37: Holdup profile plot at different time of large-scale pipes which have the same length

it also can see from Figure 3.38, when the wave reached the horizontal pipe, the holdup peak value became very small, only one-tenth of the peak value in pipe-2. At each observation point, holdup changed only once, although the distance between the three observation points was very long (about 245m), the times when the fluctuations occur were very close. This showed that in the horizontal pipeline, the wave velocities of propagation were very fast.

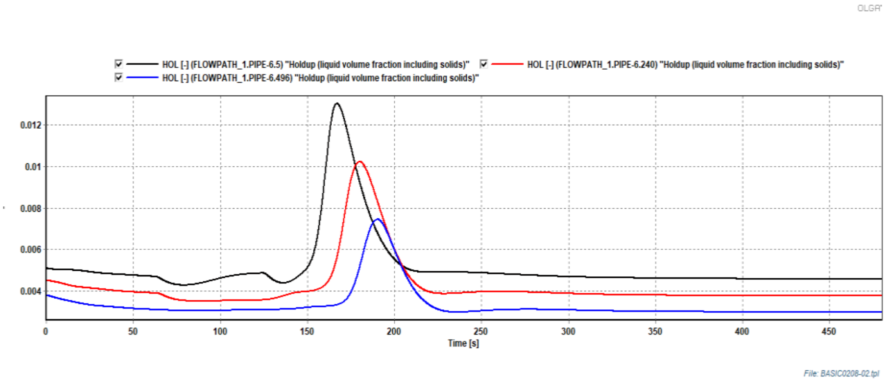


Figure3.38: Holdup trend plot in pipe-6(the horizontal pipe).

In this part, we successfully simulated the surge wave in long and large pipes. At the same time, it was found that the down pipe has a significant effect on the increase of the wave velocity, so in the following part, considering whether to reduce the length of the down pipes, it is possible to simulate the more significant surge wave and the wave merge.

3.3.2.2 The different lengths on up and down pipes

In this part, the geometry of the pipes has become more complex, and the length of each pipe was different, the length of the down pipes was significantly shorter than that of the up pipes. The angle of all pipelines is maintained at about 1.14°. The geometric configurations and dimensions of the pipes are shown in the following table, water and gas inlet all were set on section one of the pipe-1.

Table3.8: Geometry settings of different lengths on up and down pipes

Pipe	x(m)	y(m)	Length (m)	Elevation (m)	Diameter (m)
Start point	0	0	-	-	-
Pipe-1	24.98	-1	25	-1	0.3
Pipe-2	74.94	1	50	2	0.3
Pipe-3	99.92	0	25	-1	0.3
Pipe-4	299.88	4	200	4	0.3

Pipe-5	349.84	2	50	-2	0.3
Pipe-6	849.84	2	500	0	0.3

Figure3.39 showed the flow path plot. Other assumptions and boundary conditions were the same as the previous part applied.

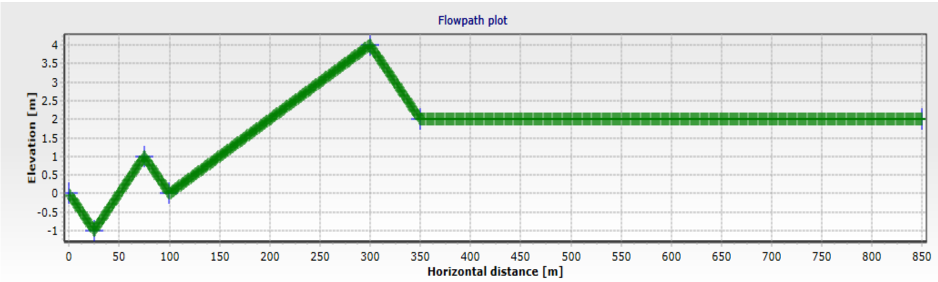


Figure3.39 Flow path plot of different lengths on up and down pipes

The flow rates applied to the initiate the wave seen in Table3.9. these data also needed to make flow regime in each pipe as the stratified flow as possible. Because the geometry of the pipes became more complex, the flow rate of gas needed to be increased and the flow rate of water needed to be reduced accordingly to ensure the stratified flow.

Table3.9: Flow rates and integration time of different lengths on up and down pipes

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	7.0	2.5
60	7.0	2.5
61	1.5	2.5
120	1.5	2.5
121	7.0	2.5
Integration		360 (s)

With the above flow settings, only one-second slug flow occurred in pipe-2, and the remaining pipes were stratified flow during the entire simulation period.

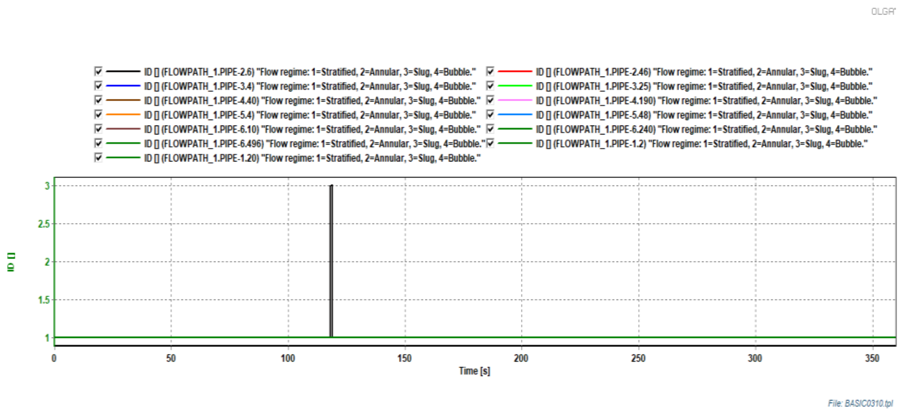
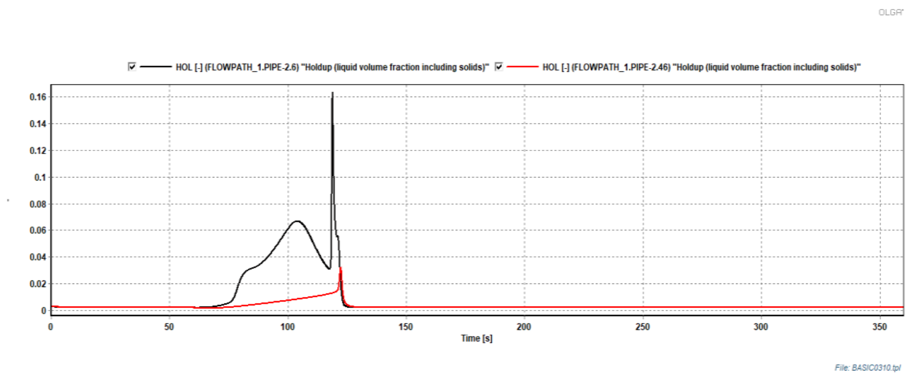
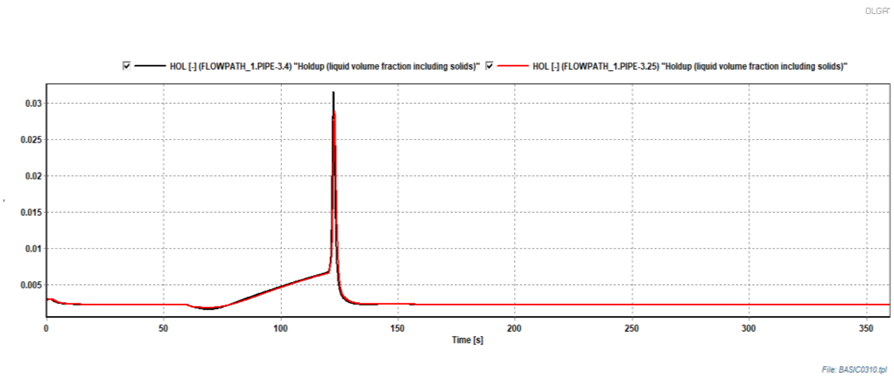
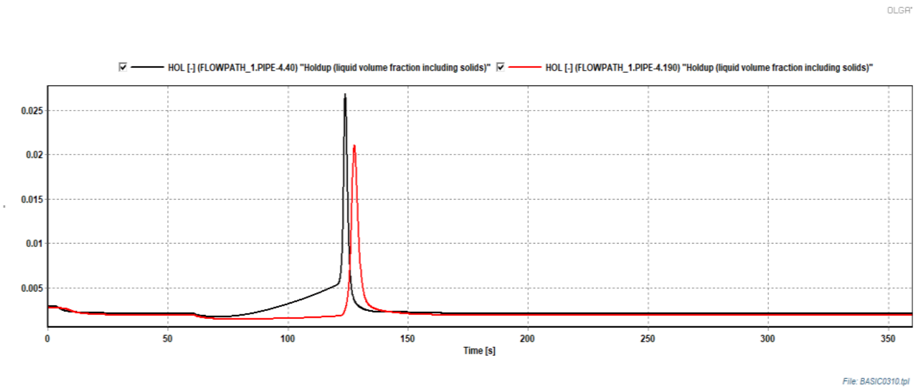


Figure3.40: Flow regimes ID plots of different lengths on up and down pipes

Holdup changes in different pipes were shown in the following Figure3.41. More complicated geometric settings made the holdup changes in pipe-2 more complicated. At the first observation point, the holdup value rose first, then dropped and finally increased to the peak. Especially in the descending pipes, there was little difference between the time when the two observation points reached the peak value, which illustrated that the fast wave speed were in the pipeline. Certainly, the peak value that holdup could reach in each pipe was also decreasing.







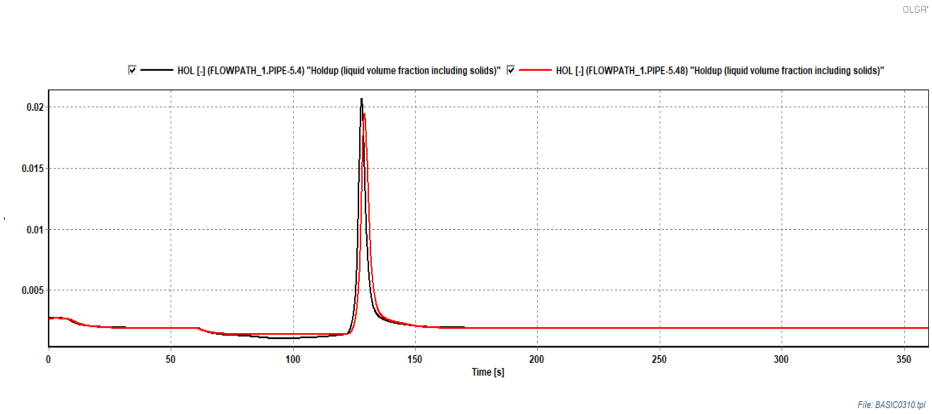


Figure3.41: Holdup trend plots in pipes which have different lengths, the first one is pipe-2, the second one is pipe-3, the third one is pipe-4 and the last one belongs to pipe-5.

The specific wave velocity calculation results were shown in the table below. Because pipe-3 was the down pipe and the length of the pipe was the shortest, the propagation of waves in pipe-3 was the fastest.

Since the length of pipe-4 was longer, the speed was gradually reduced by the negative effect of frictional resistance in the process of propagation. Therefore, when the surge wave reached pipe-5, even though gravity is beneficial to the increase in wave speed, the speed of pipe-5 was less than pipe-4 due to the shorter pipe length.

Table 3.10: Wave velocities of different lengths on up and down pipes

Pipe	Velocity (m/s)
Pipe-2	11.42
Pipe-3	42.00
Pipe-4	39.47
Pipe-5	36.67

The following profile plot showed the propagation of waves in each pipe. Similarly, the green line represents the geometry of the pipe.

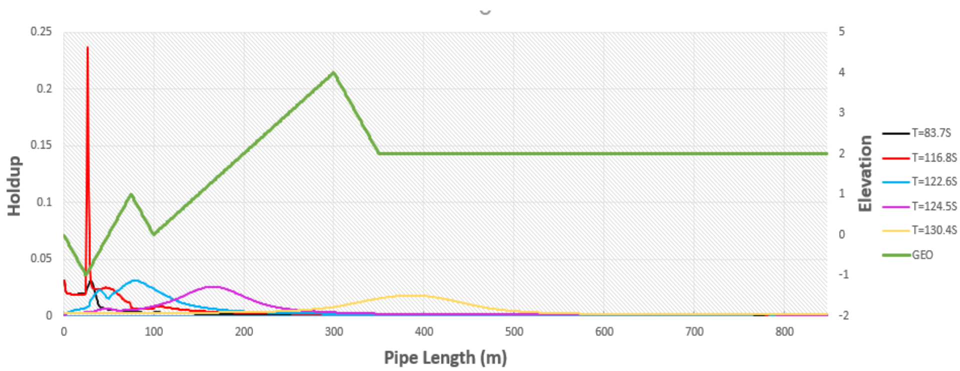


Figure3.42: Holdup profile plot at different time of different lengths on up and down pipes

In this pipeline, the dramatic changes in wave propagation were mainly carried out in pipe-2 and pipe-3. T=83.7s (black line), the holdup in pipe-2 was equal to that of pipe-1, and gradually increased over time. At T=116.8 (red line), holdup reached its maximum value, which was equal to 0.2352. Only 6 seconds passed, the restored gas rate made the wave propagate from pipe-2 to pipe-3, T=122.6s, blue line. The lines once again showed that the increase in the gas velocity was sufficient to drive the accumulated liquid forward and form a surge wave. Obviously, the holdup change of the surge wave was less than the holdup value when the liquid accumulated.

Since pipe-3 had the largest wave velocity, only two seconds, the wave has started to propagate in pipe-4, the purple line showed the processing, T=124.5s. When the wave propagated to the horizontal pipe (pipe-6), T=130.4s (yellow line), the holdup in the pipe was 0.018, which is only one-fourth of the peak value.

By reducing the length of the down pipes, it can be found that the wave completed the propagation in a shorter time. In Figure 3.43, although the peak value of the wave increased, compared with the simulation in3.3.2.1, the differences in the propagation of following pipes after the pipe-2 were no longer obvious.

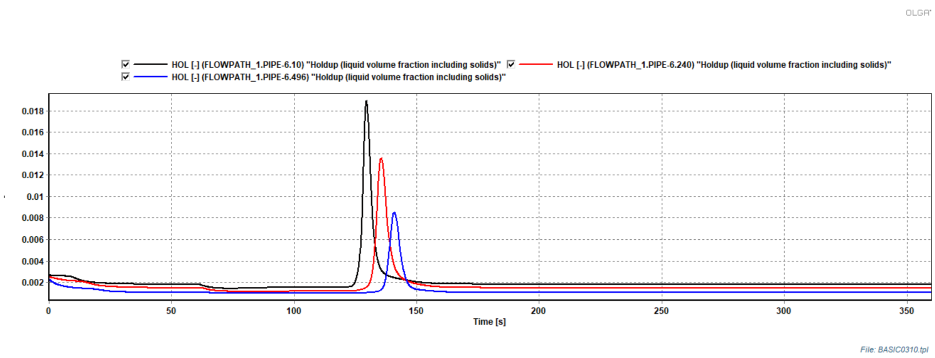


Figure3.43: Holdup trend plot in horizontal pipe

3.3.2.3 Two waves initiated at the inlet on the up and down pipe

Two waves initiated at the inlet on the up and down pipe in OLGA

In the previous part, the length reduction of the down pipes did not help to observe the merging of the waves in the propagation process. In this section, it would set two consecutive choking and then ramping up on gas flow rates at the inlet in order to form two waves at the entrance, and then observe the propagation of surge waves.

The geometric configuration of the pipelines and the boundary conditions are exactly the same as those in 3.3.2.2. The most obvious difference is reflected in gas flow rates, From the 61st second, after 30 seconds of gas flow rate choking, the gas flow rate rose to 7 kg/s, held for 1.5 seconds, and then dropped again to 1.5 kg/s. the specific data as can be seen from the table below.

Table 3.11: The flow rate settings which have two changes

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	7.0	2.8
60	7.0	2.8
61	1.5	2.8
90	1.5	2.8
91	7.0	2.8
91.5	7.0	2.8
92	1.5	2.8
122	1.5	2.8
123	7.0	2.8
Integration		360 (s)

Through the simulation in OLGA, it can see that the setting of the two-consecutive choking and then ramping up on gas flow rates at the inlet makes the flow regimes in all pipelines were stratified flow. The following figure shows it.

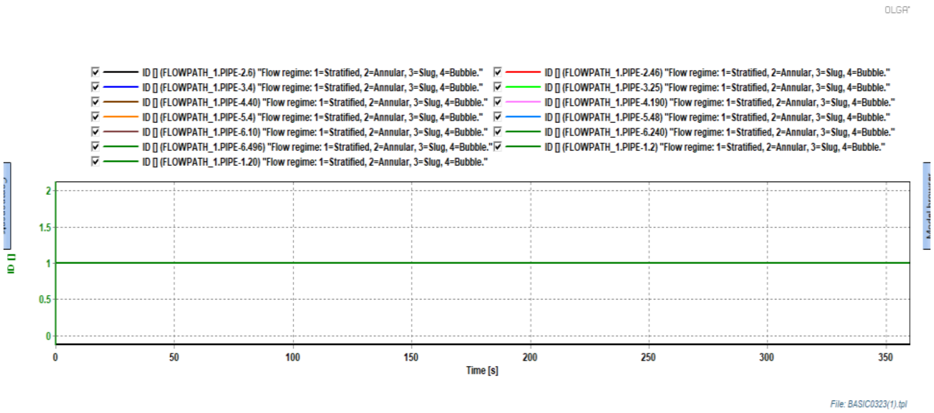
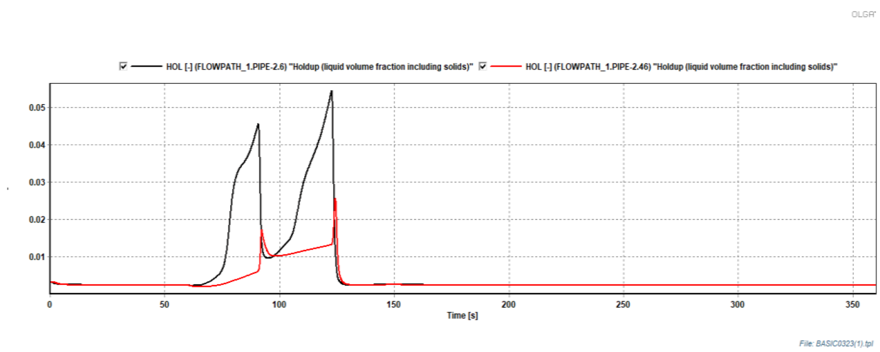


Figure3.44: Flow regime ID plot in two consecutive waves by OLGA simulation

Obvious differences can be found through the holdup trend plots for each pipe. In pipe-2 and pipe-3, there were two holdup changes for the two different observation points, and this change was continuous. In pipe-4, although there were still two holdup fluctuations, compared with pipe-2, they were too inconspicuous. Since in pipe-4, the position of the observation point was set not far from the pipe-4 inlet, we can guess that the two waves completed the merger nearby the pipe-4 inlet. This guess can also be confirmed by the profile plot afterwards. In pipe-5, there was only one holdup change. We can clearly see from Figure3.45.



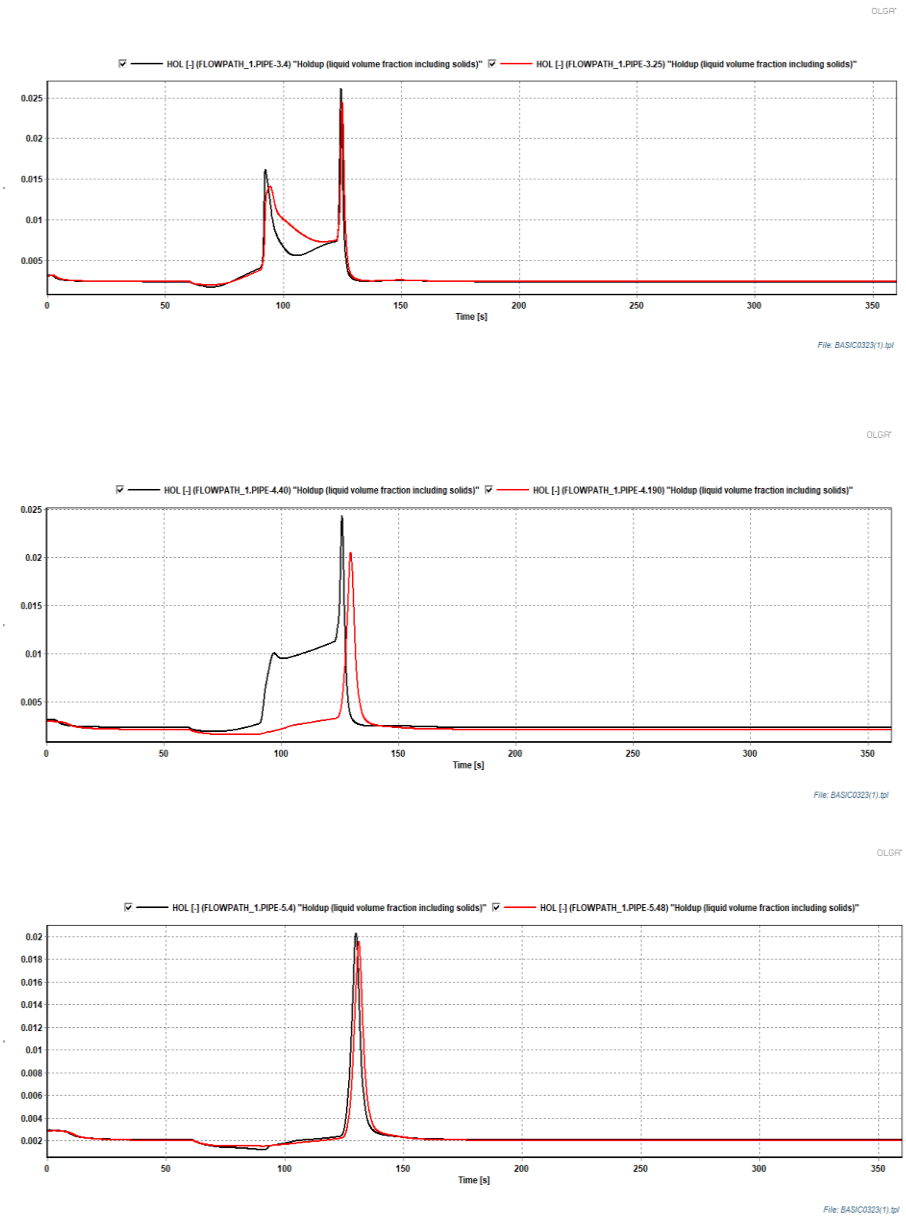


Figure3.45: Holdup trend plots in pipes which have two consecutive waves at inlet, the first one is pipe-2, the second one is pipe-3, the third one is pipe-4 and the last one belongs to pipe-5 by OLGA simulation.

The following table shows the value of wave velocity in each pipe. First of all, because two consecutive gas flow changes and down pipe, the wave velocity in pipe-3 was still higher than pipe-2. the surge wave merging occurred in pipe-4, wave speed in pipe-4 was larger than pipe-2 and smaller than pipe-3. In the pipe-5, a down pipe, the wave velocity has slightly increased.

