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Simplified First Principle Model for Severe - Slugging Flow in S-shaped Risers

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Abstract

This report is written as a part of the specialization project autumn 2012 and is part of the preparation for the master thesis.

Slug flow is an undesired multiphase flow pattern that causes problems in the processing of oil and gas. Large variations in pressure and flow conditions can cause problems as insufficient separation, damages to the equipment, excessive flaring and even plant shut-down. Severe slugging is one form for slugging that is common in riser systems due to their geometry. Research has shown that active control is an effective way to overcome the slugging problem. There is still research going on to find the best control design, however mutual for all is that they are helped by a good model of the process. A good model is one that reproduces the situation in the pipeline in enough detail that good control can be achieved without being to complex.

There has been a lot of research done for modeling and control of L-shaped risers. It has been assumed that the behavior of S-shaped risers are not very different from the behavior of L-shaped risers. However, a S-shaped riser has two bends and the dynamics of the system are slightly different. This project is aiming to investigate differences in behavior of the two types of risers. The original objective was to extend the model for the L-shaped riser by adding one more artificial valve for the second bend and then compare this with the original simple model. Due to time issues rather the parameters of the L-riser model was changed to investigate if the model also is valid for S-shaped risers. The investigation was supported by simulations in OLGA and laboratory experiments.

It was found that the simple model of a L-shaped riser imitates the behavior of an S-shaped riser well when compared to simulation data from OLGA. However, there were some differences when compared to the experimental data. It is questionable whether the simulation data received from the OLGA case created in this study can be trusted. Also, more time could be spent to modify the tuning values of the simple model. It is recommended to do more research on the issue and to see if an extended version of the simple model will give better results.

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1 Introduction

Slug flow is a multiphase flow pattern that can cause major problems for gas- and oil processing facilities, both with respect to design and to operation. Severe slugging is one form for slugging that is common in riser systems due to their geometry. It is considered to be an unstable flow pattern as it is associated with large and sudden fluctuations in pipe pressure and gas and liquid flow rates at the outlet. When slug flow occurs the production rate is not optimized and safety may be at risk. The conventional way to counteract slug flow is to use a top side choke valve which works relatively fine in practice, but is not an ideal solution to the problem as it leads to a decreased production rate. Also there exists slug catchers, but these are expensive and have to be supplied at the design stage making them dependent on good estimations of the slug size. Research has shown that active control is an effective way to overcome the slugging problem. There is still research going on to find the best control design, however mutual for all is that they are helped by a good model of the process. A good model is one that reproduces the situation in the pipeline in enough detail that good control can be achieved. The model can not be to complex as this require extensive computing power and is not beneficial in the long run. Esmaeil Jahanshahi has developed such a model for an L-shaped riser [1]. The objective of this project is to investigate the validity of this model with respect to S-shaped risers. The main focus will be on the dynamics of slug flow in S-shaped risers versus slug flow in L-shaped risers. A common riser configuration is illustrated in Figure 1.1.

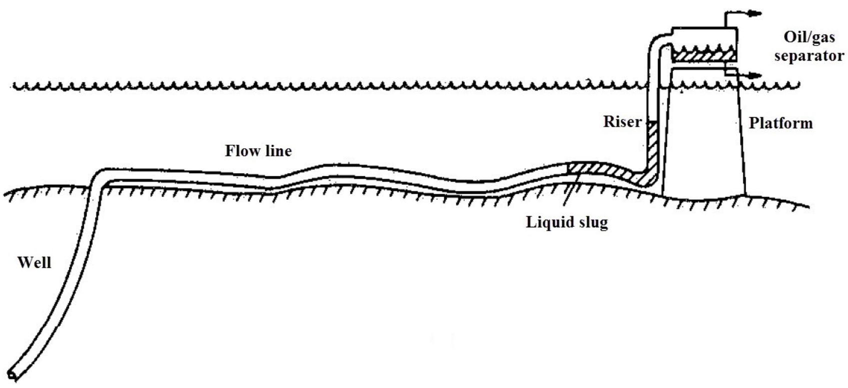

Figure 1.1: A common riser configuration

1.1 Background

When extracted from the continental shelf, oil and gas are transported to topside processing facilities in the same (multiphase) pipeline over long distances. The hydrocarbons are then brought to the surface by flowing through pipeline riser systems. Within a multiphase pipeline there is a combination of oil, natural gas, sand and water. Depending on the conditions in the pipeline and on the physical properties of the fluids in the pipeline there are several different flow patterns that may occur [2].

1.2 Multiphase Flow

The oil and gas industry has in the last three decades drawn their attention to multiphase flow transportation. The possibility to carry oil, gas and water in the same flow lines gives rise to major savings. Less expenses is for instance needed to build new infrastructures, but new problems caused by multiphase flow also arises. Hydrate formation, increasing water content, erosion, heat loss and other considerations need to be accounted for in the design of multiphase flow transport systems. For instance the velocities of gas and liquid in the pipeline is different due to density differences. In terrains with a downward slope the liquid is flowing with a higher rate than the gas, and vice versa for upward flow like in a riser. A description of the flow patterns that occurs in a horizontal pipeline is shown in Figure 1.2 adapted from the book Subsea Pipelines and Risers [3].

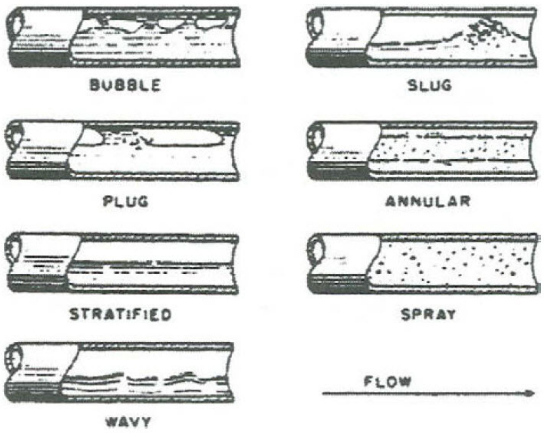

Figure 1.2: Flow patterns occurring in a horizontal pipeline

Some of the flow patterns occurring in vertical pipelines are presented in Figure 1.3 adapted from Watson et. al. [4].