Table3.12: wave velocities in different pipes of two waves by OLGA simulation

Pipe	Velocity (m/s)
Pipe-2	26.05
Pipe-3	42.00
Pipe-4	38.46
Pipe-5	40.00

In the next profile plots, we can clearly see the merger and propagation of the two waves. When the gas flow rate choked firstly, the surge wave was mainly performed in pipe-1 and pipe-2. At 70 s (black line), the effect of gas flow on holdup started to affect from pipe-1 to pipe-2. When T=87.5 (red line), holdup had the peak value in pipe-2. When the second gas flow rate change occurred (T = 91.5s blue line), since the propagation velocity was not fast enough to reach to pipe-2, holdup value remained a high level at the lowest position. While T=92s, Increased gas flow rate reached pipe-2, causing holdup's fluctuations to move forward (purple line).

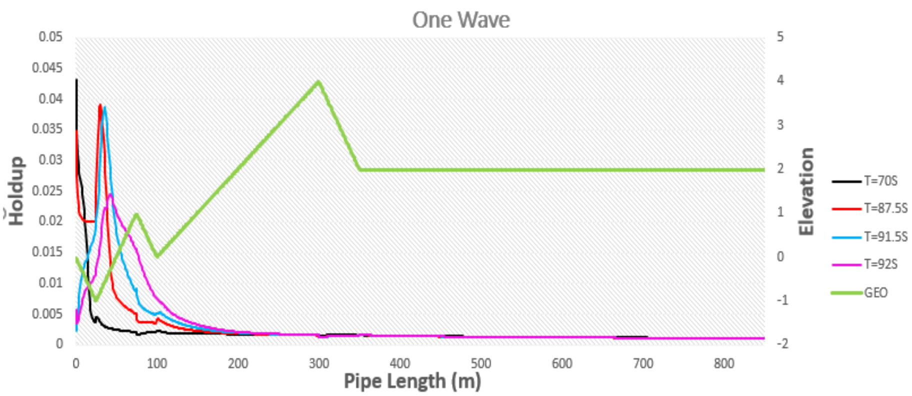


Figure3.46: Holdup profile plot at different time when one wave was in pipeline by OLGA simulation

When the second gas flow rate choked completely into the pipeline, the influence due to the first gas flow rate choking remained, so when T=97s (black line), holdup changes can be observed significantly from pipe-1,2 and 3, the formed surge wave reached the lowest point between pipe-3 and pipe-4, the holdup had a small increase, and the liquid accumulation caused by the second flow rate decrease occurred between pipe-1 and pipe-2.

When T=122.5s (red line), the holdup in pipe-2 reached its peak for the second time. At the same time, in pipe-4, the surge wave which was due to the first gas choking started to propagate. The phenomenon of propagation of two surge waves in two pipes became more apparent at T=124s (blue line), the gas rate ramped up when T=123s. The distance between the two waves also gradually shortened, and the value of holdup in pipe-2 was 0.28, and the value of holdup in pipe-4 was 0.12. At T=125.5s (purple line), two surge waves have merged in pipe-4. The holdup value is 0.26.

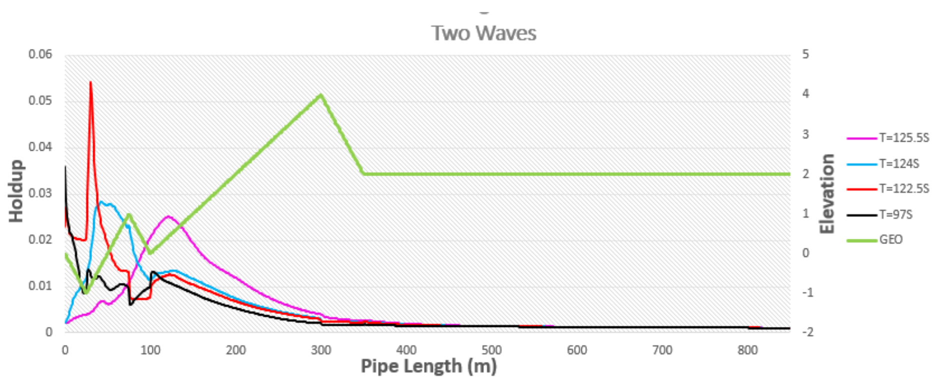


Figure3.47: Holdup profile plot at different time when two waves were in pipeline by OLGA simulation

After the merger of the two surge waves, only one wave was propagated in the following pipelines. Just 3.5 seconds, the wave propagated from pipe-4 to pipe-6(black, red and blue lines), It is further illustrated that the velocities of the waves in the pipeline were quite large. Although the holdup value has decreased as distance, it was slight. When T = 144s, the surge wave propagated to the end of the pipeline (purple line).

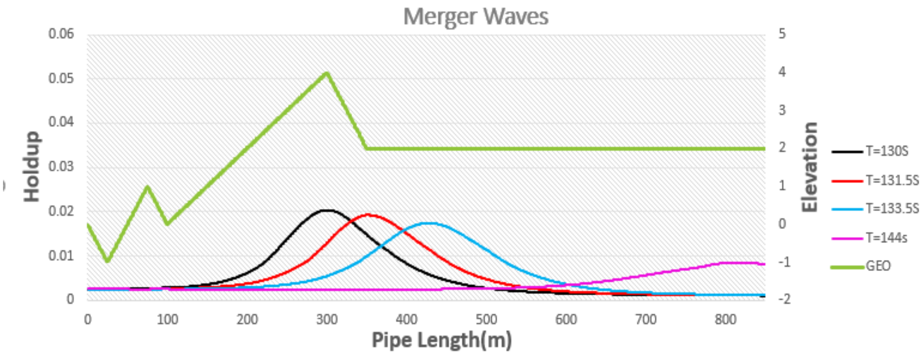


Figure3.48: Holdup profile plot at different time when merger waves were in pipeline by OLGA simulation

In the horizontal pipeline, there was no doubt that the surge wave generated. Because of the merger, the two changes of the gas flow rate at the entrance did not affect the waves in the pipe-6. The plot of change in holdup over time in the horizontal pipeline was not significantly different from the plot in the previous part.

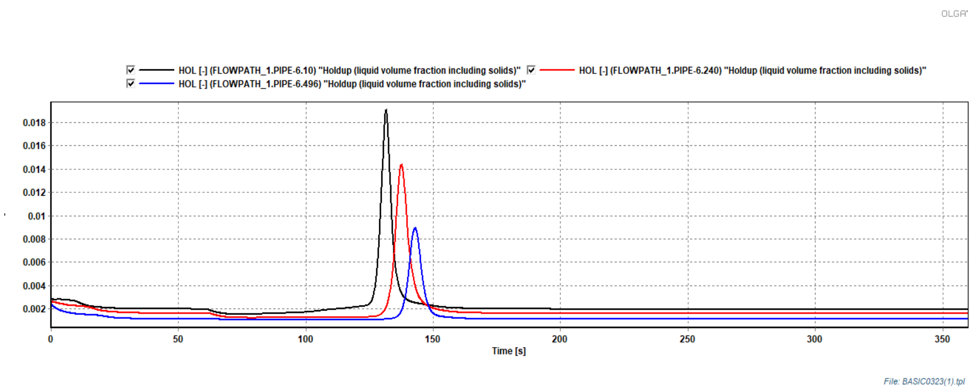


Figure3.49: Holdup trend plot in horizontal pipe when two waves initiated at inlet by OLGA simulation

Two waves initiated at the inlet on the up and down pipe in LedaFlow

In OLGA, the simulation achieved the merge of surge waves, similarly, it needed to be run again in LedaFlow. All geometric configurations, boundary conditions, and flow rate settings were consistent with those in OLGA.

The first concern was still the flow regime, which was consistent with the results simulated in OLGA. The flow regimes in the pipelines remained consistent as the stratified flow.

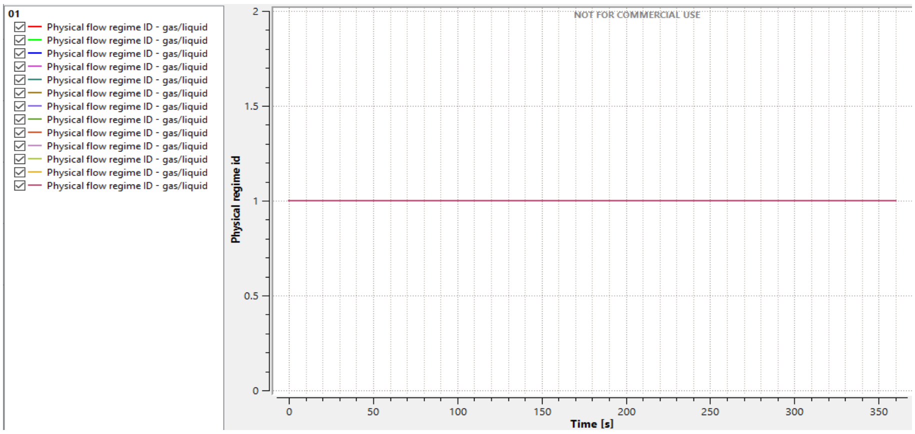
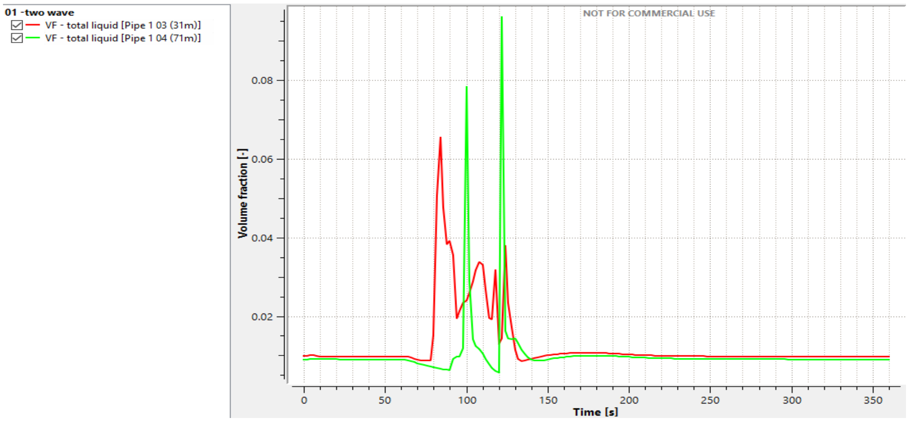
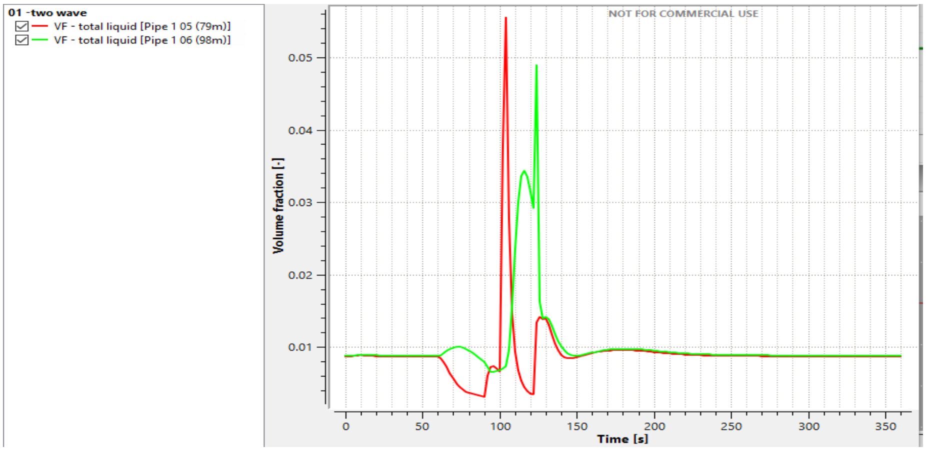
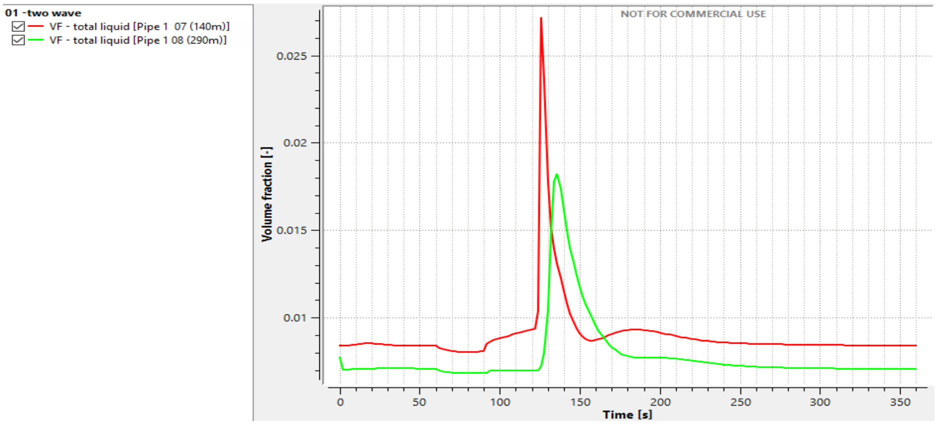


Figure3.50: Flow regime ID plot in two consecutive waves by LedaFlow simulation

From the following holdup trend charts, in pipe-2 and pipe-3, there were two consecutive changes in holdup, and different from simulation results in OLGA, only one fluctuation in holdup occurred in pipe-4. The wave velocity of each pipe can be seen in the Table3.13.


01 -two wave
VF - total liquid [Pipe 1 03 (31m)]
VF - total liquid [Pipe 1 04 (71m)]
NOT FOR COMMERCIAL USE
Volume fraction [-]
0.08
0.06
0.04
0.02
0
50
100
150
200
250
300
350
Time [s]


01 -two wave
VF - total liquid [Pipe 1 05 (79m)]
VF - total liquid [Pipe 1 06 (98m)]
NOT FOR COMMERCIAL USE
Volume fraction [-]
0.05
0.04
0.03
0.02
0.01
0
50
100
150
200
250
300
350
Time [s]


01 -two wave
VF - total liquid [Pipe 1 07 (140m)]
VF - total liquid [Pipe 1 08 (290m)]
NOT FOR COMMERCIAL USE
Volume fraction [-]
0.025
0.02
0.015
0.01
0
50
100
150
200
250
300
350
Time [s]

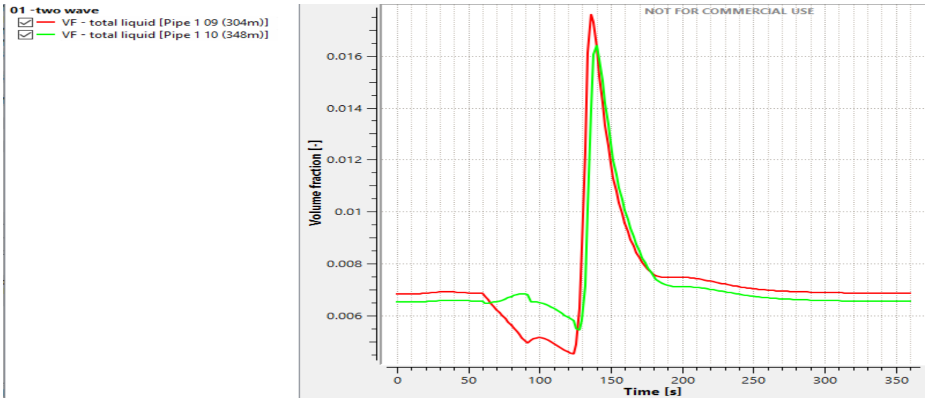


Figure3.51: Holdup trend plots in pipes which have two consecutive waves at inlet, the first one is pipe-2, the second one is pipe-3, the third one is pipe-4 and the last one belongs to pipe-5 by LedaFlow simulation

Table 3.13: wave velocities in different pipes of two waves by LedaFlow simulation

Pipe	Velocity (m/s)
Pipe-2	10.25
Pipe-3	15.55
Pipe-4	12.00
Pipe-5	14.67

From the above table, it found that wave velocities for each pipeline were significantly different from the OLGA simulation results. Although the variation trend of wave velocities was similar, the values in the LedaFlow were only a quarter or one-third of those in the OLGA.

When the first gas choking occurred, wave undoubtedly propagated from pipe-1 to pipe-2. When T=72s (black line), holdup reached a peak in pipe-2. This value was close to 0.08. Through the red line (T=90s), it was not difficult to find that before the gas flow had recovered, the holdup could remain the peak state in pipe-2, but compared with the lowest point, the value of holdup fluctuation slightly decreased.

When T = 92s (blue line), the second gas choking started at the entrance, while only one holdup changes showed in pipe-2, and this value was also decreasing. This trend was exactly the same as the OLGA simulation. However, during the entire process, a wave due to liquid flow and geometric configuration appeared at the junction of pipe-3 and pipe-4, because in the figure below, a small holdup change can be seen.

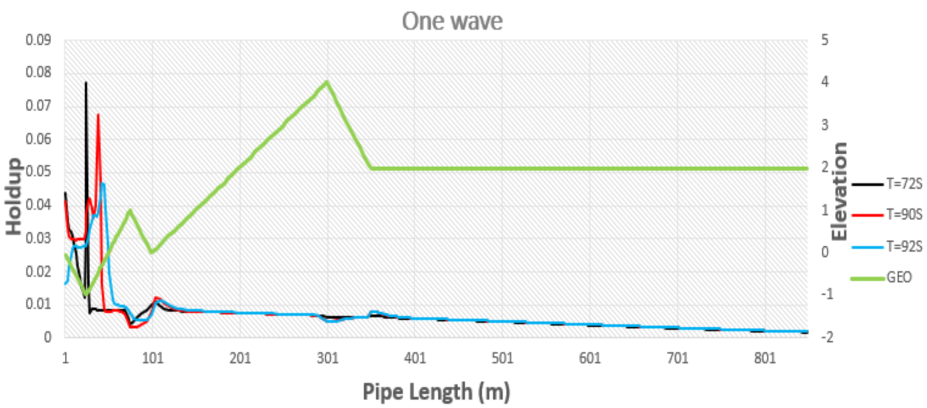


Figure3.52: Holdup profile plot at different time when one wave was in pipeline by LedaFlow simulation

When T=98s (black line), From the following profile plot, there were two holdup fluctuations in the pipeline, one of which occurred between pipe-1 and pipe-2, the holdup value was equal to 0.05, due to liquid accumulation, and the other showed in pipe-2, the value was 0.08, due to the surge wave.

For 20 seconds of propagation, the red line(T=118s) reflected that the two holdup fluctuations have been propagated to pipe-2 and pipe-3, meaning that the changes caused by the first gas choking can be seen in pipe-3, while the second choking caused the highest value of holdup in the pipe -2, it was 0.12.

After 10 seconds, at T = 128s (blue line), the gas flow rate has recovered to 7kg/s. Large gas flow rate drove two surge waves in the pipeline, one was in pipe-2 and the other was in pipe-4. After the acceleration of the pipe-3 (down pipe), when time was 130s, in pipe-4, the wave has merged at the 200 meters, and the holdup value is 0.021(purple line).

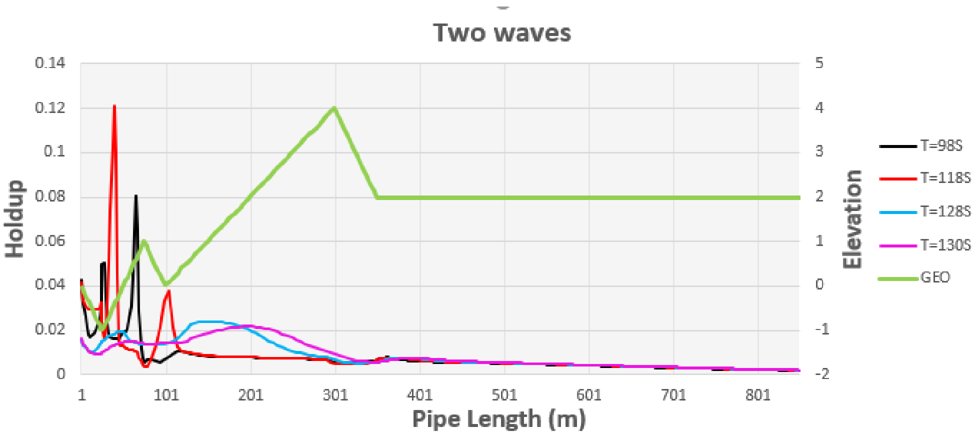


Figure3.53: Holdup profile plot at different time when two waves were in pipeline by LedaFlow simulation

After the two holdup fluctuations merged, the surge wave steadily propagated forward. As can be seen from the profile plot below, unlike the OLGA, the holdup at the entrance remained at around 0.015, and the surge wave lasted longer in the entire pipeline. In OLGA, it took only 4 seconds to make wave spread from pipe-4 to pipe-6. while in the LedAFlow simulation, this time was twice as long as which spent in OLGA. At the same distance, the propagation of waves in LedaFlow took longer, which is why the wave speed in the pipeline is very different in the simulation of the two programs. Until the time was close to 190 seconds (yellow line), the holdup in the pipeline became completely stable.

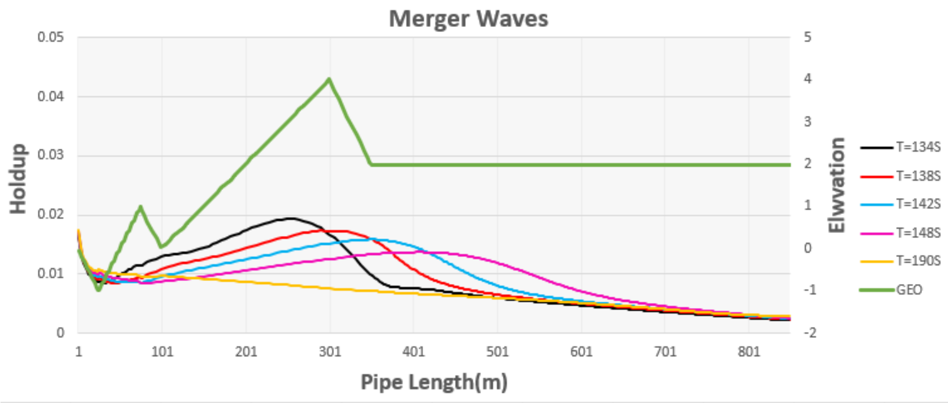


Figure3.54: Holdup profile plot at different time when merger waves were in pipeline by OLGA simulation

As for the holdup trend in the horizontal pipe, there was no big difference between the two software's results. Only at the observation point which was close to the entrance of the horizontal pipeline, the holdup had one slight fluctuations before significant change occurred in LedaFlow, the reason was likely that different calculation model principles were used in the two software.

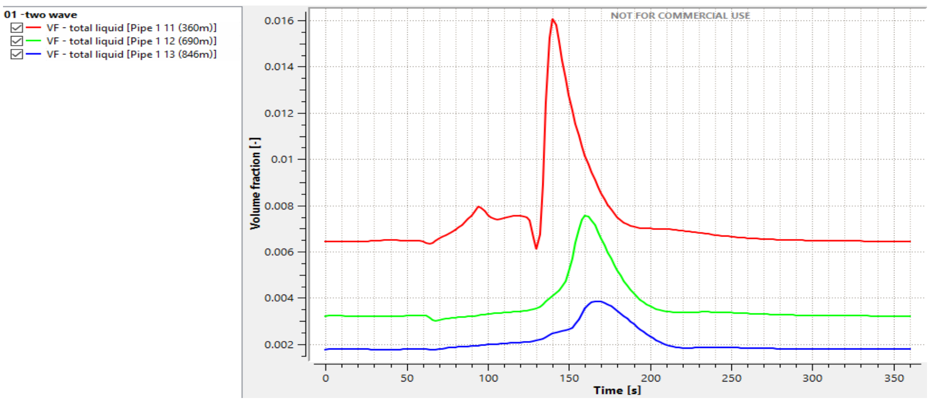


Figure3.55: Holdup trend plot in horizontal pipe when two waves initiated at inlet by LedaFlow simulation

3.3.2.4 Effect of water fraction on surge waves propagation

All previous simulations were conducted in gas-liquid two-phase flow. In this section, the effect of water fraction on the surge wave in three-phase flow (water, oil and gas) was studied. The geometry of the pipeline remained unchanged. The flow path was shown in Figure 4.40. New flow rate data and boundary conditions would be applied. This simulation was only performed in OLGA 2016.2.1.