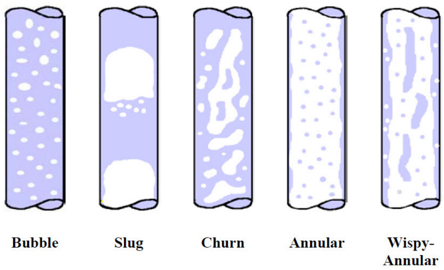

Figure 1.3: Flow patterns occurring in a vertical pipeline

1.3 Riser Configurations

A riser system is essentially the pipeline system connecting the wellheads to the topside floating facilities. There are two main types of risers, flexible- and rigid risers, and a combined version of those two called a hybrid riser [3]. Risers come in lots of different sizes and configurations, even if they in this project only are referred to as either L-shaped risers or S-shaped risers. A minor selection of the varieties are shown in figure below

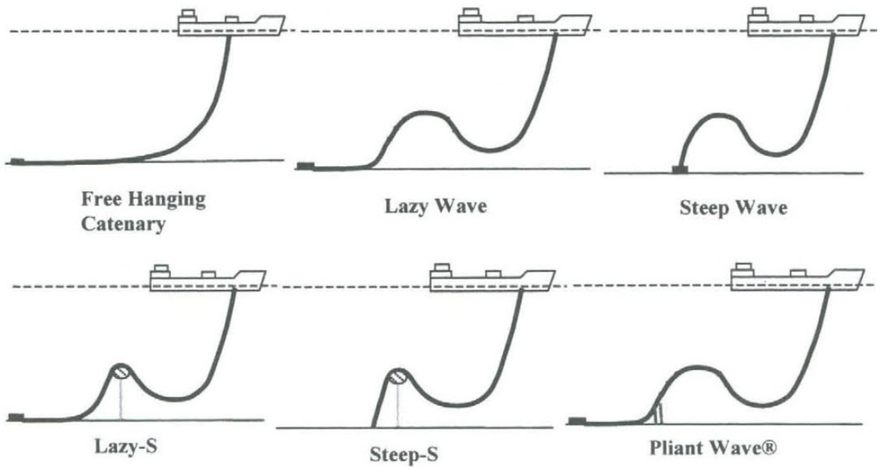

Figure 1.4: An overview of different riser configurations

The sort of riser configuration that is chosen depends on a number of factors like global behavior and geometry, structural integrity, rigidity and continuity, cross sectional properties, means of support, material and last but not least costs [3].

1.4 Slug flow

Slug flow is one of the flow patterns occurring in multiphase pipelines. It is characterized by a flow pattern containing liquid cylinders called slugs that travels along the pipeline separated by stratified flow. There exists different types of slug regimes depending on the flow rates and on the geometries of the pipeline systems. Due to their geometry, risers often give rise to severe slugging. Severe slugging typically occurs when the velocities of gas and liquid are low. Severe slugging also requires a stratified flow pattern in the pipeline and that during slug formation the liquid reaches the choke valve before the gas reaches the bottom of the riser.A description of the different slug regimes that may occur is given below [5].

- **Hydrodynamic slugs** - this form of slugging occurs in horizontal pipelines due to differences in velocities of the different phases. Liquid builds up and forms slugs which are short, but with a high frequency [6]. This type of slugging causes less problems than the severe type of slugging.
- **Terrain slugging** - arises when liquid is blocked due to inclination in the pipe caused by the terrain.
- **Riser slugging** - this type of slugging is induced by the presence of a vertical riser. The liquid blocks the entrance to the riser so that the gas can not enter into the riser. This is the case until the pressure of the upstream gas exceeds the gravitational pressure of the liquid in the riser column. This type of slugging causes long liquid slugs and large pressure variations. It is also known as severe slugging.
- **Transient slugging** - slugs induced either by an operational change or by instabilities in the gas/liquid interface [7].
- **Pig induced slugging** - slugs arising from a pig being sent through the pipeline which pushes the liquid out of the pipeline. This type of slugging is outside the scope of this project.

1.4.1 Mechanism of Riser Slug Flow Formation

One of the main reasons why slug flow occur in risers is the downward inclination of the pipeline into the riser. This enables liquid to block the entrance in to the riser, and causes liquid to accumulate in the entrance to the riser. This causes compression of the gas in the pipeline and expansion of the gas in the riser [8]. The mechanism of riser slug formation can be described by the following four steps:

- **Step 1** - Liquid accumulates in the riser low-point due to gravity. This is the case if the gas and liquid velocities are low enough to allow for it.
- **Step 2** - As long as the hydrostatic head of the liquid in the riser is higher than the pressure drop over the riser the slug continues to grow as gas can not penetrate the liquid blocking the entrance.
- **Step 3** - When the pressure drop over the riser exceeds the hydrostatic head, the liquid is pushed out of the riser.
- **Step 4** - When all the liquid has left the riser the velocities are so small that liquid falls back in to the low-point of the riser and starts to accumulate again.

The four steps are illustrated in Figure 1.5 adapted from Watson et. al. [4].

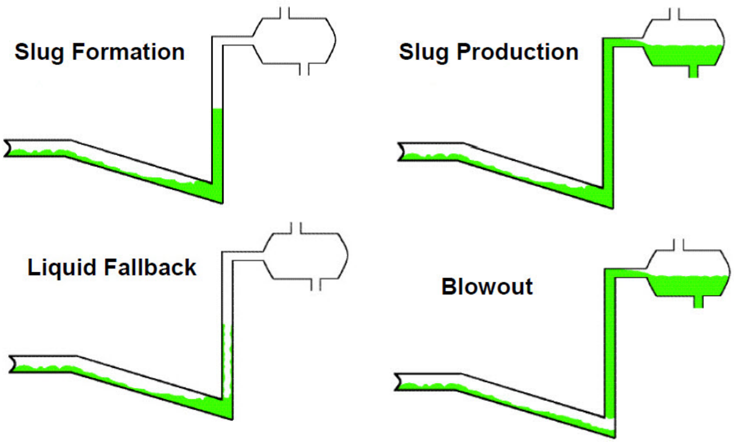

Figure 1.5: The mechanism of slug formation

The first fields that were explored in the history of oil and gas production was the simple and not so technically demanding fields. However, as these resources are drained the demand for more advanced technology is increasing. One ironic fact is that even if the reservoirs are existing on deeper waters the depth of the formations below the seabed on top of the reservoirs tend to be smaller. The result is that the reservoirs is low energy reservoirs, meaning lower temperatures and lower pressure than your average reservoir and therefore making it more difficult to exploit. The driving force to the flow is limited making it more susceptible to slugging, and the low temperatures makes it more difficult with heat conservation and to avoid solids formation like hydrates and waxes. Deeper waters also requires higher risers, which has important implications for system stability. Increasing the riser height causes instability and the higher the risers the more severe is the pressure variations in the slugging cycles. Also, it is important that engineers consider carefully how pipelines will be depressurized. In certain pipeline topographies it may be difficult to reduce the pressure to the desired value when the increase in hydrostatic head is large. This is important to avoid unplanned shutdowns [4]. Slug flow is a strongly unwanted flow pattern and gives rise to a lot of problems during the production of oil and gas. It may cause severe and dangerous vibrations in equipment because of impact of the high-velocity slugs against fittings [3]. Also separators have problems in handling the incoming flows and this may lead to poor separation, poor production rates and may causes excessive flaring [9]. Severe slugging causes large fluctuations in the flow rates and in the pressure. A large liquid slug may cause overflow and separator shut down, large gas rates might cause operational problems during flaring, and the large pressure fluctuations might reduce the production capacity of the field. The definition of severe slugging is the build up of a slug with length equal to or larger than one riser length [10]. There are several conventional solutions to the problem established, and a description of some is given below.

1.4.2 Choke Valve

Choking was recognized as a method to eliminate severe slugging in 1979 by Schmidt et. al. [11]. This approach involves detecting the slugs and then use the pipeline choke to minimize effect of the slug on the separator unit. It was found that by increasing the back pressure proportionally to the velocity increase at the choke severe slugging could be eliminated. Steady flow will eventually occur if the acceleration of the gas front into the riser is stabilized before reaching the choke [8]. However if the choke is closed to much the slug may return to the riser base and a new larger slug is formed [9].

1.4.3 Gas Lift

Gas lift is also a method used to eliminate severe slugging. By reducing the hydrostatic head in the riser the pipeline pressure is reduced. One drawback with the method, apart from it being expensive is the large gas volumes that are needed in order to achieve satisfactory flow stability [8].

1.4.4 Slug Catcher

A slug catcher is in fact just a large separator installed as the first element in the topside process facility. It acts as a buffer volume to accommodate the change in incoming flow rates of gas and liquid. Determining its size is critical to optimal operation. There are two main types of slug catchers, the vessel type and the multiple-pipe type of separators. Which type that is used depends on the type of fluid that exists in the streams, where the multiple-pipe separator is mostly used when having gas condensate system. The fundamental purpose of a slug catcher is to remove free gas from the liquid phase and supply a relatively constant flow of liquid to the rest of the processing facility [12]. However, installing a slug catcher is not a real solution to counteract slug flow, but rather a way of accepting the problem. In that sense it is an expensive solution to the problem. The quality of the solution is dependent on the slug catcher is sized correctly which essentially has to be determined in the design stage. At that time the exact size of the slugs are not known so it have to be designed for the worst case scenario which is an unnecessarily expensive solution to the problem as well as not always appropriate with respect to space in an offshore platform.

1.5 The Reliability of Simplified Modeling and Testing

Watson et.al. [4] is questioning the conventional techniques used to develop flow models for riser systems. They suspect that the method of using models found by investigations of small diameter risers and then extrapolating these in order to make them valid for bigger diameter risers is not adequate. When it comes to modeling of multiphase systems the objective is to use the models for flow assurance. That is, ability to predict the pressure drop, the phase distributions, the potential for slugging and the thermal characteristics of the system. This is most relevant in the design stage of a project in order to avoid configurations that are prone to instabilities. It is not possible to accurately model multiphase flow for turbulent systems. The modeling is therefore heavily reliant on empirical correlations which are only as accurate as the empirical data themselves. Therefore it can be questioned whether this model would be valid if applied to real systems. It is tested by the use of small diameters risers and it may be that the model is more then good enough for such systems, but it still may be invalid for use in larger systems [4].