Two mass resources were still used, one for air, one for liquid, which included the water and oil. The mass ratio of water to oil was set by the option of total water fraction in OLGA. The flow rate data should satisfy the stratified flow in pipeline. Two resources set at the first section of pipe-1, 15 minutes needed to complete to the simulations.

Table 3.14: Flow rate settings and integration time of air and liquid

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	12	2.8
60	12	2.8
61	2	2.8
120	2	2.8
121	12	2.8
Integration		900 (s)

Mesh=3.3D was still used as a calculation grid. The following assumptions and boundary conditions were applied in this simulation:

• Adiabatic model without any temperature calculations and all temperatures were set to 20° C.

•Outlet node pressure boundary set to 10 atm.

•A constant pipeline roughness of 0,05 mm was assumed for the entire pipeline.

•A three-phase PVT-file provided by OLGA2016.2.1

•Max dt = 0.5sec, Min dt = 0,001 sec.

•Slugvoid Sintef.

•HYDSLUG was off

•1 st. order mass equation discretization

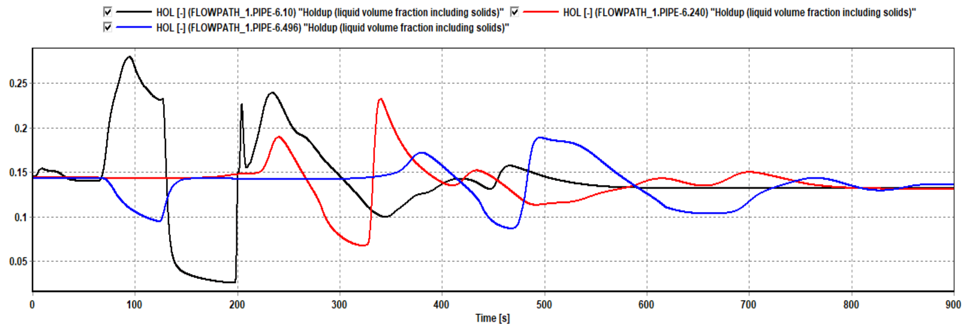
•OLGA Flowmodel

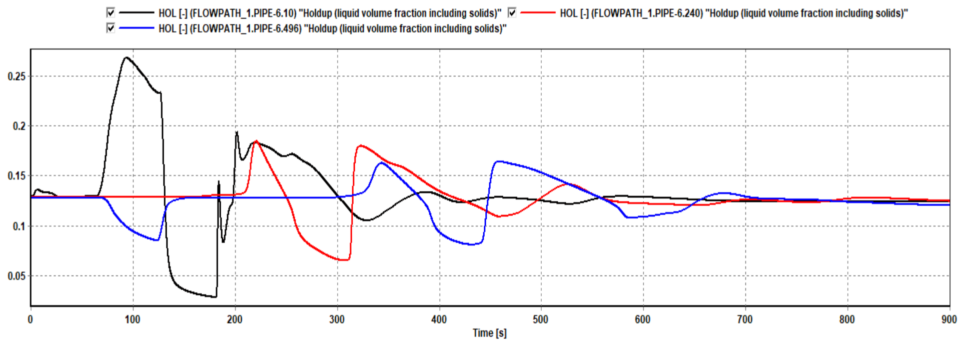
Holdup in horizontal pipe

Although only one wave initiated at the inlet, the setting of the three-phase fluid case brought about a complicated holdup fluctuation in the horizontal pipe. From Figure 4.56, when there was no oil in the pipeline, total water fraction in liquid resource was equal to one, since the three-phase PVT-file was applied to the calculation, so that not only the number of fluctuations in each observation point but also the peak value of holdup, the three-phase flow performed significantly more than two-phase flow.

When increasing the mass content of oil in the pipeline, that is, lowering the value of total water fraction, from 1 to 0, we can find that the addition of oil in the liquid made the holdup's fluctuations more concentrated. For example, when the pipeline showed oil and gas two phases, At the position near the horizontal pipeline entrance (the black line), holdup fluctuations were fierce, from 190 seconds to 245 seconds, holdup fluctuations in the range of 0.12 to 0.3 three times, in fact, the oil-gas two-phase flow had the largest holdup peak among these three cases. While in the water-air two phase flow, from the 200 second to 300 seconds, the holdup fluctuated twice in the interval from 0.14 to 0.24 and was a smoother curve. This was consistent with the results of the surge wave observed in the Midgard and Mikkel-Åsgard B (section 3.4.3). The condensate surge wave occurred earlier than the mixture of water and the MEG wave, but the MEG/water surge wave lasted longer time.

When the three-phase flow appeared in the pipeline, the mass flow rate ratio of oil to water in the liquid was 1 to 1, the effect of oil and water was both reflected in the holdup trend plot. Compared with the two phases of water and gas, the time at which the holdup changes occurred at each observation point moves forward; compared with only two phases of oil and gas, each fluctuation lasted longer. It can be seen from Fig. 4.56 that the surge wave of the water and gas two-phase flow lasted for the entire simulation time, the holdup fluctuation of the oil-gas-water three phases tended to be stable at about 850 seconds, and in the oil and gas two phases, after 600 seconds, no fluctuations have occurred.





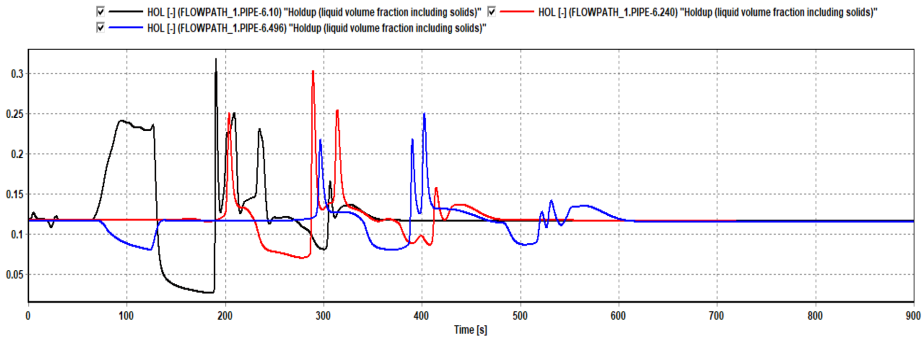


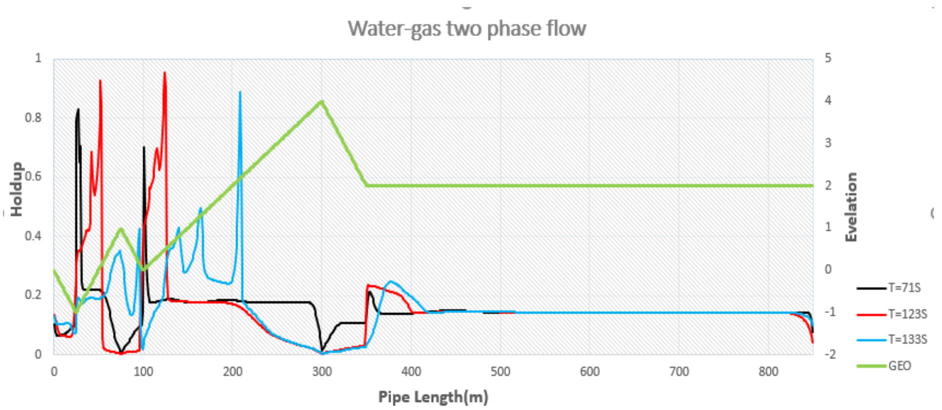
Figure3.56: Holdup trend plots in horizontal pipe, the top is the water-gas two phase flow, the middle one is the water-oil -gas three phase flow, the bottom is the oil-gas two phase flow.

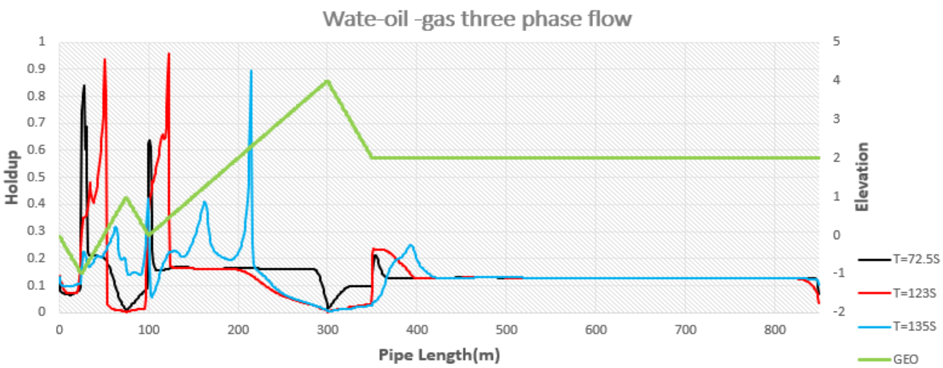
Holdup profile plots

Before the wave entered the horizontal pipe, the holdup profile plots at different times for the three cases were shown in the following figure. Because of the up and down of the pipes, the holdup changes in the three-phase flow model were complicated. First, taking the water and gas flow as an example, at T= 71s, the choked gas rate effected the whole pipeline, three liquid accumulations occurred at the low positions, the holdup values increased obviously, as shown by black line. When the gas flow recovered, the waves move forward, until T = 133 seconds, two waves merged at the junction of pipe-2 and pipe-3, no distance existed between the waves.

The surge wave formation and merger trends were similar among these three cases. The addition of oil made the wave propagation and merger in non-horizontal pipelines delay. The merger of water-oil-gas three-phase flow occurred in 135 seconds, and the surge wave of oil-gas two-phase flow merged in 138 seconds. This is likely to be related to viscosity, the viscosity of the oil is large, and the propagations were slower in non-horizontal pipelines.

However, when the wave merged, in the pipe-4 and pipe-5, the frictional resistance between the oil and the pipe wall was smaller than that of between water and pipe wall, so that the fluid containing the oil entered the horizontal pipeline earlier.





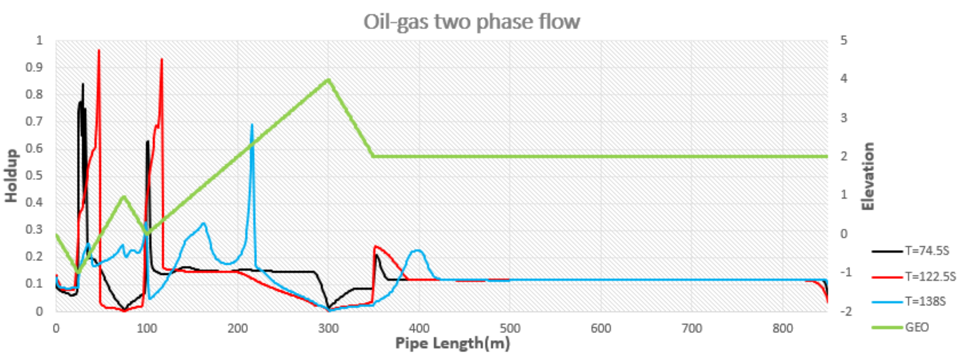


Figure3.57: Holdup profile plots in the pipeline, the top is the water-gas two phase flow, the middle one is the water-oil -gas three phase flows, the bottom is the oil-gas two phase flow.

4. Field case study by OLGA

From the previous simulations, we found that the OLGA performed well for surge wave numerical simulation. It could not only prove the presence of the surge wave by the holdup trend plots, but also simulate the merger of surge waves in large-scale and long-distance pipelines. Now in this part, it will analyze a field case and focus on the influence of flow rate changes on fluid propagation. If the flow rate decreases to a certain value, there will be unstable flow which is the surge wave at the end of the pipeline. This is also an evaluation of OLGA, as a commercial software, in actual working conditions.

4.1 Geometry of pipeline

In field conditions, the geometry of the pipeline is not independent of the terrain. Whether it is sub-sea or land, the ups and downs of the terrain are common, the differences are in the slope size.

In the given case, the diameters of the pipe were from 0.42 meters to 0.47 meters and there are more than 35,000 meters of undulating pipes with small inclination angles before the obvious low spot. After a riser pipe, a horizontal pipe with a length of 150 meters was connected, and all observation points were set on the horizontal pipe. As shown in the figures below, when the gas flow decreases, the liquid would accumulate at the dips. According to previous studies, liquid accumulation is an important factor in the occurrence of surge waves.

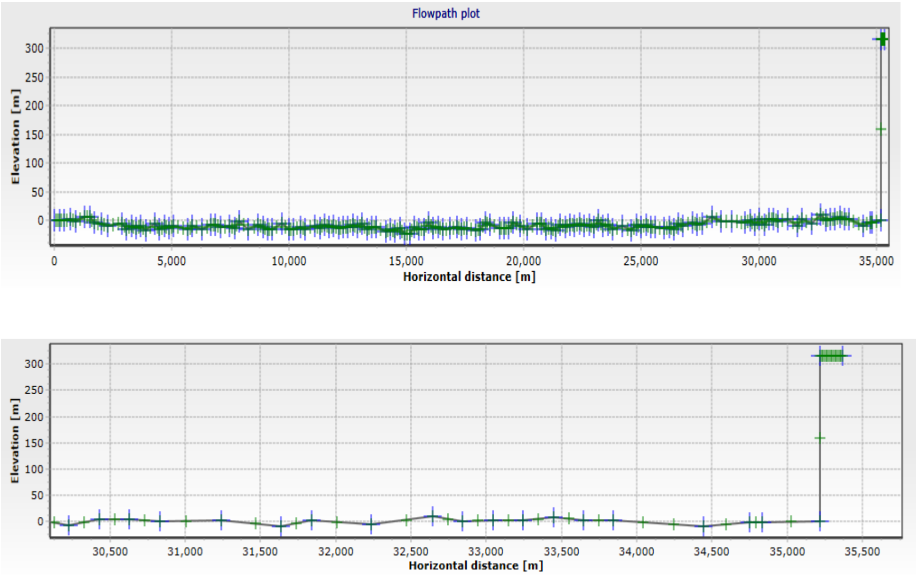


Figure4.1: Flow path plot of the real case, the first one is for the whole pipeline, the second one is a detailed view of the low-lying and horizontal pipe.

One mass resource which contained water, oil, and gas was used. Boundary conditions have been set by the original file, for mass equation, it chose the first order, for flow model, it chose the OLGA model and interfacial friction used the default value.

Mesh=2.37D (1 meter) was still applied as a calculation grid for the horizontal pipe, the section 20, 70 and 149 as observation points, respectively 20, 70 and 149 meters from the entrance of the horizontal pipeline and a fluid PVT file has been included in the case.

4.2 Field case study

In order to clearly observe the propagation of the surge wave, selecting 24 hours as the time for each simulation, fluid flow rate settings are shown in the following table. Throughout the simulation time, the flow rate in each case remained constant.

Table4.1: Flow rate settings for field case study

Case name	Flow rate (kg/s)
Case a	70
Case b	44.4246
Case c	30
Case d	22
Case e	10
Case f	5

For all flow rates, in the horizontal pipeline, the flow regime of the stratified flow can be maintained, as shown in Figure 4.2, and the surge wave also belongs to the stratified flow. Obvious differences of different flow rates can be seen in the holdup trend plots.

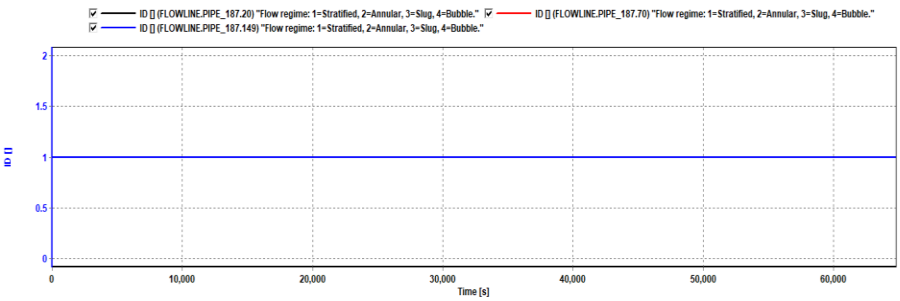


Figure4.2: Flow regime in horizontal pipe of all flow rates

Fig. 4.3 and Fig. 4.4 correspond to the plots of holdup over time from Case a to Case b. When the flow rate was large, the holdup fluctuations in the horizontal pipeline were subtle. When the flow rate was equal to 70 kg/s, the holdup variation range was from 0.046 to 0,054. When the flow rate dropped to the default value of case, 44.4246 kg/s, the holdup changed slightly within 24 hours from 0.048 to 0.066. But all changes are not dramatic, which means the flowing under these flow rates were stable. So, when the flow is greater, the fluid flow is more stable at the end of the entire pipe.

At the position near the horizontal pipe entrance, the value of holdup was the smallest, the black line was at the bottom of the figures. This is because the slope of the riser pipe before the horizontal pipe was very large, resulting in less liquid entering the horizontal pipe at the beginning.

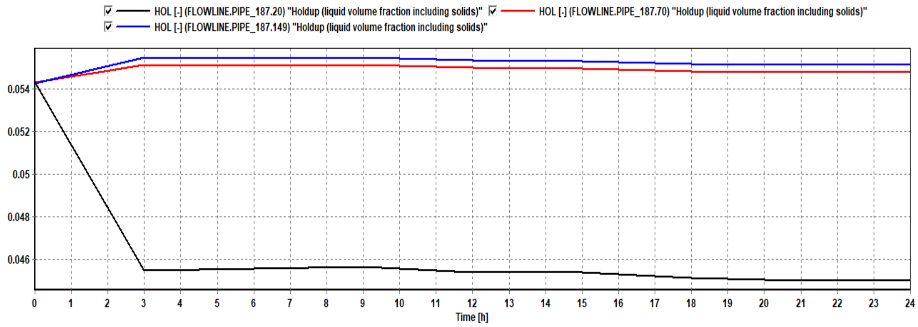


Figure4.3: Holdup trend plot of horizontal pipe when flow rate is 70kg/s

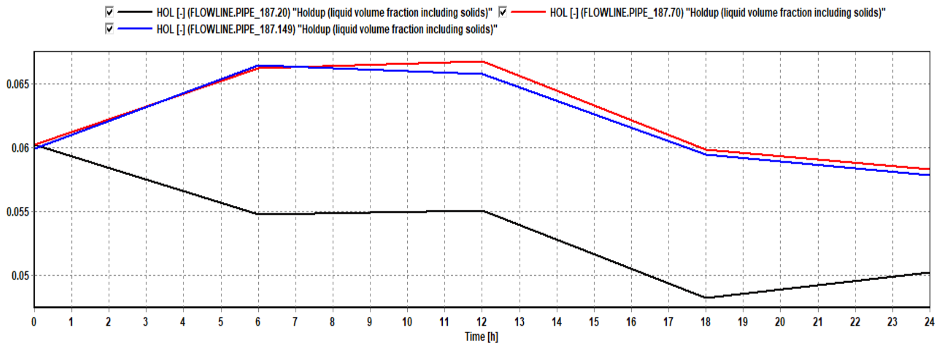


Figure4.4: Holdup trend plot of horizontal pipe when flow rate is 44.4246kg/s

When the initial flow rate in the pipeline started to decrease gradually, the apparent fluctuation of holdup began to appear in the horizontal pipeline. Figure 4.5 shows the change of holdup when the flow rate was equal to 30kg/s. A significant fluctuation occurred, with the maximum peak value reaching 0.095 and the entire fluctuation duration lasting nearly 8 hours. According to the previous research and the propagation characteristics of the surge wave, it can be shown that at this flow rate, the surge wave propagated in the horizontal pipeline. When the flow rate further decreased to 22 kg/s, as shown in Figure 4.6, both the wave peak value of the surge wave and the duration time increased, indicating that the smaller the flow rate, the more likely the unstable flow occurs in the pipeline.

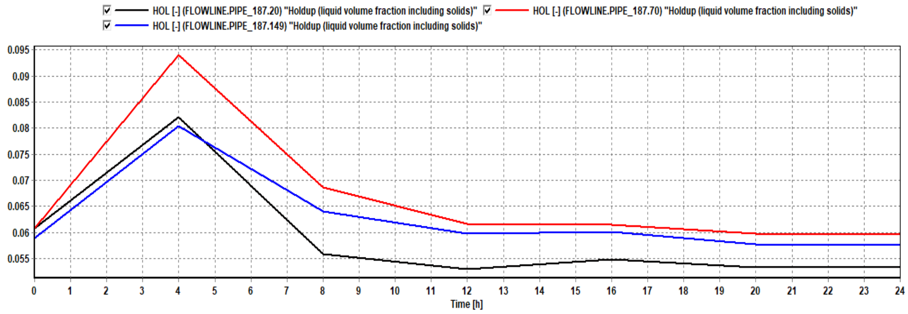


Figure4.5: Holdup trend plot of horizontal pipe when flow rate is 30kg/s

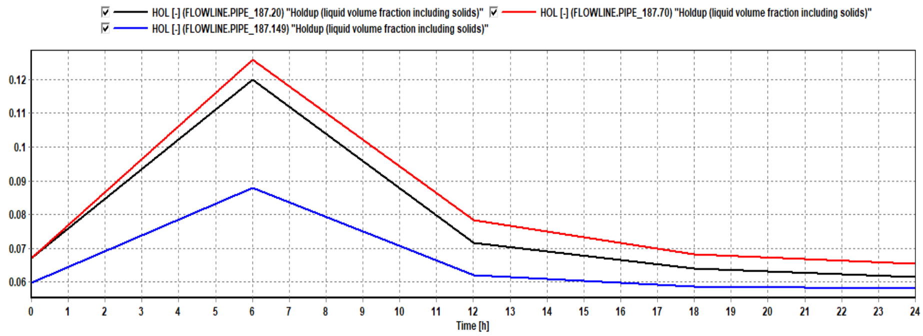


Figure4.6: Holdup trend plot of horizontal pipe when flow rate is 22kg/s

At smaller flow rates, changes in holdup became more complex. At a flow rate of 10 kg/s (Fig. 4.7), more than one change occurred at each observation point. This is a result of a combination of fluid flow and pipe geometry settings. This also proves that unstable flow was more pronounced, and the propagation of surge waves was more obvious. When the flow rate equaled 5 kg/s (Fig. 4.8), the flow in the pipeline did not stabilize until the end of the simulation time. Another significant feature is that the peak has a plateau period. From the 9th hour to the 13th hour, the holdup values of all observation points in the pipeline were kept at their respective peak values. It may be due to the appearance of the plateau period that the surge wave peak value with a flow rate equal to 5 kg/s was smaller than the peak wave value with a flow rate of 10 kg/s.

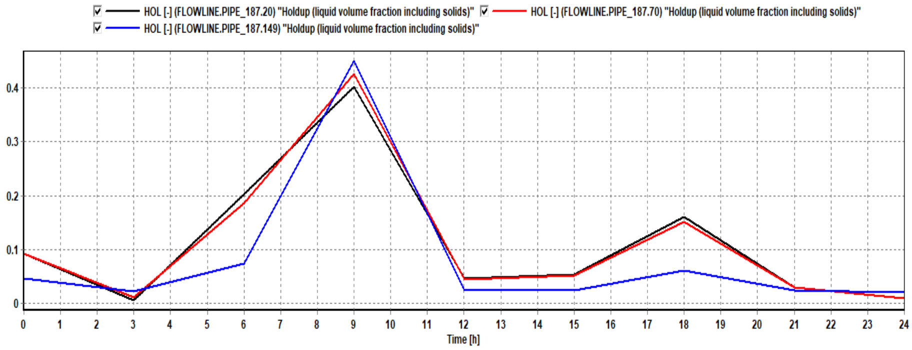


Figure4.7: Holdup trend plot of horizontal pipe when flow rate is 10kg/s.

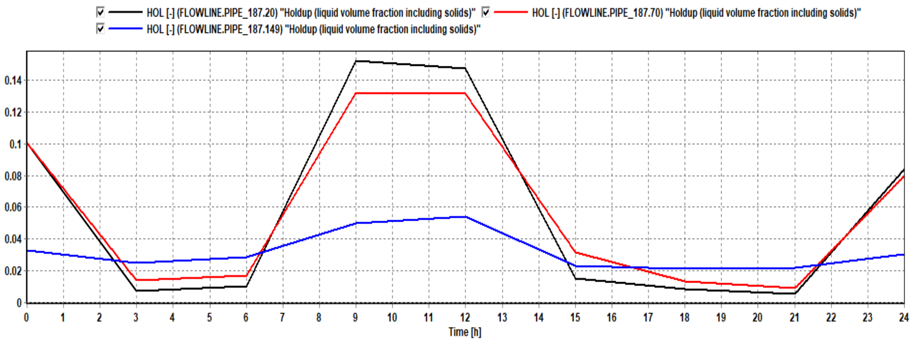


Figure4.8: Holdup trend plot of horizontal pipe when flow rate is 5kg/s.

In the field case study, using the OLGA software, it can be seen that with the decrease of the fluid flow rate, the surge wave starts to appear at the end of the pipe, the flow regime of the fluid is stratified flow, there is a significant change in the holdup, and continuing for a long time. Although compared with the previous simulation study, the curves were changed to straight lines, but this does not affect the judgment of surge wave propagation.

Therefore, in gas field production, it is possible to use software to predict when the surge wave reaches the receiving device under the production rate became small, thereby reducing the impact of unstable conditions on the operation of the devices.

5. Conclusion

OLGA 2016.2.1 and LedaFlow Engineering v2.3.254.029 have replicated the previous experimental conditions. The low spot of the pipeline formed the liquid accumulation when the gas flow decreased. When the gas flow rate ramped up again, the accumulated liquid would be swept into the horizontal pipe, causing the holdup value increased, although the holdup's volatility decreased as the pipe distance increased, but this fluctuation lasted longer. The time for the change in gas flow was 10 seconds, but the fluctuation in holdup lasted 100 seconds or longer. These performances were consistent with the propagation of surge waves in gas-condensate flowlines.

For OLGA software, the points near the entrance to the horizontal pipeline had performances which were close to the experimental results, after passing the half length of horizontal pipeline, the fluctuations of the holdup were no longer obvious. When the smallest Usg was used, the flow regime of slug flow also appeared for one second in OLGA. In general, the OLGA simulated wave peaks and wave speeds are less than the experimental results, but compared with LedaFlow, OLGA had a more stable simulation performance. For LedaFlow, only two cases had good agreements with lab results. Slug capturing was used in all cases, but there was no advantage. Therefore, OLGA is more suitable than LedaFlow in predicting the surge wave in small-diameter and short-distance pipelines.

In the gas-condensate filed, the geometries of the pipeline are more complex, which also affect the changes in the holdup and the propagation of the surge wave. Therefore, large-diameter, long-distance pipes were introduced for simulation.

In the up and down pipes, if the wave speeds of the ascending and descending pipes are the same, the holdup cannot be changed, and there will be no surge wave, so the wave speed is an important judgment factor. When there was only one initial wave at the entrance, the wave velocities of the up and down pipes are found to be different by calculation. The low spot of the undulating pipe was easy to reach the peak of the holdup, and the surge waves were observed in the horizontal pipe, but no merger of the waves.

When there were two waves at the entrance, the second wave after passed the down pipe could catch up with the first wave because of gravity acceleration, so the merger of the two waves could be observed before entering the horizontal pipeline. That is to say, in actual productions, the surge waves were generated because of the change of the flow rate and the irregular geometry pipes. In the propagation process, the waves of different flow speeds would be combined, so that the entire surge wave lasts longer. In the simulations of surge wave propagation, OLGA and LedaFlow have similar performances, except that the wave had a longer propagation time in the Ledaflow.

The simulation of the three-phase fluid was considered in this paper. In OLGA, the 3-phase PVT file was used to calculate the change of holdup. In the holdup trend plots, it can be found that the two phases of oil and gas fluctuated significantly earlier than the two phases of water and gas and the three phases of oil, gas and water. In three phase flow, the greater the water content, the longer the span of the surge wave.

In the simulation of the field data, OLGA was evaluated, as a commercial software, by adjusting the flow rate, it showed the capability of surge wave simulation and prediction. The decrease of the flow rate caused the horizontal pipeline generate surge waves, and the duration was relatively long. Therefore, in the field production, the operating conditions of the receiving equipment may be adjusted according to the simulation results.

Through a series of numerical simulations on surge waves, it can be found that both OLGA and LedaFlow are suitable for large diameter, long-distance pipeline simulations. For OLGA, the first-order mass calculation and OLGA fluid model can be widely used, and usually it is not necessary to set the tuning in the interfacial friction. For the

LedaFlow, when the calculation grid is set, it needs a larger value, higher order discretization is also not often used.

6. Suggestions for further work

In the propagation of surge waves, it could be observed that the merger of the waves in the pipeline required the setting of two initial waves, and that the wave speeds of the waves propagating in the pipeline were very fast, and the wave combination completed in a few seconds. Therefore, in the future research, the number of initial waves at the entrance can be increased, and the geometric configuration and flow rate of the gas can be adjusted, so that the wave speeds can be decreased, and the wave merger and propagation can be better observed.

On the other hand, the three-phase fluid surge waves that are closer to the field conditions can be designed to observe whether there will be two different surge waves, one is the condensate surge wave and the other is the MEG/water surge wave.

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Appendix

In the appendix, it mainly shows simulations results of eight experiment cases by different software. For OLGA, it includes OLGA 7.3.5, (provided by NTNU in 2017) and OLGA 2016.2.1 (provided by NTNU in 2018). In the OLGA2016.2.1 flow model, the OLGA model and the OLGA HD model were used to complete the simulation. LedaFlow Engineering v2.3.254.029 simulated the experimental data as the latest updated LedaFlow software. All results mainly show two parts, including flow regimes and holdup trend plots. A table was used to describe the flow rate change and simulation time. Experiment plots are also shown, in order to see the development of the wave along the pipeline, the holdup trend plots have been smoothed with the Matlab function yy = smooth (y,0.01, 'moving').

Case 1: Usg = 13.4 m/s, Usl = 0.0113 m/s

Usg = 13.4 m/s means that the initial gas flow is 0.045 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s. Table A1 shows the details of the flow rate. Figures A1 and A2 show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A3-A6, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A7 and A8. The result plot of the previous experiment is in Figure A9.

Table A1: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.045	0.032
10	0.045	0.032
11	0.013	0.032
22	0.013	0.032
23	0.045	0.032
Integration		120 (s)

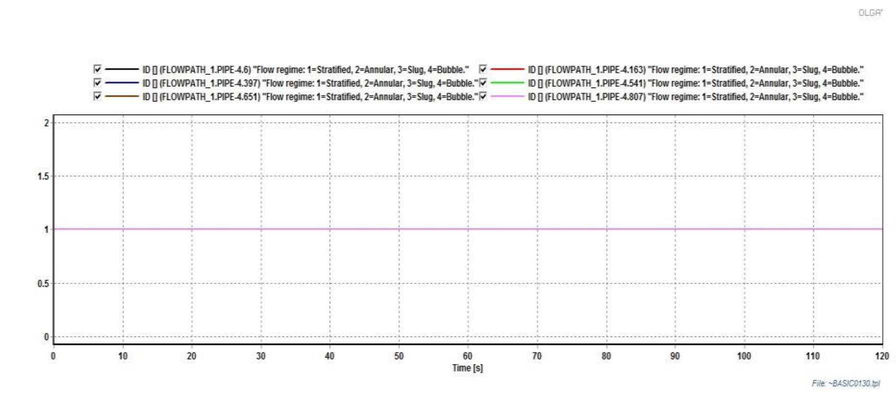

Figure A1: OLGA7.3.5 flow regime ID trend plot

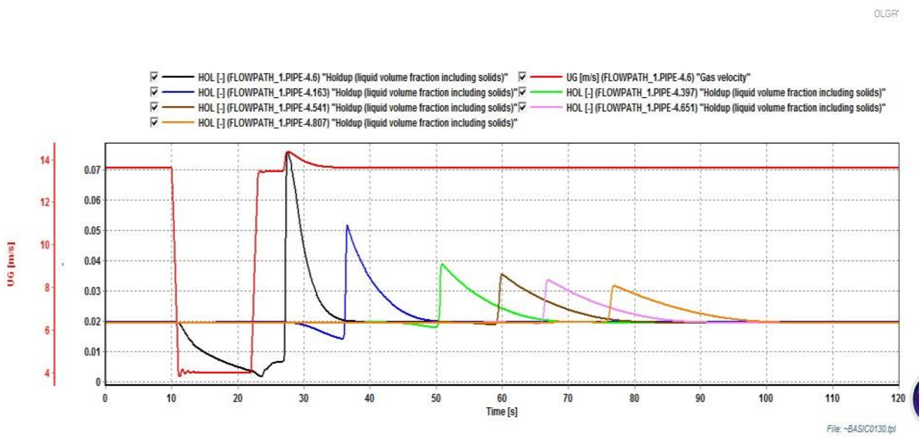

Figure A2: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

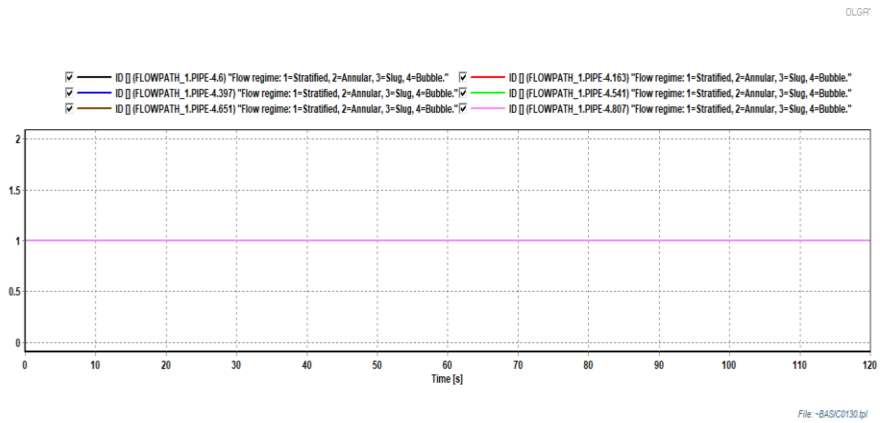

Figure A3: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

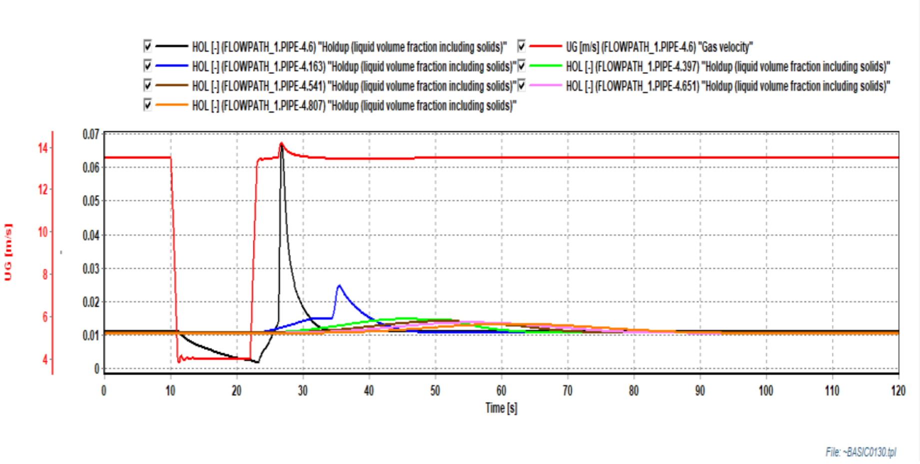

Figure A4: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

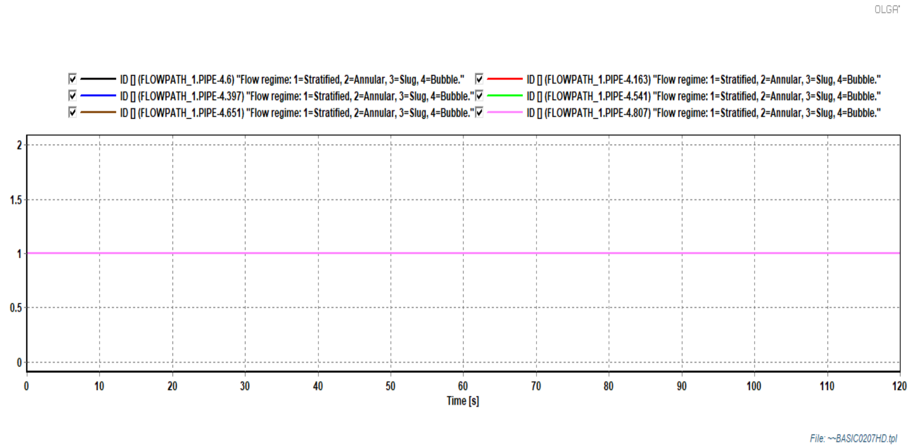

Figure A5: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

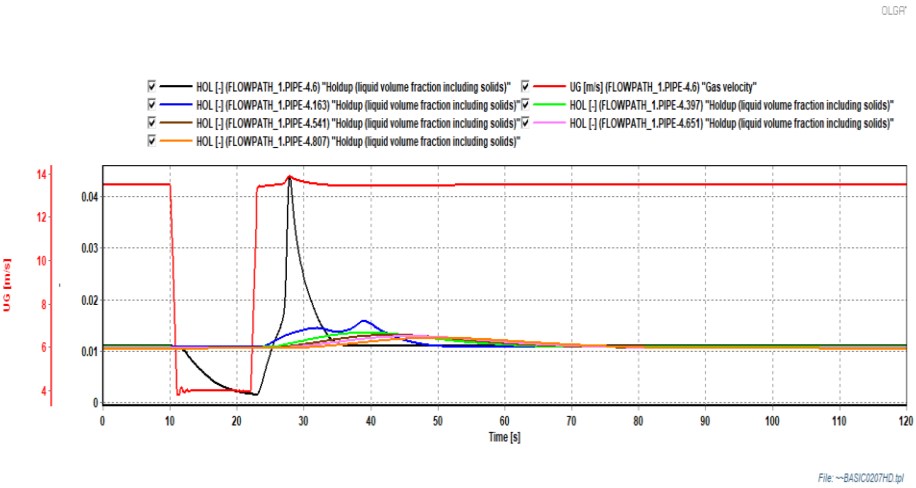

Figure A6: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

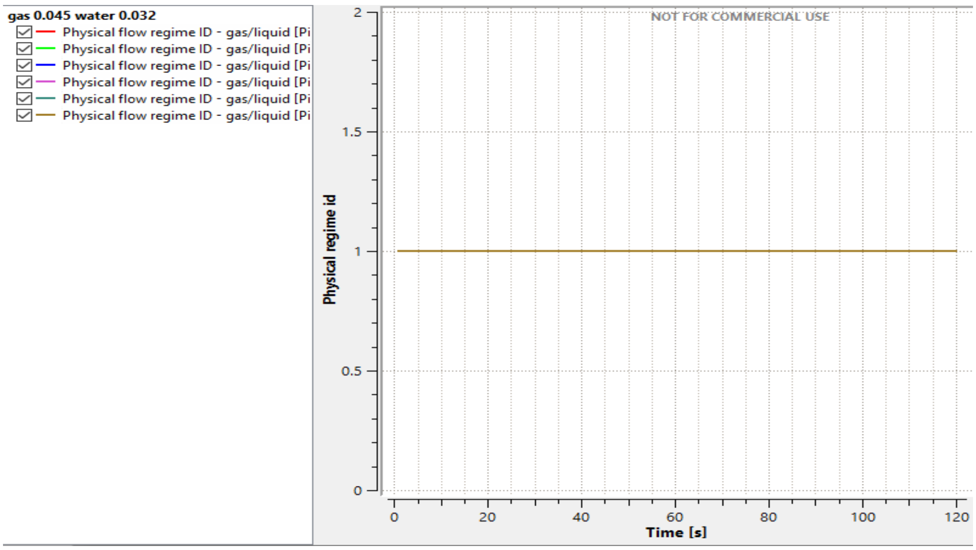

Figure A7: LedaFlow flow regime ID trend plot

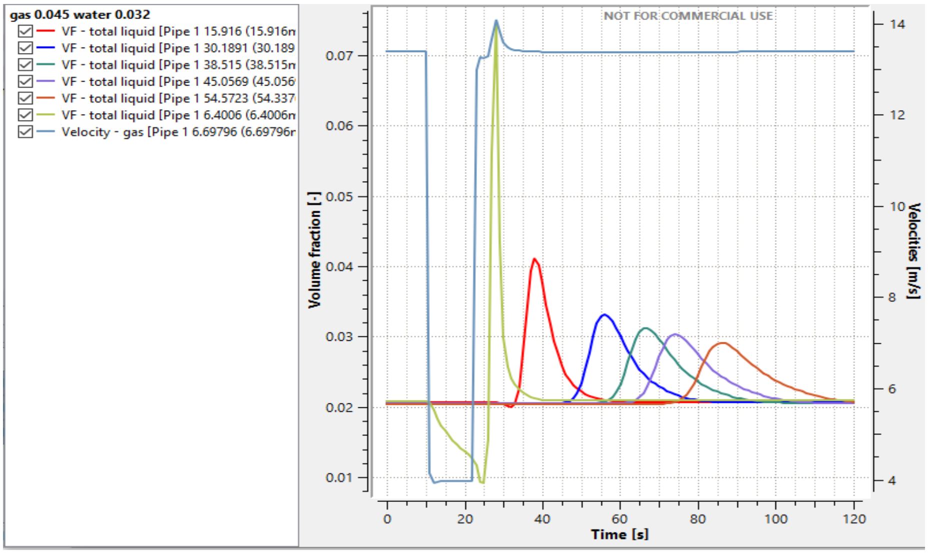

Figure A8: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

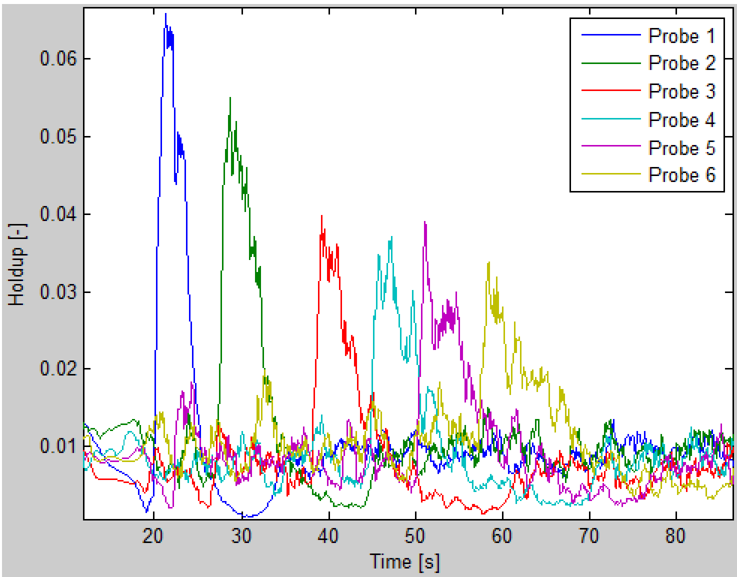

Figure A9: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.85]

Case 2: Usg = 10.9 m/s, Usl = 0.0113 m/s

Usg = 10.9 m/s means that the initial gas flow is 0.037 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s. Table A2 shows the details of the flow rate. Figures A10 and A11show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A12-A15, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A16 and A17. The result plot of the previous experiment is in Figure A18.