1.6 Simplified model

The simplified model for an L-shaped riser made by Jahanshahi is presented in Appendix A. The model is based on the mass balances over the different sections of the system and it uses simple relationships to calculate the phase distributions over the different sections. A simplified geometrical correlation is used to find the cross sectional area for flow in the low point of the riser. An illustration of the geometrical relationships used in the calculations are shown in Figure 1.6

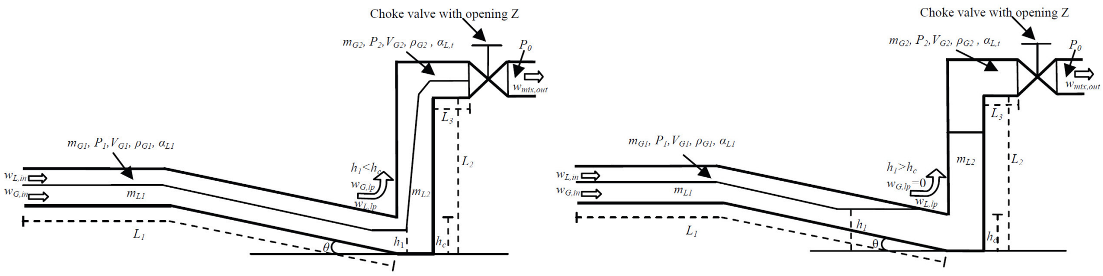

Figure 1.6: A simplified illustration of the desired flow regime (left) and the liquid blocking the entrance to the riser

1.6.1 Bifurcation Diagrams

In order to compare the different models with each other in a simple way, the results are plotted in the form of a bifurcation diagram. A bifurcation diagram is essentially a plot of the relative sizes of the oscillations of the slugs. The diagram consists of three curves, one for steady state conditions, and two which shows the maximum and minimum respectively of the oscillations over the whole work range of the choke valve.

2 OLGA

One of the objectives in this project was to investigate the differences in the dynamics between L-shaped risers and S-shaped risers. In order to compare the simple model for a L-shaped riser to the behavior of an S-shaped riser the multiphase flow simulator OLGA® was used.

2.1 History

In the beginning of the 1980's the existence of adequate technology to describe multiphase flow was scarce. Before the technological breakthrough each oil- and gas field was dependent on having their own platform. In close cooperation with the industry, Institute for Energy Technology developed the first version of OLGA (OiL and GAs simulator) in 1980. SINTEF joined the further development this simulator in 1983 at the same time as the large scale multiphase flow loop in Trondheim was opened. Data from experiments with this multiphase flow loop was compared with and used to improve the simulator. This new technology lead to the development of more fields and smaller fields than what was previously possible. Untreated well flow (oil, water and gas) could be transported in long distances in the same pipeline, either to a neighboring field or all the way to the shore. This opened a new window of possibilities, and it is an important reason why it now is possible to install entire production facilities subsea without exposing workers for unnecessary risk, and minimizes costs and effects on the environment [13]. OLGA was recently awarded a price as the best invention in Norway after 1980.

2.2 Simulations in OLGA

Two OLGA cases are used to create the OLGA simulation results. The first case that was made was the "complex-case", this contained more sections and where all the physical parameters were standard conditions supplied by OLGA. However, due to problems of getting this case to numerically converge at low superficial gas velocities another case was made. The "simple-case" contained fewer sections in the geometry and some of the parameters were manipulated within reasonably limits to create the desired results. Which of the parameters that were changed is discussed later in this section. OLGA ® version 7.1 was used for the simulations. More time than expected was needed to learn the intermittent properties of the software. It was early discovered that the numerics of the software tend to be a bit unpredictable. It took some experience and guided help to overcome this problem.

2.3 Making the S-riser in OLGA

The geometry for the S-shaped riser in OLGA is based on the experimental set-up at the Department of Energy and Process Engineering. The exact geometry was received in the form of a table that is shown in Table 2.1.

Table 2.1: The geometry of the S-riser experimental set-up (with acrylic pipes)

Pipe	L [m]	D [m]	θ [^{o}]	θ_{out} [^{o}]	θ_{in} [^{o}]	R
1	8.125	0.20	-45 .0			
2	3.000	0.05	-10.0			
3	6.050	0.05	-4.0			
4	1.200	0.05	-1.8			
5	1.106	0.05		-1.8	-61.8	0.966
6	4.110	0.05	61.8			
7	0.719	0.05		61.8	-32.0	0.439
8	2.160	0.05	-32.0			
9	1.716	0.05		-32.0	79.0	0.886
10	1.820	0.05	79 .0			
11	1.150	0.05	90.0			

The exact geometry was only available for the laboratory S-shaped riser set-up that was not used, the acrylic S-shaped riser, and it is this geometry that is implemented in OLGA. However, considering that the the two riser set-ups were so similar and the fact that the geometry would have to be altered before being implemented anyway this difference is minor. In order to be implemented in OLGA this geometry had to be converted into x- and y-coordinates. This was done by approximating the circular bends in the pipeline system by straight pipeline sections. The resulting geometry used in OLGA is shown in figure 2.1

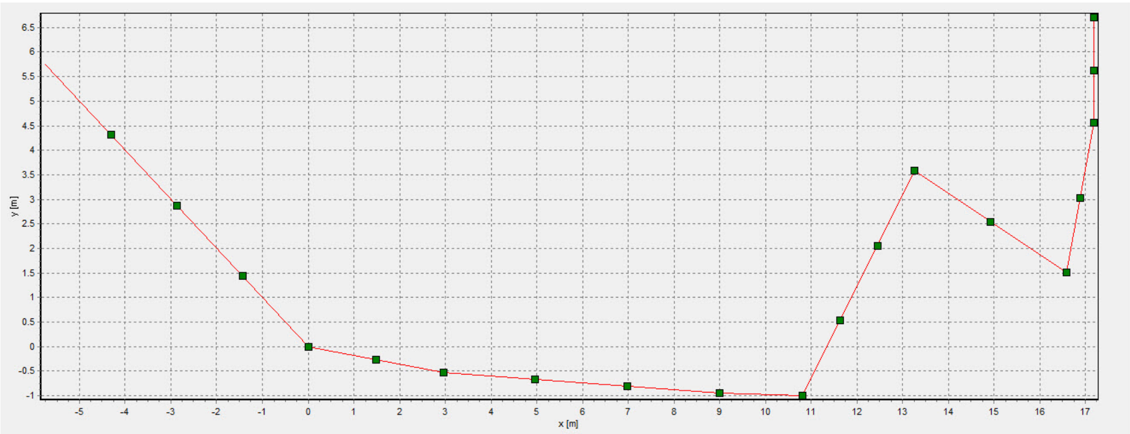

Figure 2.1: The geometry of the s-riser in Olga

The calculations were done such that the origo of the axes was laid at the end of the buffer tank and at the beginning of the pipeline. The resulting x- and y-coordinates are presented in Table 2.2.