Table A2: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.037	0.032
10	0.037	0.032
11	0.013	0.032
22	0.013	0.032
23	0.037	0.032
Integration		120 (s)

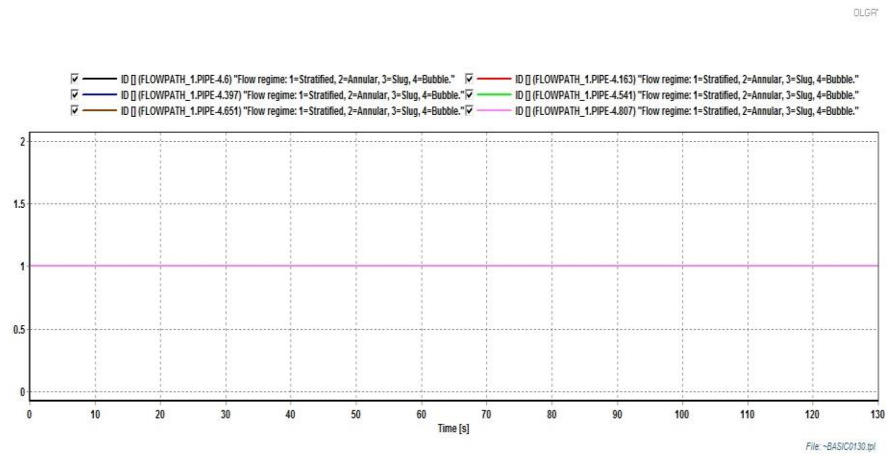

Figure A10: OLGA7.3.5 flow regime ID trend plot

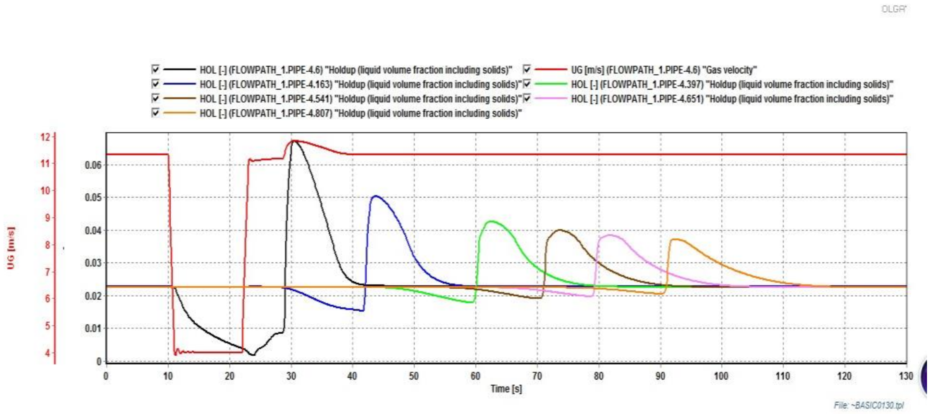

Figure A11: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

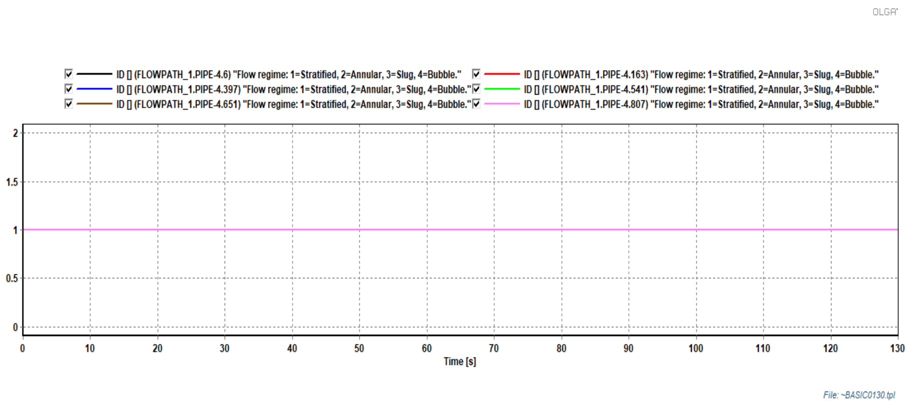

Figure A12: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

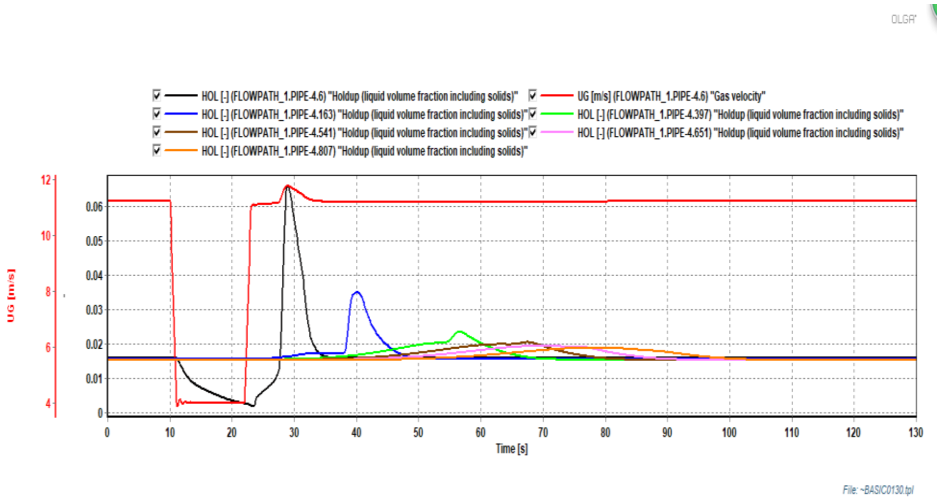

Figure A13: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

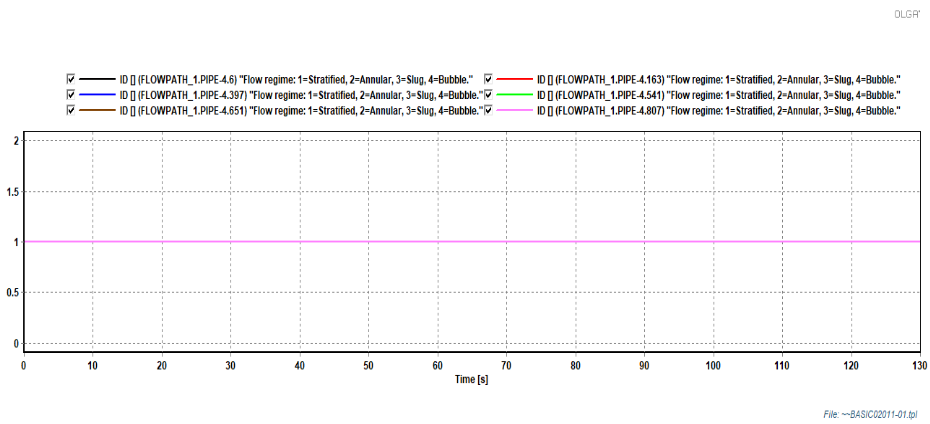

Figure A14: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

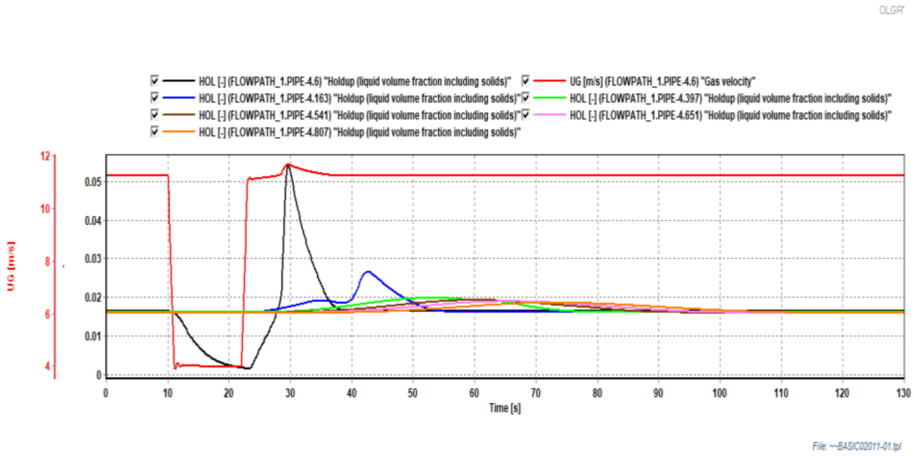

Figure A15: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

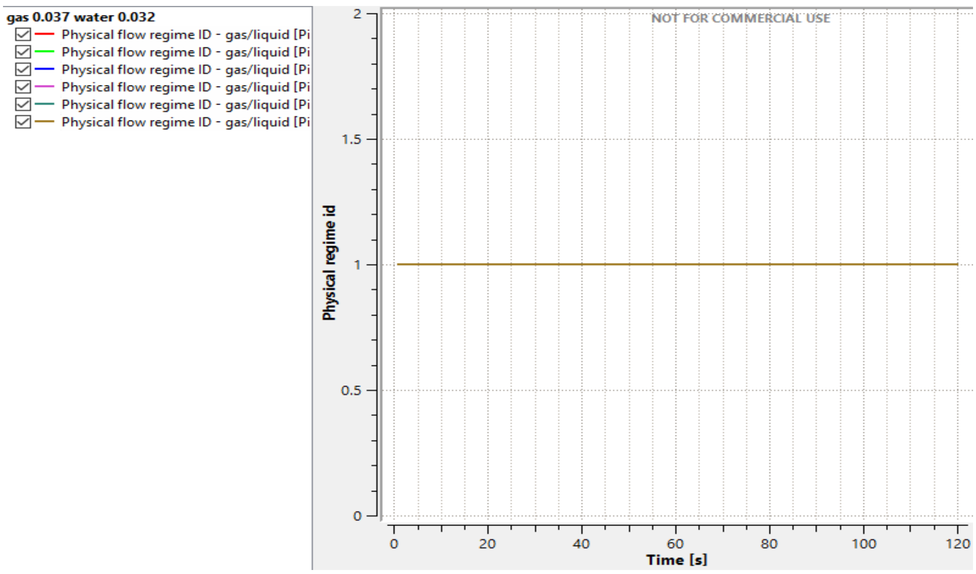

Figure A16: LedaFlow flow regime ID trend plot

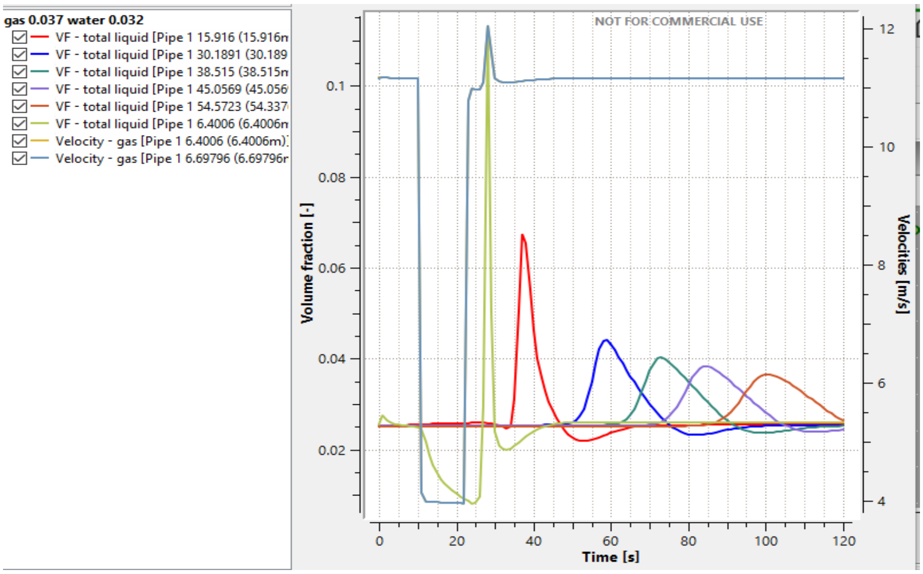

Figure A17: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

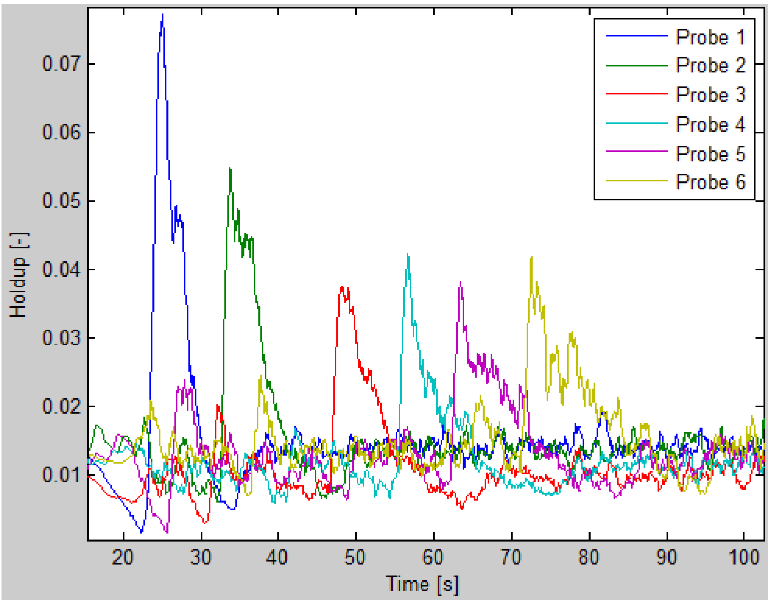

Figure A18: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.89]

Case3: Usg = 8.5 m/s, Usl = 0.0113 m/s

Usg = 8.5m/s means that the initial gas flow is 0.029 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s. Table A3 shows the details of the flow rate. Figures A19 and A20 show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A21-A24, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A25 and A26. The result plot of the previous experiment is in Figure A27.

Table A3: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.029	0.032
10	0.029	0.032
11	0.013	0.032
22	0.013	0.032
23	0.029	0.032
Integration		220 (s)

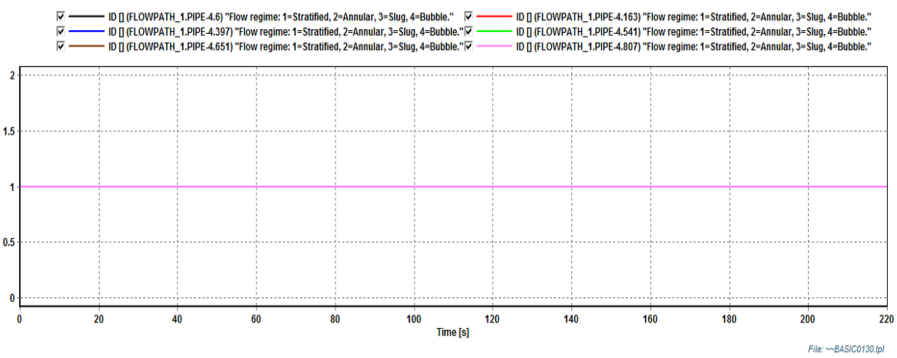

Figure A19: OLGA7.3.5 flow regime ID trend plot

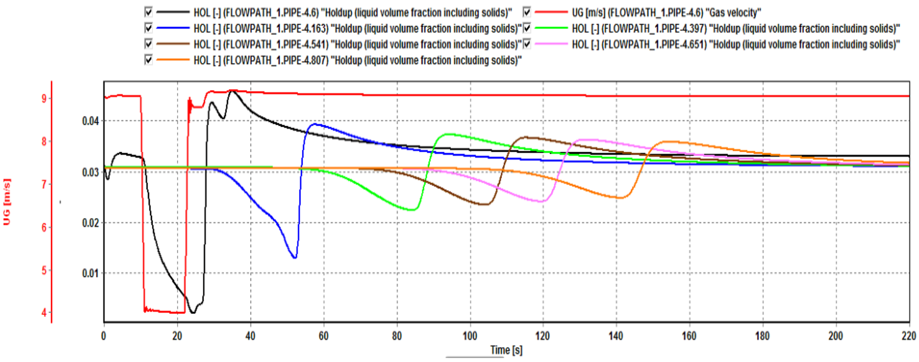

Figure A20: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

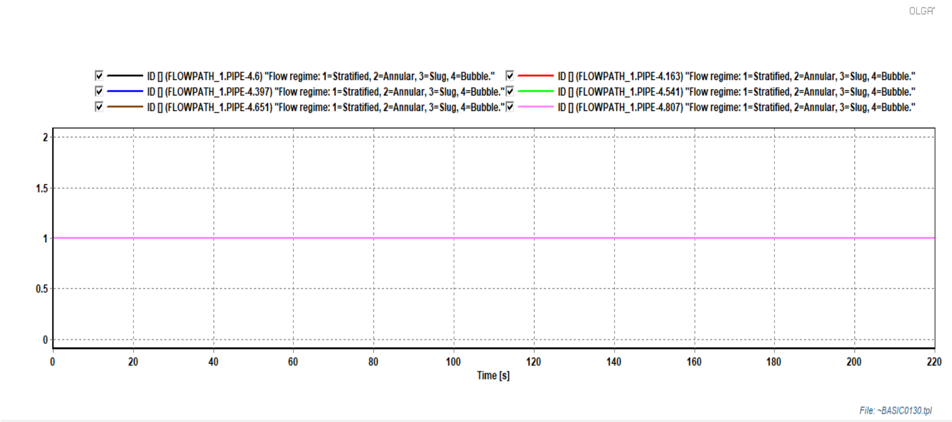

Figure A21: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

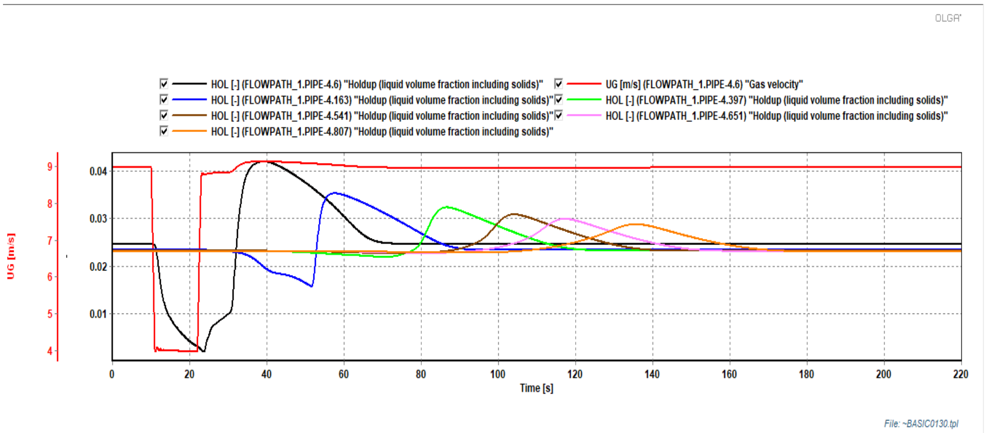

Figure A22: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

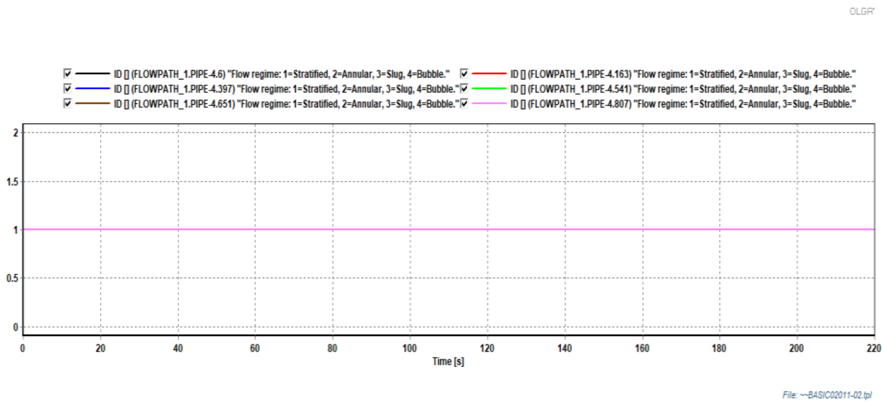

Figure A23: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

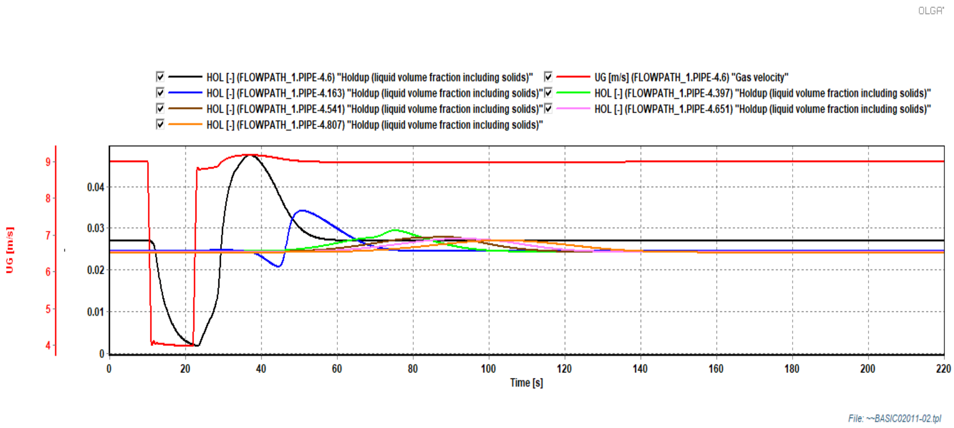

Figure A24: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

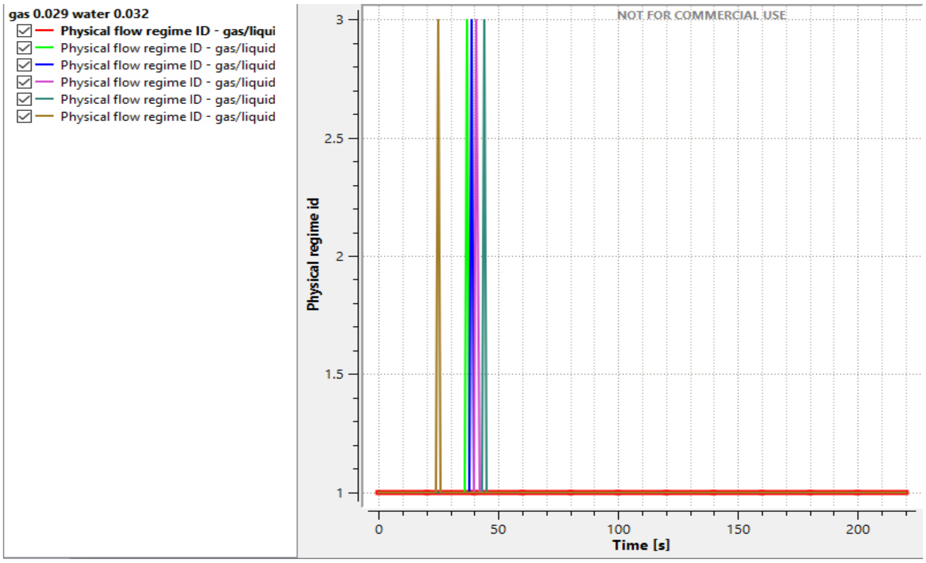

Figure A25: LedaFlow flow regime ID trend plot

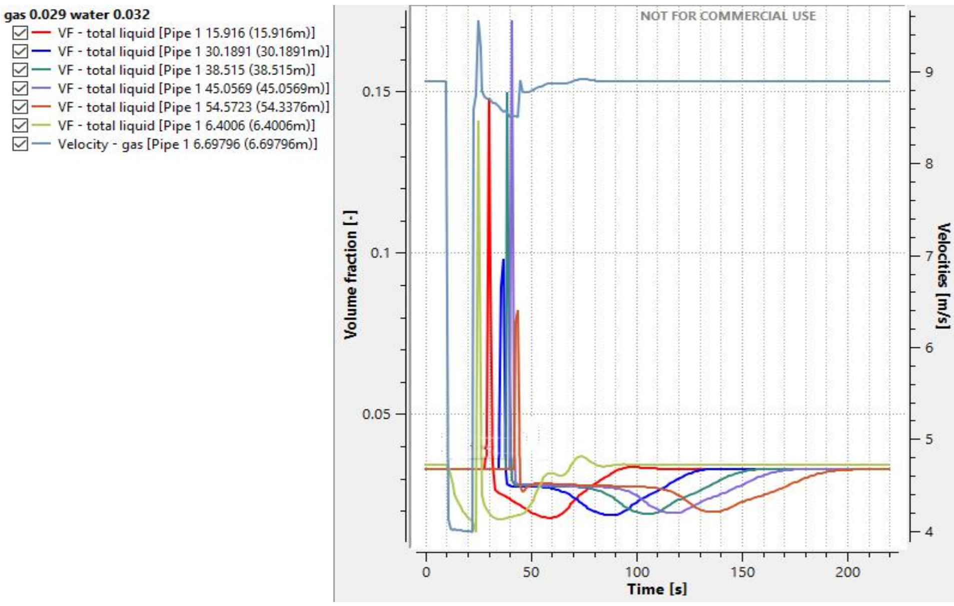

Figure A26: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

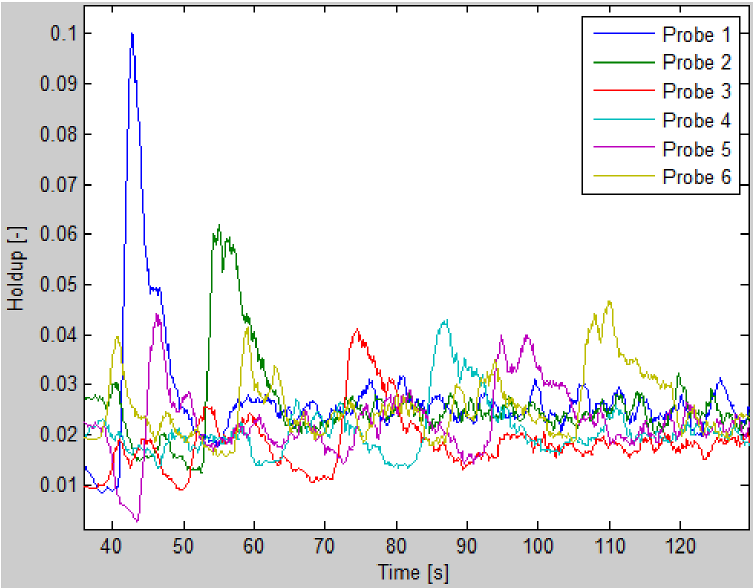

Figure A18: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.93]

Case4: Usg = 7.6 m/s, Usl = 0.0113 m/s

Usg = 7.6m/s means that the initial gas flow is 0.026 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s. Table A4 shows the details of the flow rate. Figures A28 and A29 show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A30-A33, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A34 and A35. The result plot of the previous experiment is in Figure A36.