Table 2.2: The x- and y-coordinates for the geometry of the s-riser implemented in olga

Pipe	x [m]	y [m]	Length [m]	Number of sections
Start point	-5.7452	5.7452		
1	0	0	8.12494	4
2	2.9544	-0.5209	2.99997	2
3	8.9897	-0.943	6.05004	3
4	10.8063	-1.0001	1.8175	1
5	13.262	3.5798	5.19672	3
6	16.5849	1.5034	3.9183	2
7	17.1782	4.5554	3.10913	2
8	17.1782	6.7054	2.15	2

The first case in OLGA was made using a one way check valve after the buffer tank. This was to avoid water flowing against the flow direction which seemed to be the case without this valve. In the later simulations however this was removed to make the simulations run more smoothly. The OLGA case that was used to create the results is presented in Figure 2.2.

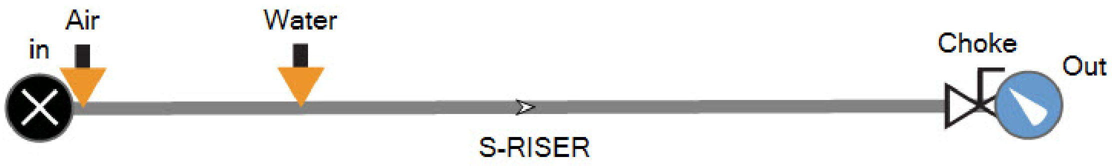

Figure 2.2: The simulation case in OLGA

The sources of air and water were placed in the beginning and the end of the buffer tank respectively.

2.3.1 Main problems with the software and solutions

An intermittent problem with the software was its unwillingness to converge numerically at low superficial gas velocities. Several different parameters were changed in an attempt to counteract this problem, and below there is an overview of the parameters that was changed along with a description of the effect of changing the values.

Isothermal The flow in the riser is approximately isothermal. As the problem with the simulations was numerical it was believed that simplifying the simulation by making it isothermal would be helpful. However, the result was that the numerical problem remained and the results became more inaccurate. Just to demonstrate the difference, Figure 2.3 shows the results of two nearly identical simulations where the difference is that one is run under isothermal conditions and the other not.

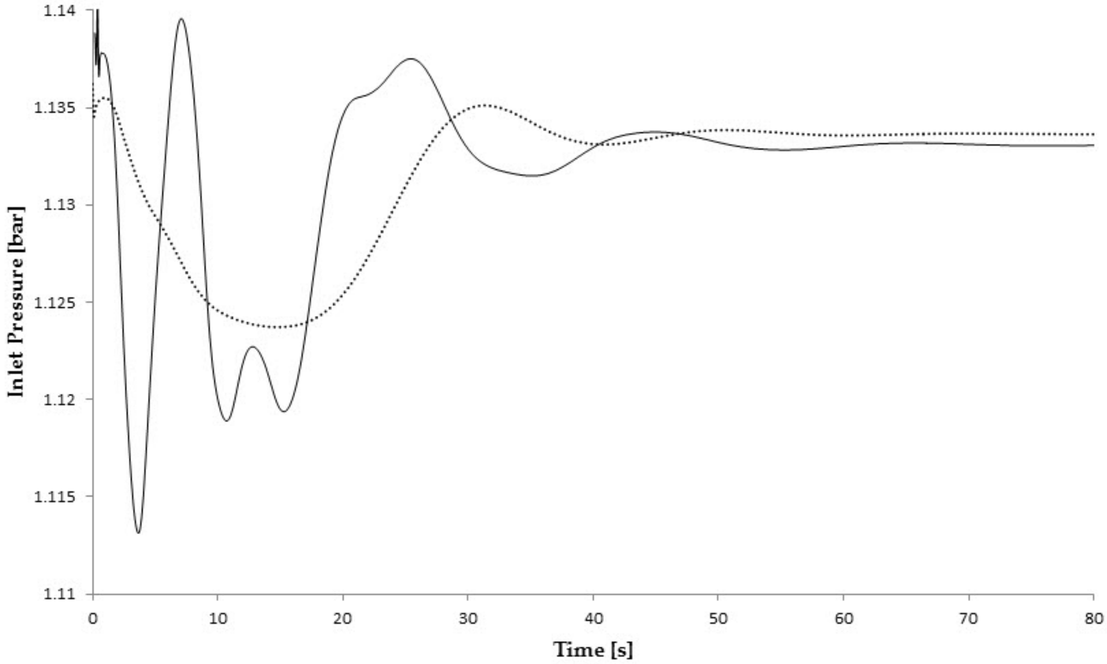

Figure 2.3: The Differences between isothermal simulation (solid line) and non-isothermal simulation (dotted line)

It can be seen that the isothermal simulation is more numerically unstable in the first simulation period. From this it was chosen to continue the simulations non-isothermally.

Coefficient of discharge The coefficient of discharge is a valve constant depending on the pressure drop over the valve. Decreasing the value of c_d made the flow less stable with the same valve opening. This value was therefore manipulated such that the bifurcation point in Olga came out the same as for the experiment. The validity of this manipulation, however is discussable. The coefficient of discharge is as defined by equation 1

$$Q = c_d A_0 \sqrt{\frac{2\Delta P}{\rho\left(1 - \left(\frac{d_{orifice}}{d_{pipeline}}\right)\right)}} \tag{1}$$

So in fact it is a parameter that is dependent on the conditions in the pipeline and not a variable that can be freely manipulated.