Table A4: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.026	0.032
10	0.026	0.032

11	0.013	0.032
22	0.013	0.032
23	0.026	0.032
Integration		240 (s)

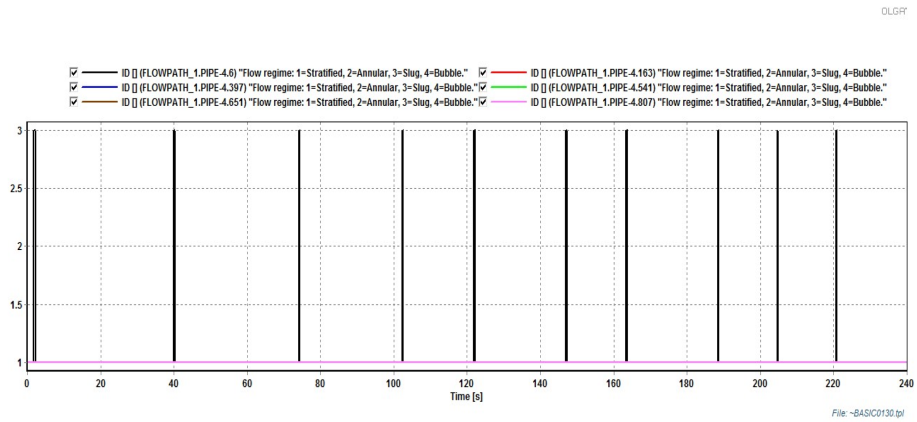

Figure A28: OLGA7.3.5 flow regime ID trend plot

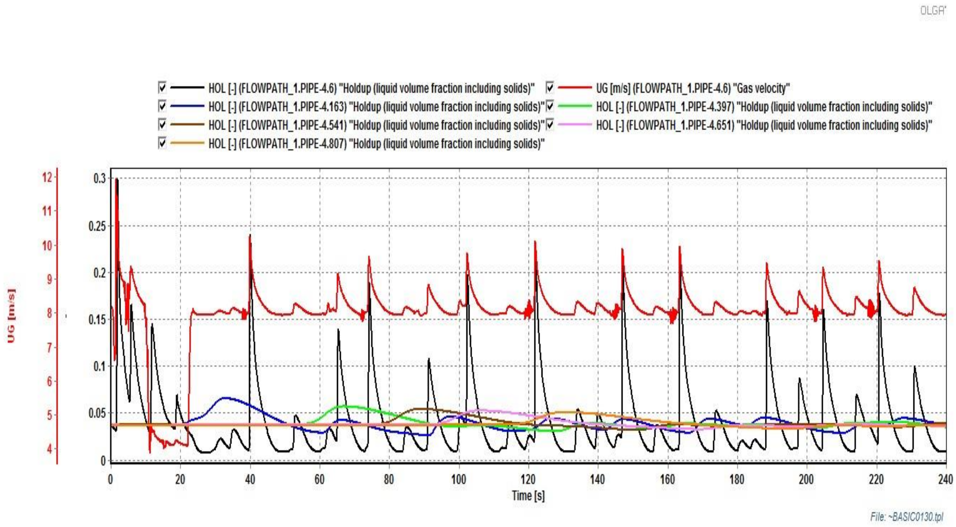

Figure A29: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

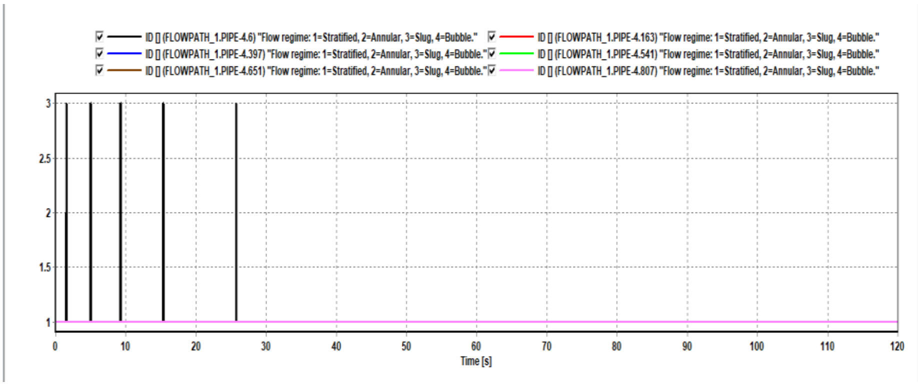

Figure A30: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

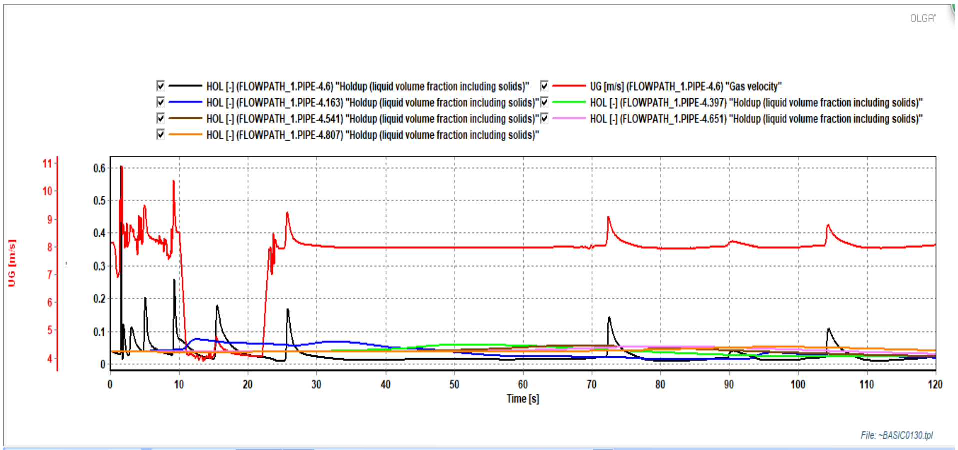

Figure A31: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

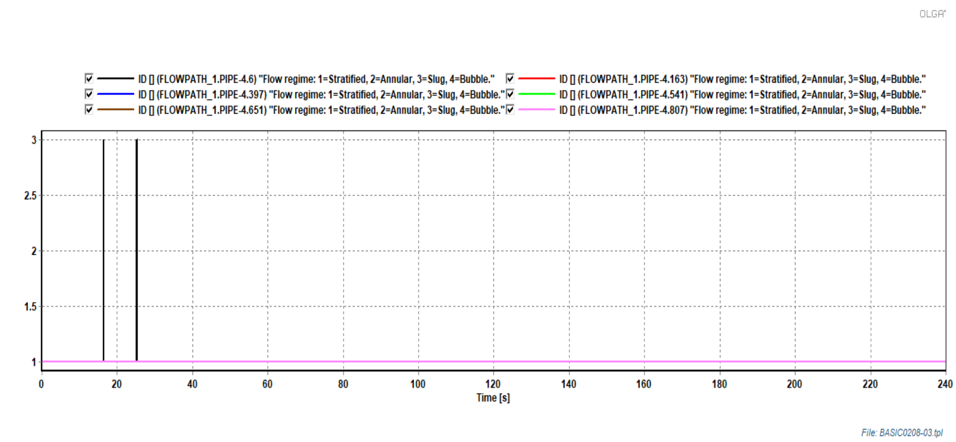

Figure A32: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

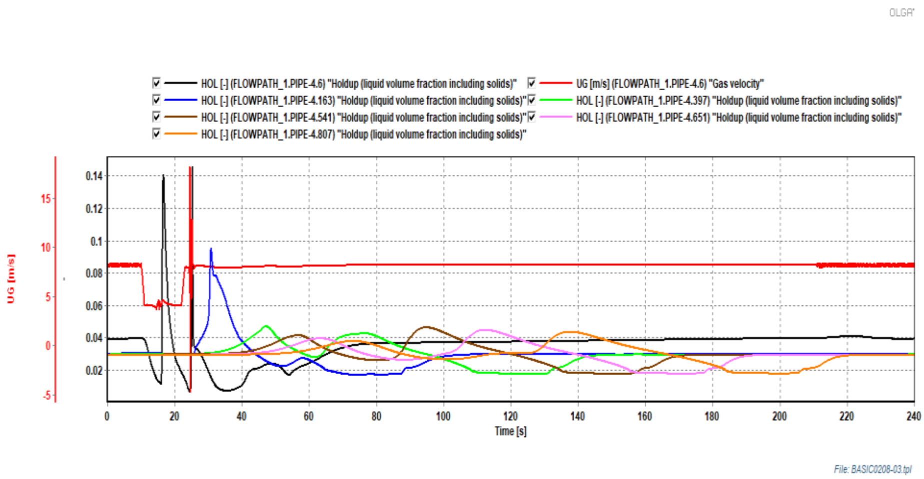

Figure A33: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

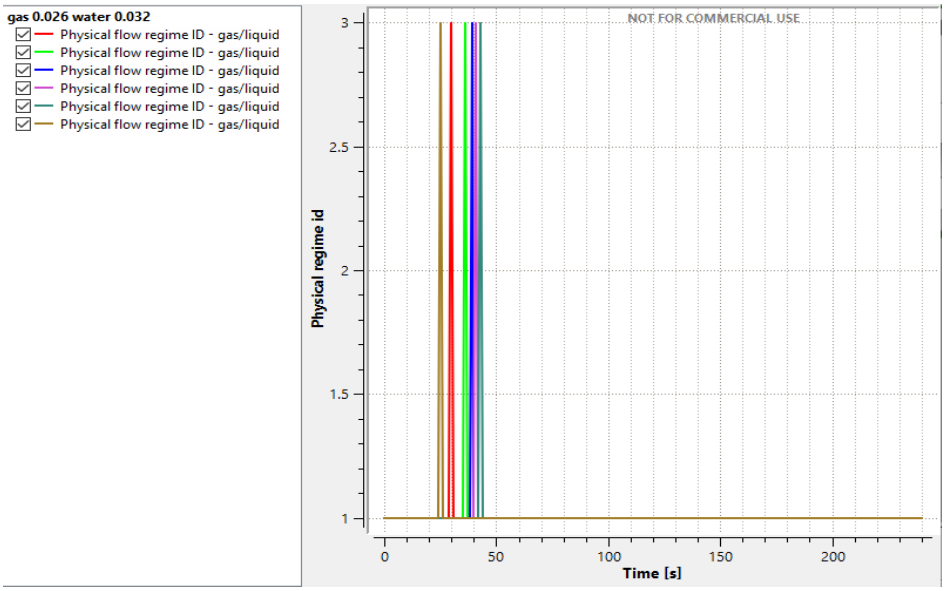

Figure A34: LedaFlow flow regime ID trend plot

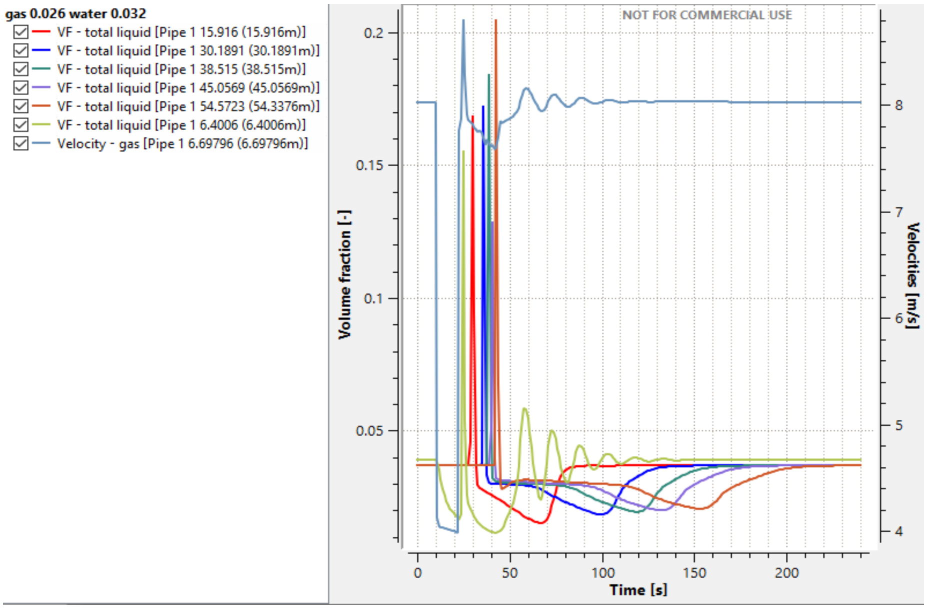

Figure A35: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

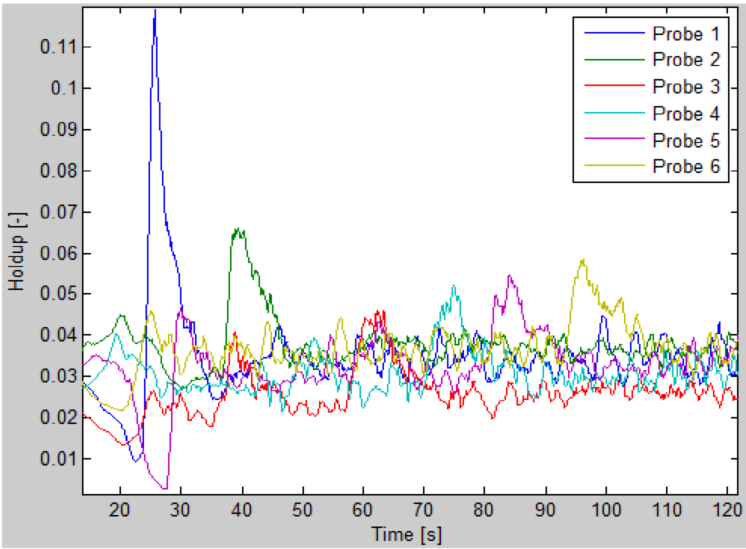

Figure A18: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.97]

Case5: Usg = 13.4 m/s, Usl = 0.0264m/s

Usg = 13.4m/s means that the initial gas flow is 0.045 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s, the water rate increases to 0.075kg/s. Table A5 shows the details of the flow rate. Figures A37 and A38 show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A39-A42, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A43and A44. The result plot of the previous experiment is in Figure A45.

Table A5: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.045	0.075
10	0.045	0.075
11	0.013	0.075
22	0.013	0.075
23	0.045	0.075
Integration		100 (s)