PVT files The simulations in OLGA are based on a table of thermodynamical data known as the PVT-file. It is a table of phase compositions under different temperatures and pressures which can be made by a program called PVT-sim. By specifying temperature and pressure limits and the compositions of the fluids involved, the program calculates the values for the phase compositions used in the simulations. When starting up with the simulations in OLGA the PVT-file used was one made by Jahanshahi [1]. It contained thermodynamical data for pressure ranging from 1 bar to 5 bar and 5^oC to 35^oC. This should be more than adequate enough for the purpose of our simulations. However, most of the complaints when the simulator did not converge involved this PVT-file not being large enough. The reason why this may be the case is that even though the real temperatures is well away from these limits, the numerics in the simulator requires to go beyond those limits to be able to converge with their calculations. Therefore, PVT-sim was installed and a new much larger PVT table was created ranging from pressure values from 0.1 bar to 50 bar, and temperatures from -50 to 50 degree Celsius. It was worth an attempt and it did in fact improve the simulations.

Number of Sections The number of sections in the geometry was found by trial and error. Several attempts showed that the best configuration, i.e. the configuration which was numerically the most stable, was one with very few sections. This may come with the cost of less accuracy, but as the differences lay in the minor detail this was overlooked. The number of sections was originally such that the length of each section was equal to one meter. However, this caused the simulations to be unstable and there was large uncertainties whether they would converge or not. Low superficial velocities was with these sizes virtually impossible to run at all. It was essential to fix this problem in order to compare OLGA to the experiment. Before the PVT-file was changed some attempts were done to minimize the number of sections, but as this in fact made the simulations less unstable it was assumed that there would be nothing to gain to change the number of sections. It turned out that all the changes needed to be done at the same time to create the desired simulation case.

Outlet Pressure Conditions The outlet pressure conditions under real conditions is atmospheric. However, it was found that by increasing the initial pressure from 1 atm to 1.15 atm the simulations ran more smoothly. Considering the small difference compared to atmospheric conditions it is a reasonable manipulation.

3 Laboratory Experiment

In order to investigate the validity of the model, in addition to running simulations in OLGA it was conducted medium scale experiments. This experience was useful also to see how the results from the OLGA simulations corresponded with the experimental set-up.

3.1 The Experimental Set-up

The experimental setup is located at the Department of Energy and Process Engineering at NTNU. There are two S-riser set-ups at this laboratory, one made of steel pipes and one with pipes made of an acrylic material. The S-shaped riser used in these experiments are the one made with steel pipes. It has a length of approximately 14 meters and a height of approximately 6 meters. A buffer tank with compressed air is used to simulate the long pipeline that is present in real systems. A detailed description of the dimensions of the acrylic S-riser is given in Table 2.1 in Section2. A rough flow-diagram of the experimental set-up is shown in Figure 3.1

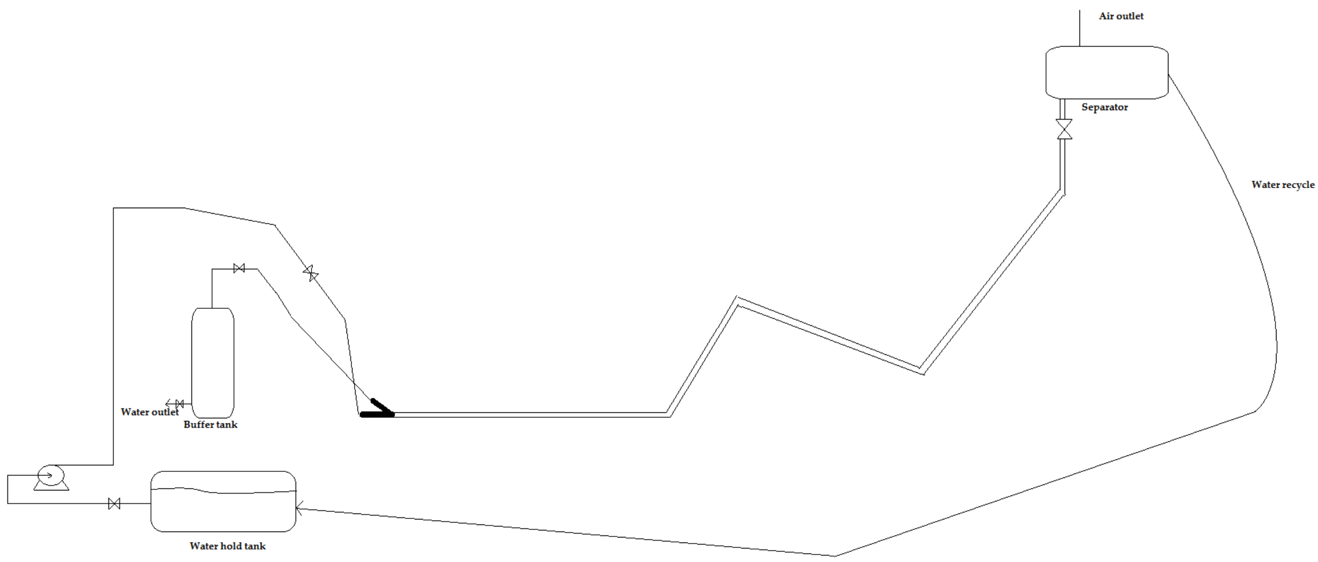

Figure 3.1: A simplified flow diagram of the experimental set up

Water and air is used as the fluids in the experiment. Water is pumped from a hold tank, which is located one floor below, and into the s-riser where it is mixed with air coming from the buffer tank. This mixture is then sent up the riser where the relevant measurements are done. The measurements that are relevant from these experiments are the flow rates for the two fluids as well as the pressures in the buffer tank and top. The top pressure measurement device was not installed before the last bifurcation diagram was made.

The dimensions of the riser are as presented in Figure 3.2.

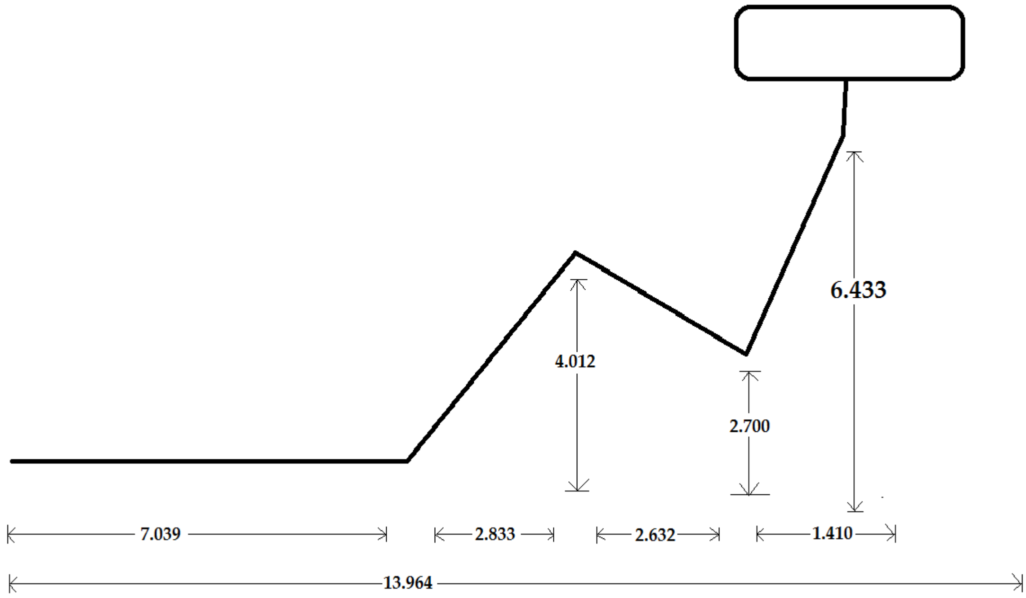

Figure 3.2: Relative sizes of the experimental setup

A picture of the experimental set-up can be seen in Figure 3.3.

Figure 3.3: The experimental setup

The buffer tank is made of steel and is shaped like a cylinder. A picture of the buffer tank is shown in Figure 3.4.

Figure 3.4: The buffer tank

The S-shaped riser used in the experiments has sharper bends than the S-riser made of acrylic. This makes the model that is built in OLGA more similar to the experiment. This is shown in Figure 3.5.

Figure 3.5: The bend in the steel pipe compared with the bend in the acrylic pipeline

4 Matlab Model

Esmaeil Jahanshahi has made a simplified model for describing slug flow in a L-shaped riser. The main objective of this project was to investigate the validity of the simplified model with respect to modeling slug flow in S-shaped risers. Thereafter this simple model should be expanded into a 8th state model to fit a S-shaped riser. However due to time issues this simple model was rather kept as a four state model and then modified to be similar to the experimental setup.

4.1 Changing Parameters

First the geometry was changed to suit the experimental set-up. It was taken starting point in the values implemented in OLGA, and from this the pipeline length and the pipeline length of the riser was calculated. The volume of the buffer tank also had to be implemented. In the original model of the L-shaped riser the whole pipeline length was implemented instead of a buffer tank. Also in OLGA the buffer tank was approximated as a long and narrow cylinder whereas it in reality is a shorter cylinder with a larger radius. It was taken measurements of the buffer tank in the laboratory and from this the volume of the buffer tank was estimated. Also the equation for the friction factor in the original script was replaced with the Haaland factor in order to increase the friction in the pipeline.

$$\frac{1}{\sqrt{\lambda}} = -1.8log\left[\left(\frac{\varepsilon/D}{3.3}\right)^{1.11} + \frac{6.9}{Re}\right] \tag{2}$$

where ε/D is relative roughness, Re is Reynolds number and λ is the Darcy friction factor. The Haaland equation is used to solve for the friction factor directly for a full-flowing circular pipe.
In addition to the obvious geometrical changes that had to be done, the four tuning parameters that could be changed was K_G, K_L, K_{pc} and K_h. These were essentially estimated from trial and error to fit the experimental data where the main focus was to fit the critical value of the valve opening.
As it is a simple model it need to be manipulated to achieve the desired results. While starting out with physical values of the riser lengths identical to the experimental set-up it soon became clear that these had to be changed. The final geometrical values used in the simple model is therefore not the same as calculated from the geometry. The final tuning values used is presented in Table 4.1.

Table 4.1: The tuning parameters implemented in the new model

Parameter	value
K_G	0.5
K_L	4
K_{pc}	2
K_h	1

The length of the pipeline and riser that are implemented in the simple model is shown in Table 4.2.

Table 4.2: The length of the riser and pipeline implemented in the simple model

Variable	Value implemented	Value Calculated
Length of upstream pipe	10.8 m	10.8 m
Length of riser	11 m	14.37 m
Buffer tank radius	0.20 m	0.11 m

4.2 Bifurcation Diagrams

In order to compare the simple MATLAB model to the experimental results bifurcation diagrams were made. These are explained in Section 1.6.1 and was made with the help of a MATLAB script constructed by Esmaeil Jahanshahi.

5 Results

The results from the different investigations are presented below. All the bifurcation diagrams are constructed whith a valve opening of 27 % as the critical point.

5.1 OLGA Simulation

5.1.1 Simulation of the Stability Map

The main objective for making the stability map was to see the regions of stability and to be able to compare them with the experimental results. The stability map was made in OLGA by manually implementing the different flow rates, observe the occurring flow regime and then collect the data manually. Two stability maps were created using OLGA. The first was made with the "complex case", meaning the case with a smaller PVT-table and more sections in the geometry. The "complex case" is considered to be more accurate than the simple case, but it has the disadvantage that it does not converge at low flow rates. This stability map was made some time before the experiments were executed, and is therefore not very strategically made, however the regions of slugging and stable flow can easily be observed. The result can be seen in Figure 5.1.