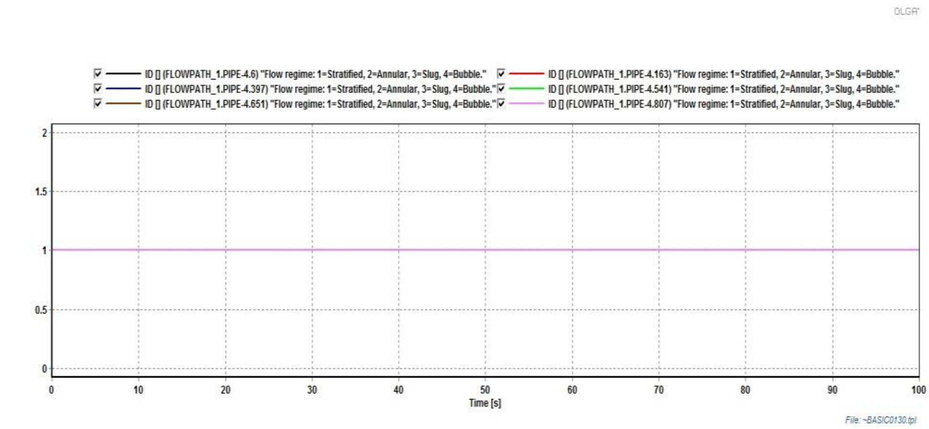

Figure A37: OLGA7.3.5 flow regime ID trend plot

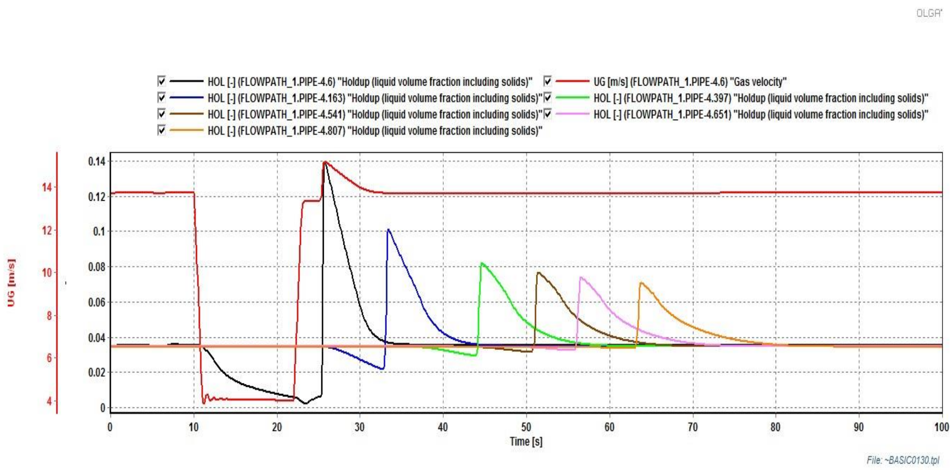

Figure A38: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

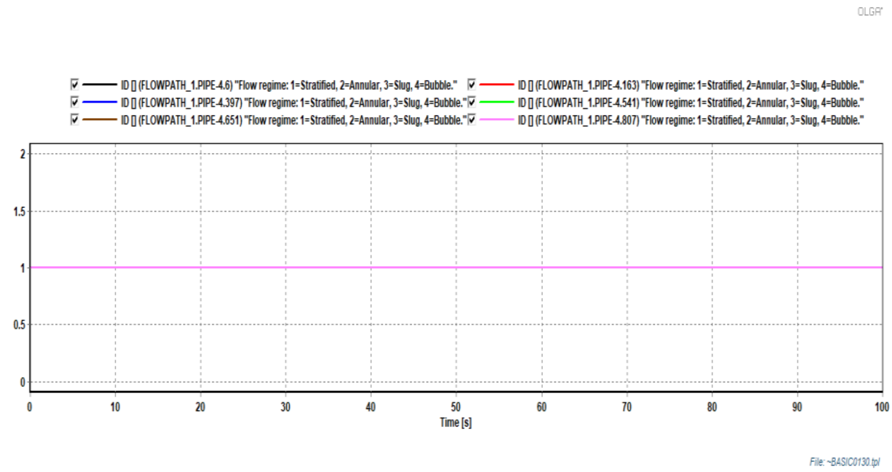

Figure A39: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

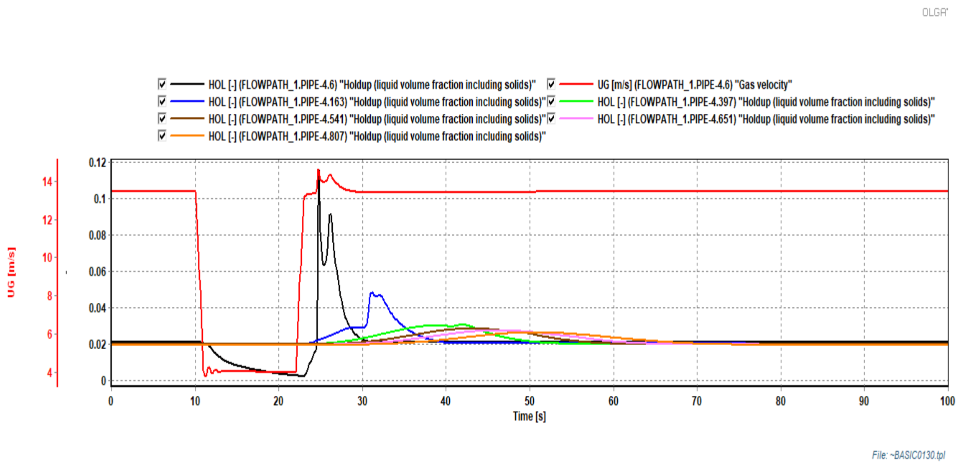

Figure A40: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

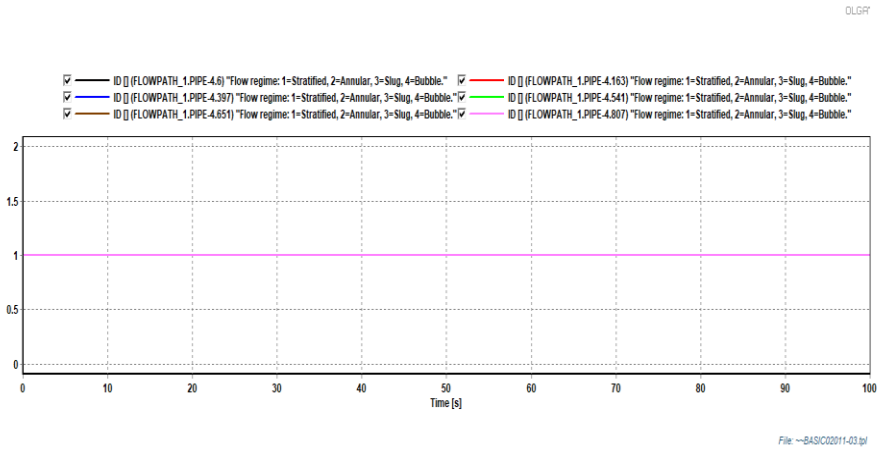

Figure A41: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

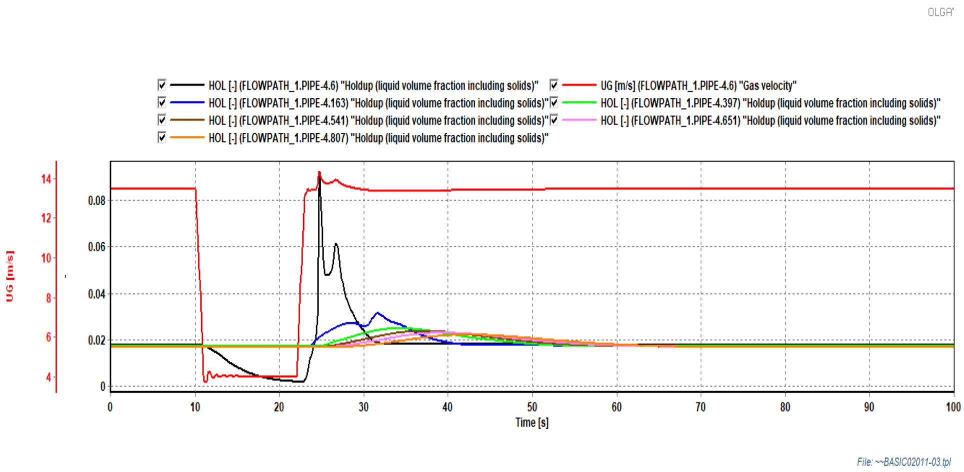

Figure A42: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

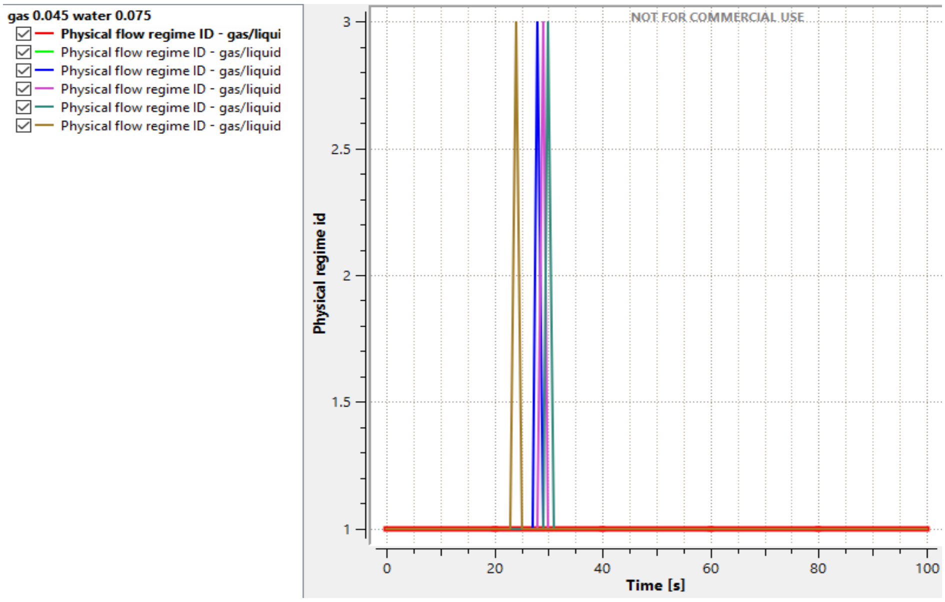

Figure A43: LedaFlow flow regime ID trend plot

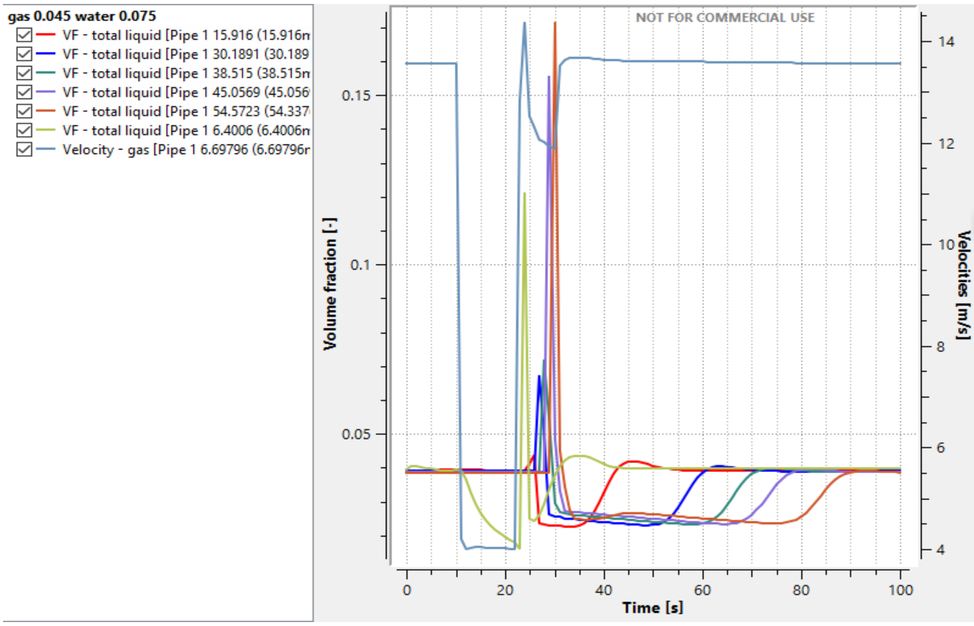

Figure A44: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

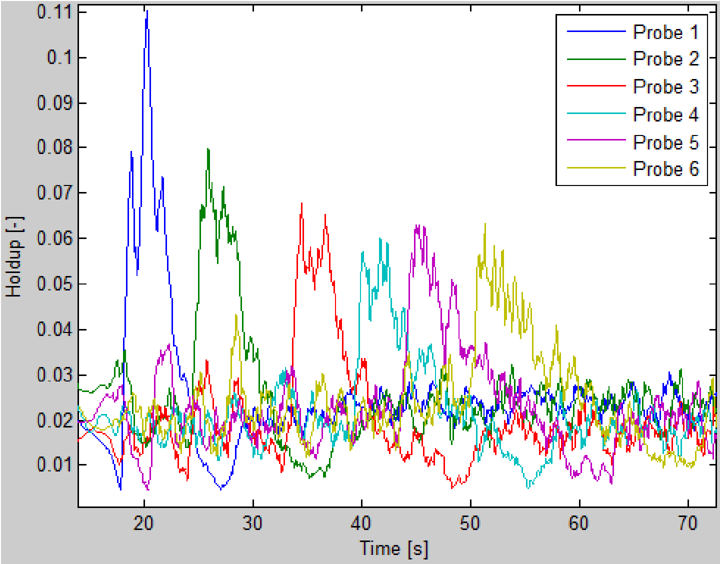

Figure A45: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.102]

Case6: Usg = 10.9 m/s, Usl = 0.0264m/s

Usg = 10.9m/s means that the initial gas flow is 0.037 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s, the water flow rate remains 0.075kg/s. Table A6 shows the details of the flow rate. Figures A46 and A47 show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A48-A51, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A52and A53. The result plot of the previous experiment is in Figure A54.

Table A6: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.037	0.075
10	0.037	0.075
11	0.013	0.075

22	0.013	0.075
23	0.037	0.075
Integration		135(s)

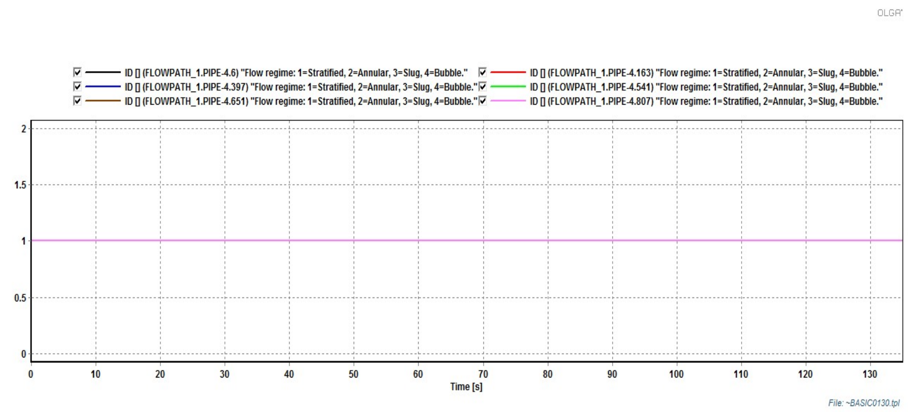

Figure A46: OLGA7.3.5 flow regime ID trend plot

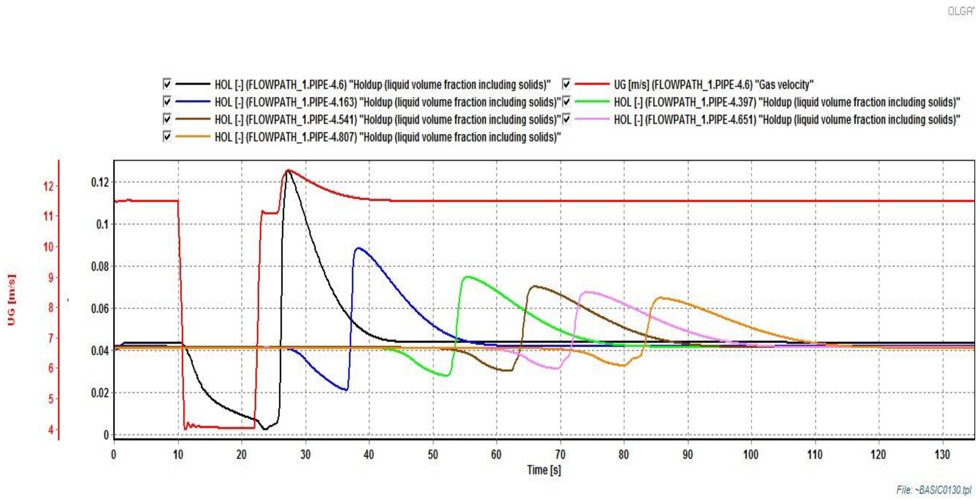

Figure A47: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

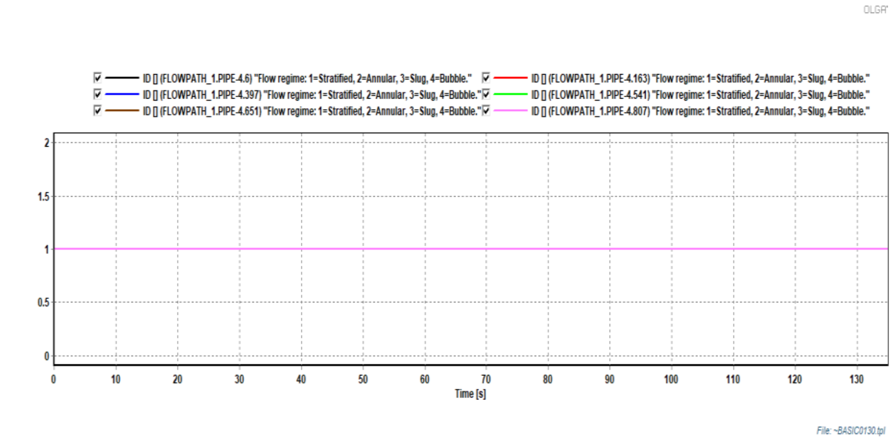

Figure A48: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

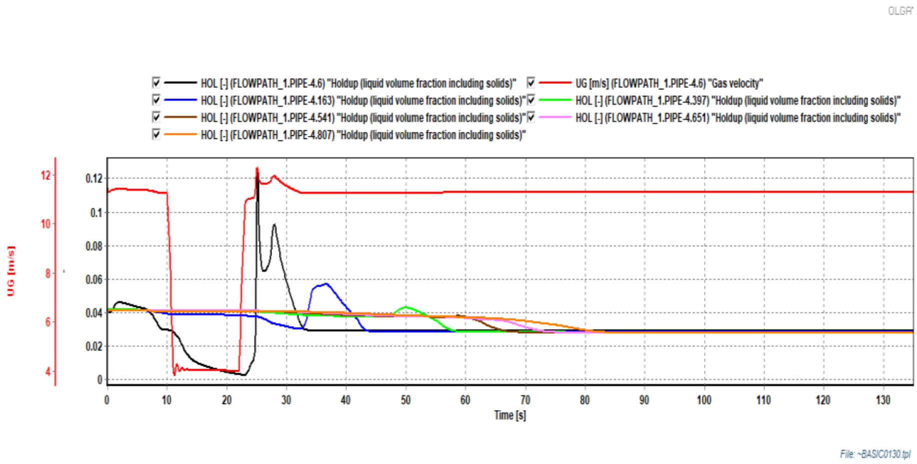

Figure A49: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

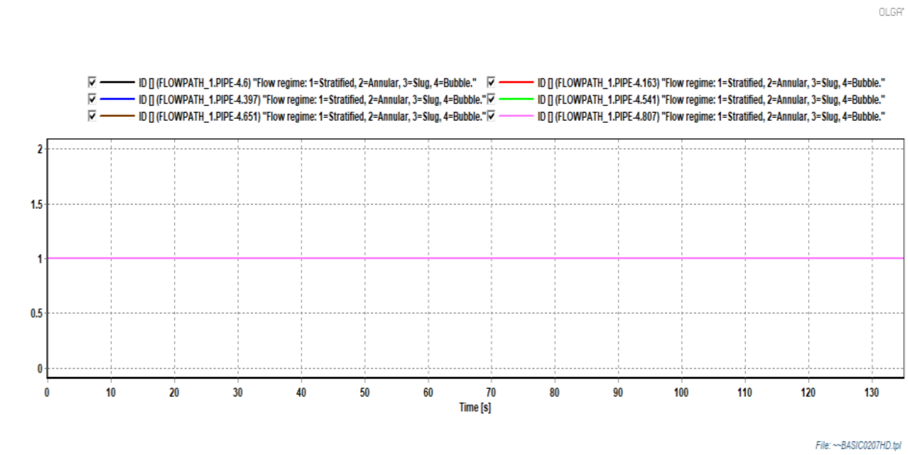

Figure A50: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

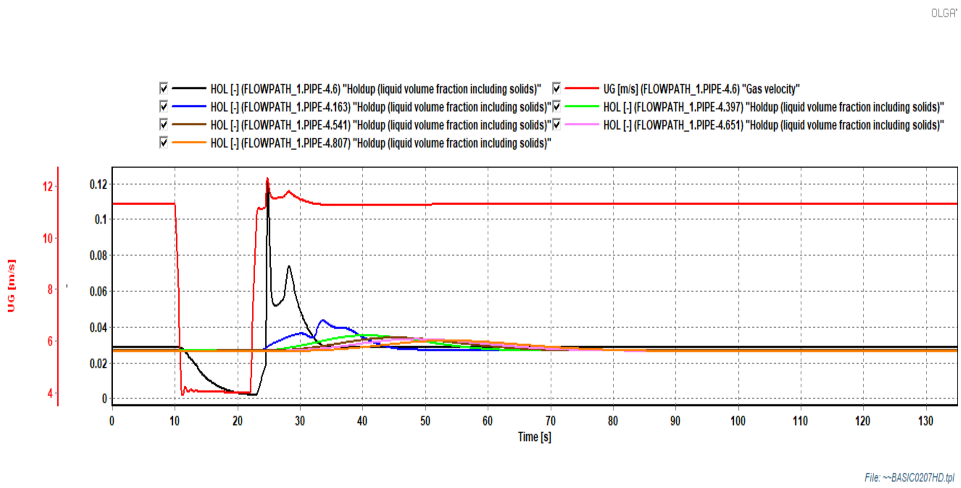

Figure A51: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

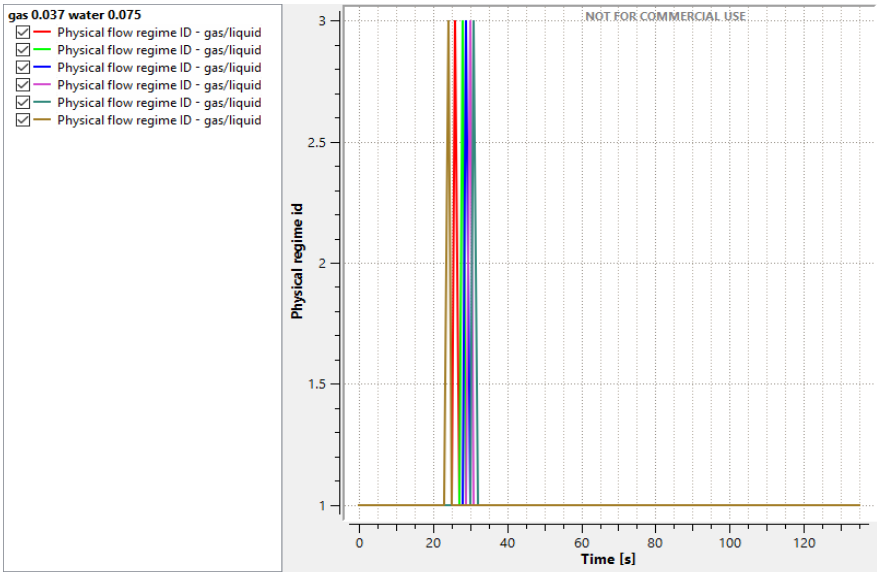

Figure A52: LedaFlow flow regime ID trend plot

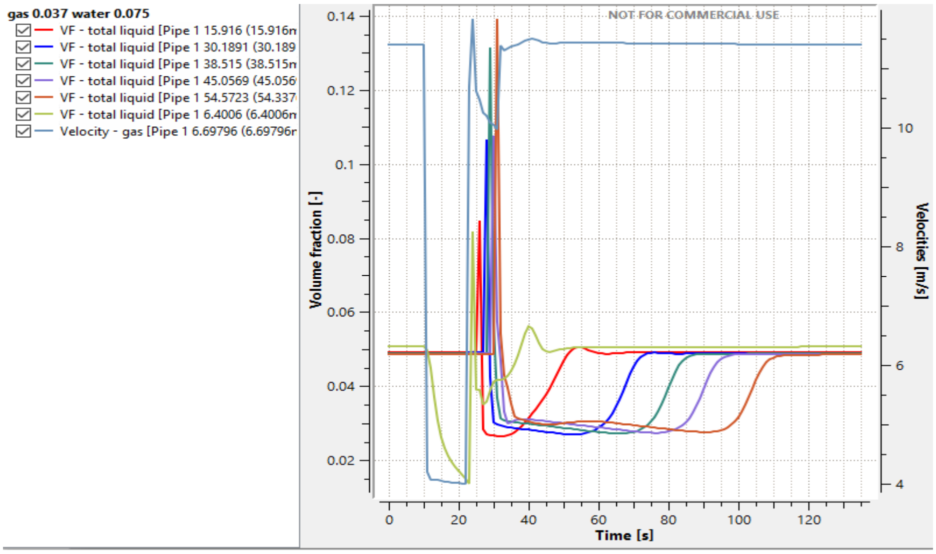

Figure A53: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

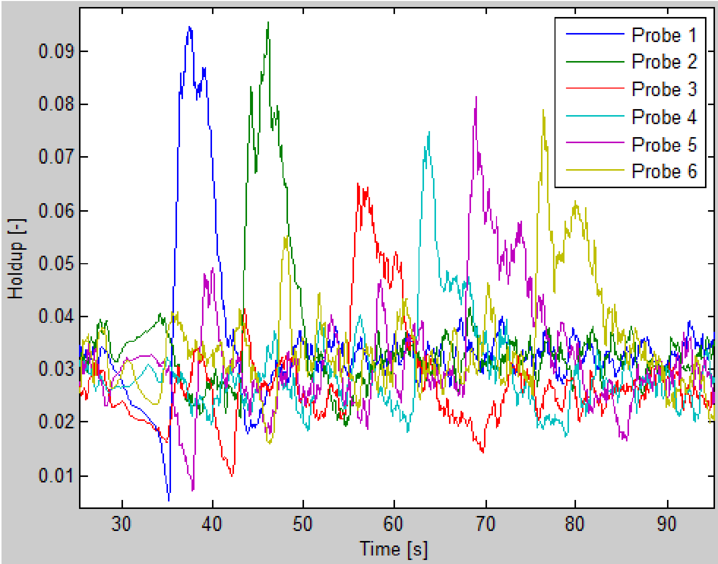

Figure A18: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.106]

Case7: Usg = 8.5 m/s, Usl = 0.0264m/s

Usg = 10.9m/s means that the initial gas flow is 0.029 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s, the water flow rate remains 0.075kg/s. Table A7 shows the details of the flow rate. Figures A55 and A56 show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A57-A60, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A61and A62. The result plot of the previous experiment is in Figure A63.

Table A7: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.029	0.075
10	0.029	0.075
11	0.013	0.075
22	0.013	0.075
23	0.029	0.075
Integration		200(s)

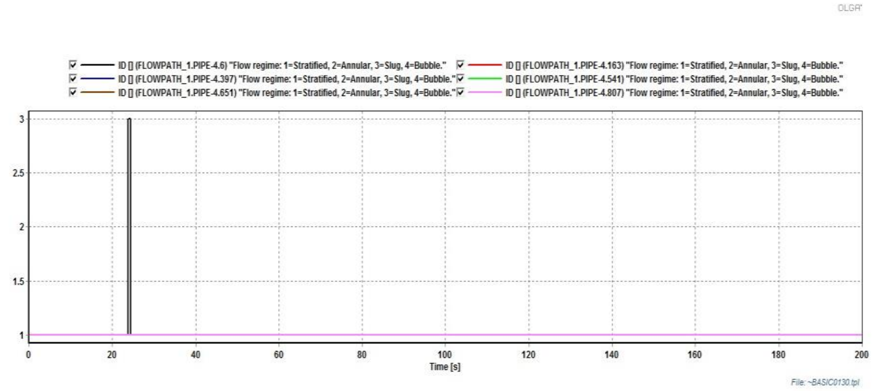

Figure A55: OLGA7.3.5 flow regime ID trend plot

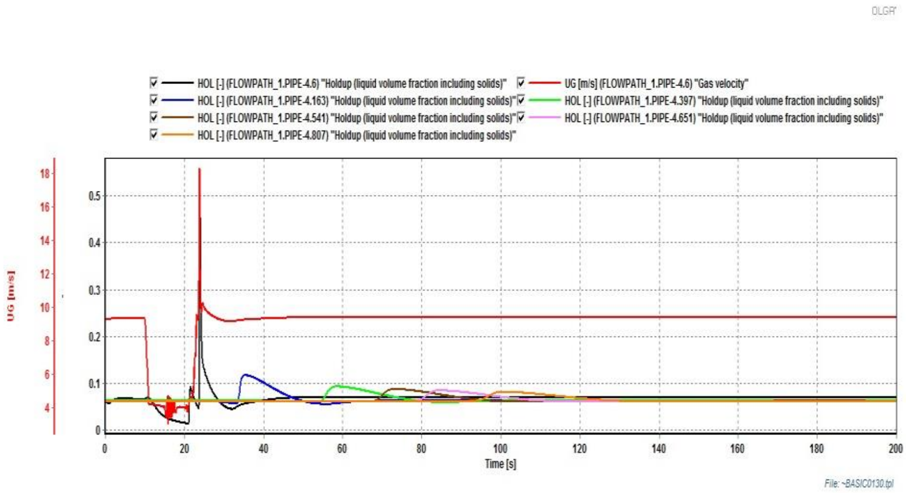

Figure A56: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

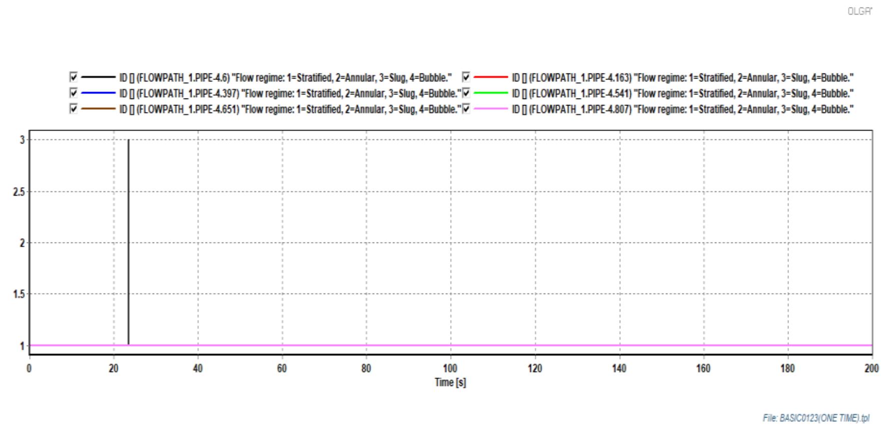

Figure A57: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

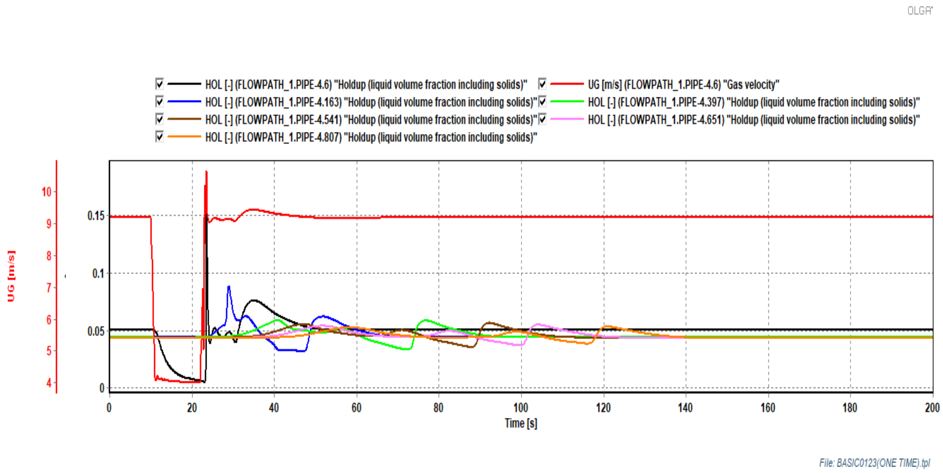

Figure A58: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

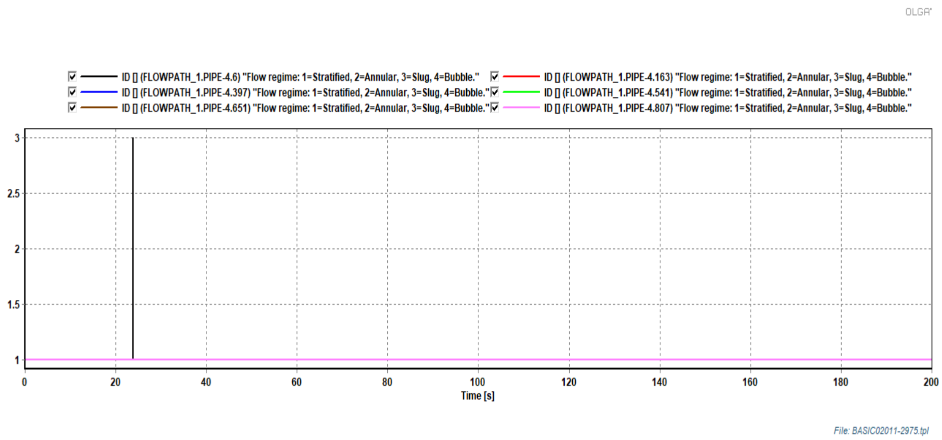

Figure A59: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

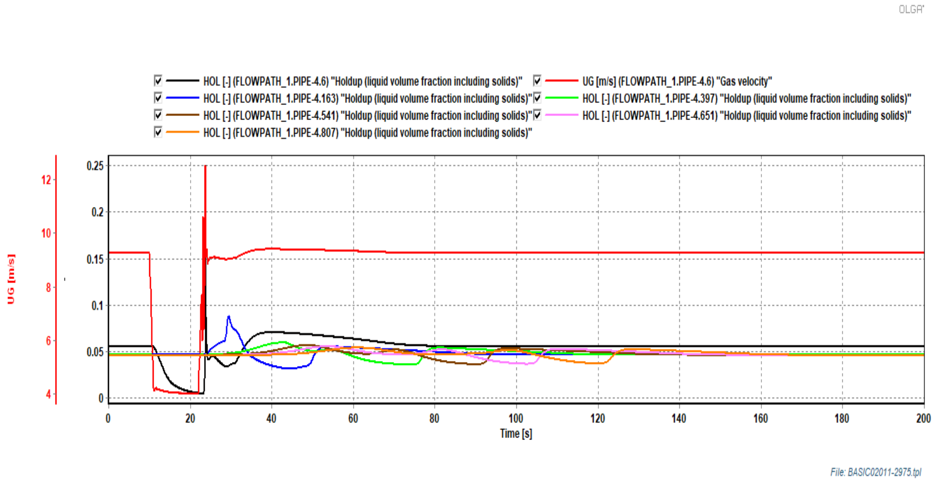

Figure A60: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

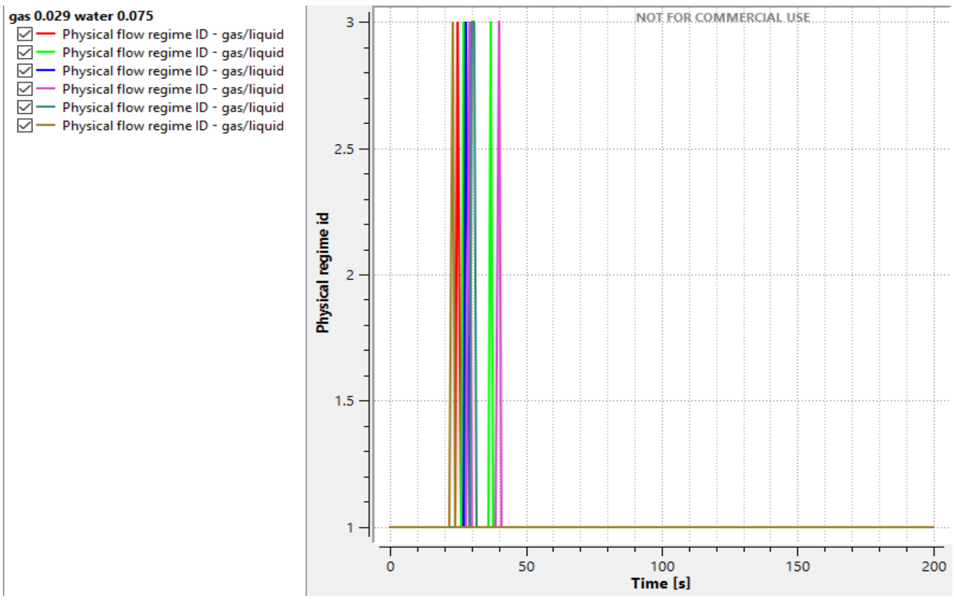

Figure A61: LedaFlow flow regime ID trend plot

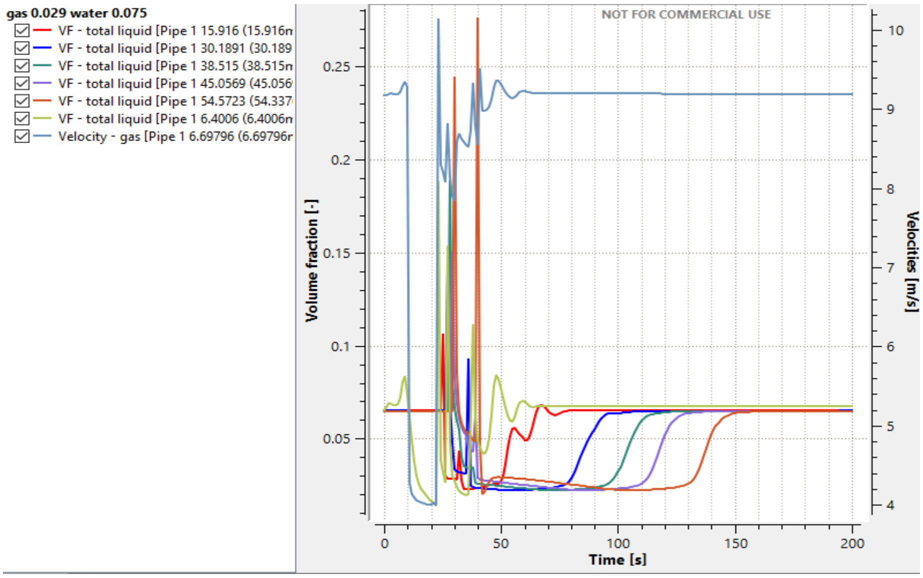

Figure A17: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

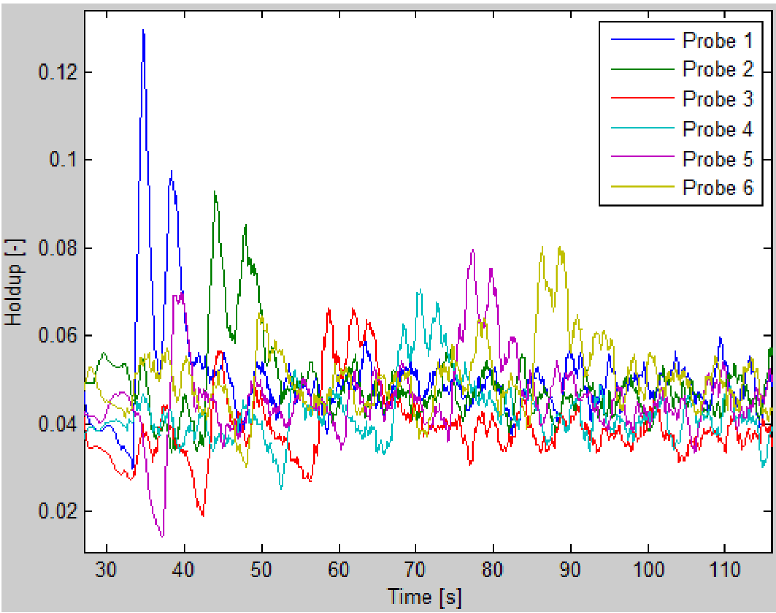

Figure A63: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.111]

Case8: Usg = 7.4 m/s, Usl = 0.0264m/s

Usg = 7.4m/s means that the initial gas flow is 0.025 kg/s, and the minimum gas flow rate would be reduced to 0.013 kg/s, the water flow rate remains 0.075kg/s. Table A8 shows the details of the flow rate. Figures A64 and A65 show the simulation results of OLGA 7.3.5. The results of OLGA 2016.2.1 are shown in Figure A66-A69, the first two figures are OLGA models, and the last two are OLGA HD models. The numerical simulation results of LedaFlow are seen in Figures A70and A71. The result plot of the previous experiment is in Figure A72.

Table A8: Flow rate settings and integration time of the fluid flow rate

Time (s)	Air flow rate (kg/s)	Water flow rate (kg/s)
0	0.025	0.075
10	0.025	0.075
11	0.013	0.075
22	0.013	0.075
23	0.025	0.075
Integration		240(s)

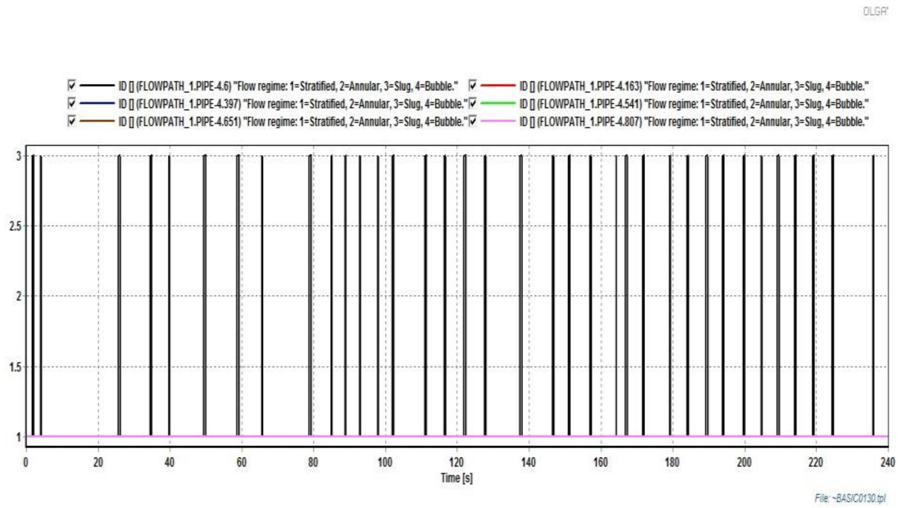

Figure A64: OLGA7.3.5 flow regime ID trend plot

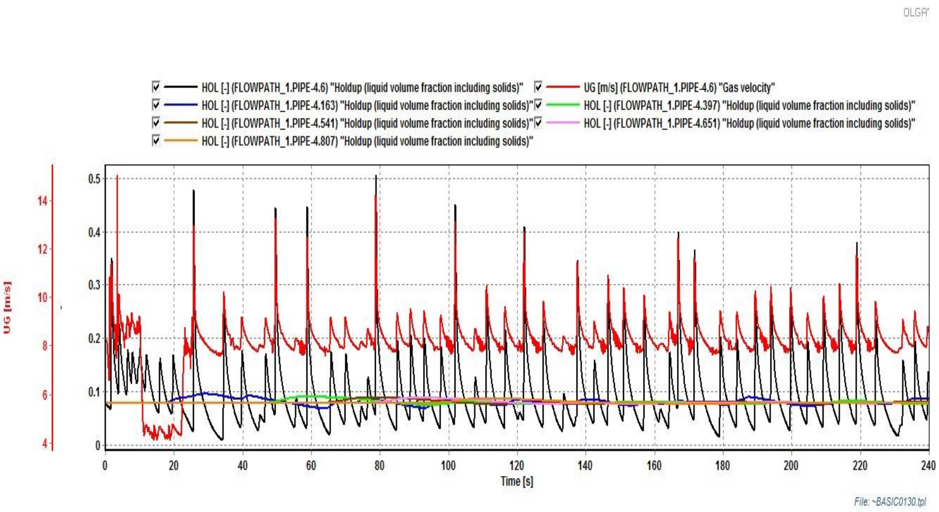

Figure A65: OLGA7.3.5 simulation holdup plot of the wave. The initiative gas velocity is also included.

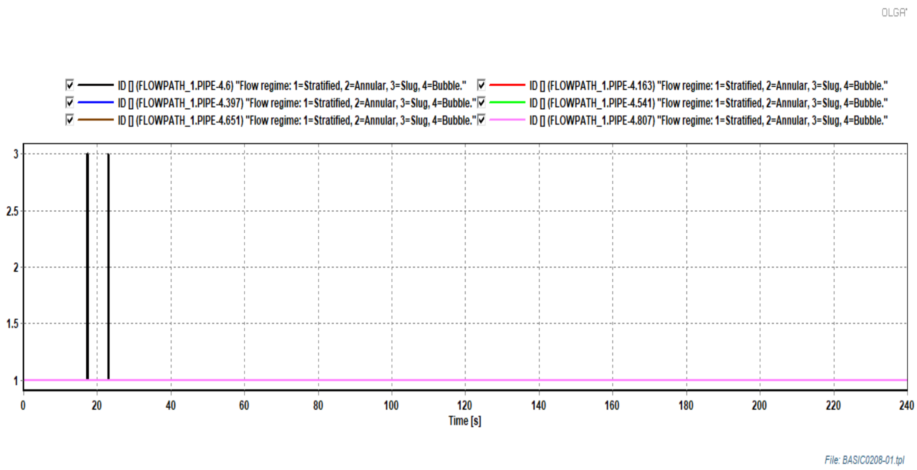

Figure A66: OLGA2016.2.1 flow regime ID trend plot (OLGA model)

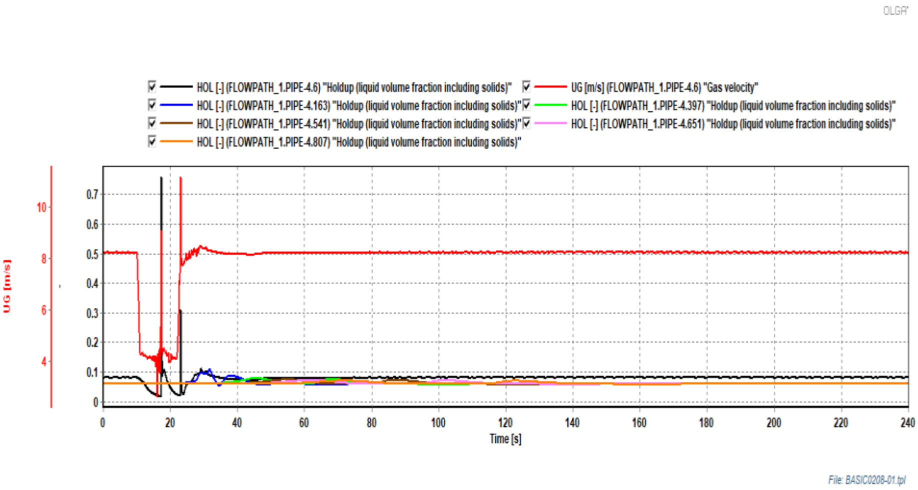

Figure A67: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA model)

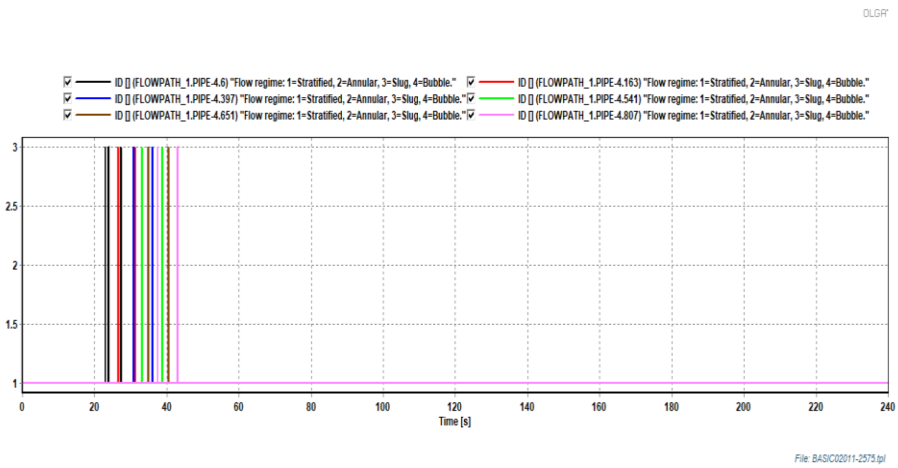

Figure A68: OLGA2016.2.1 flow regime ID trend plot (OLGA HD model)

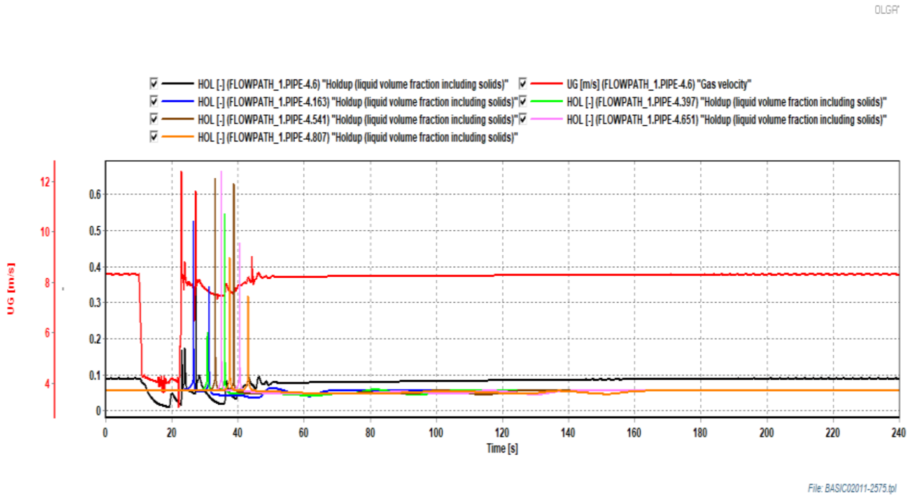

Figure A69: OLGA2016.2.1 simulation holdup plot of the wave. The initiative gas velocity is also included. (OLGA HD model)

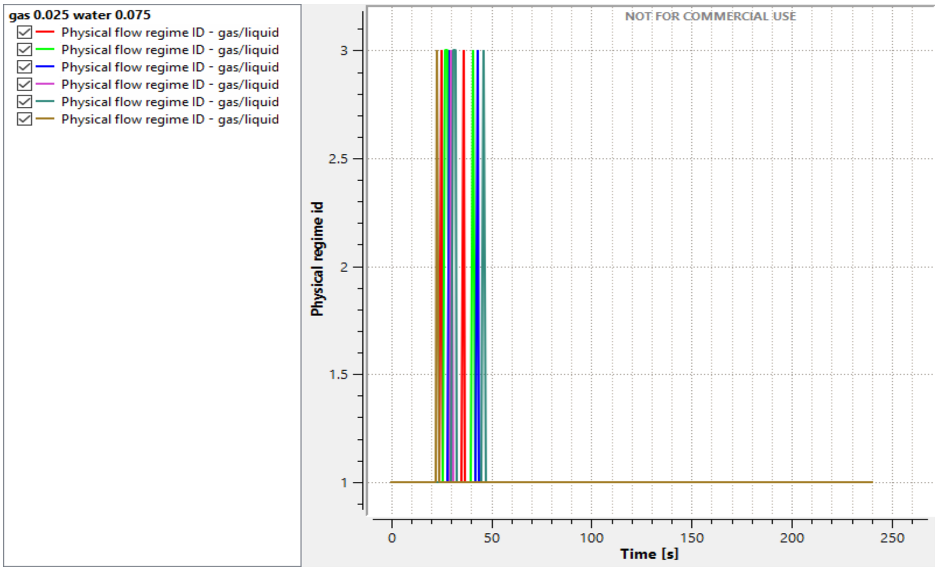

Figure A70: LedaFlow flow regime ID trend plot

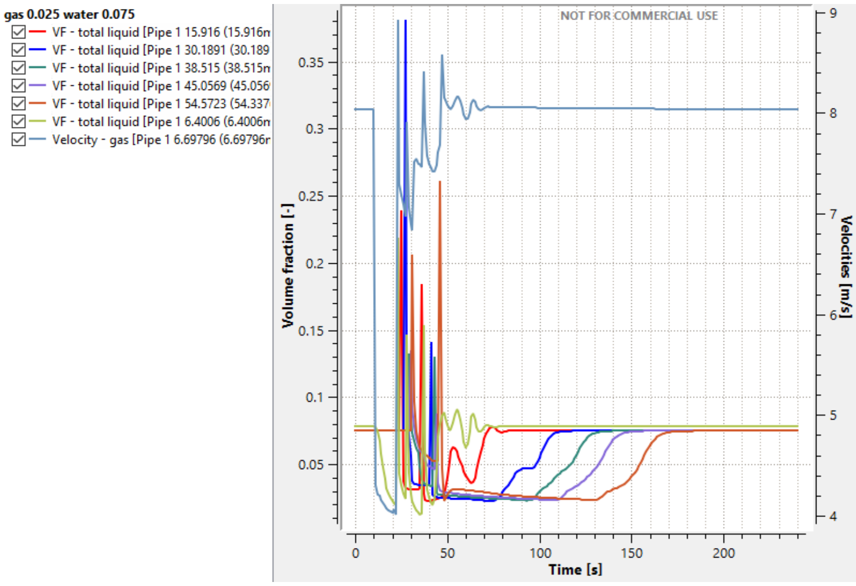

Figure A71: LedaFlow simulation holdup plot of the wave. The initiative gas velocity is also included.

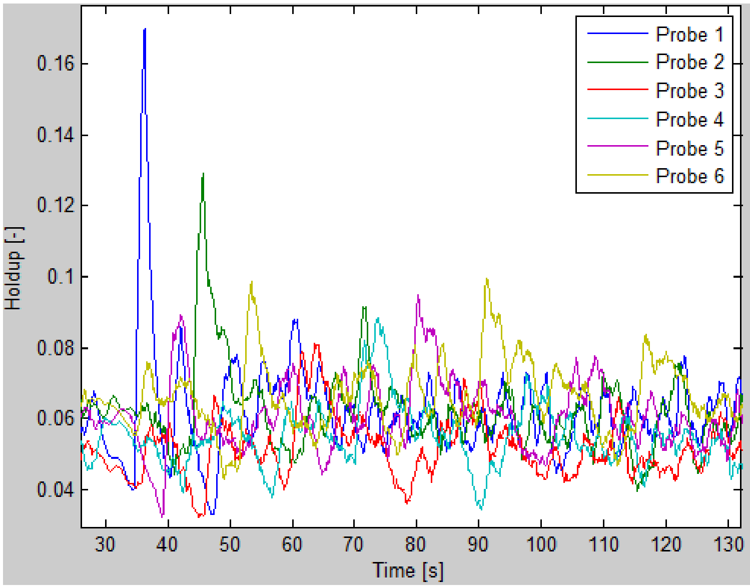

Figure A72: Holdup trend plot of the surge wave propagation from probe 1 to probe 6. [3, p.115]