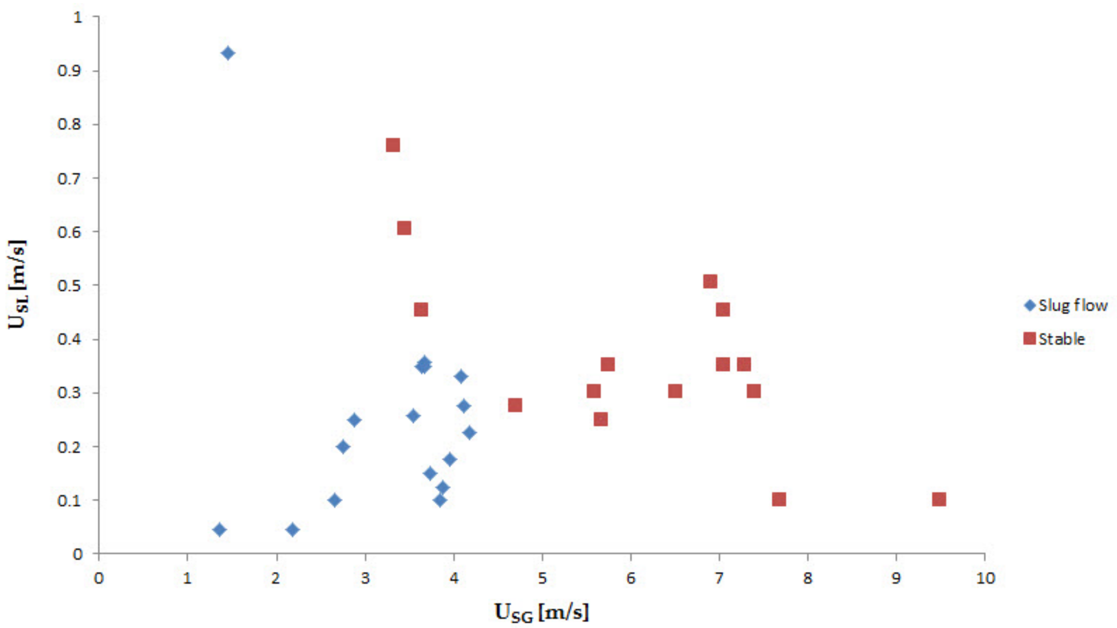

Figure 5.1: Stability map achieved using the complex simulation case in OLGA

After the experiments had been executed it became more clear which range of the superficial velocities the different flow regimes occurred. It was therefore necessary to make a new stability map using OLGA. However, to be able to construct a stability map for such low superficial velocities the simplified case needed to be used. The result can be seen in Figure 5.2.

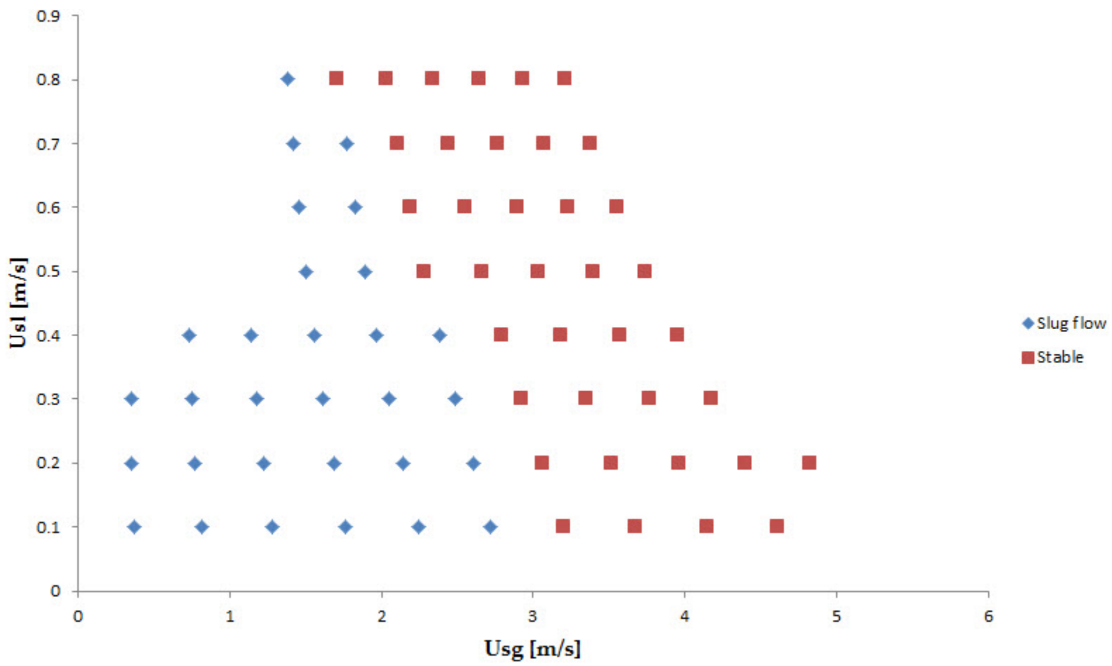

Figure 5.2: Stability map achieved using the simplified simulation case in OLGA

5.1.2 Simulation of the Bifurcation Diagram

The bifurcation diagram in OLGA was created using a value of $U_{sg} = 1\ m/s$ and $U_{sl} = 0.2\ m/s$. To manipulate the placement of the critical valve opening (the bifurcation point) the value of the coefficient of discharge was changed to $c_d = 0.40$. The resulting bifurcation diagrams can be seen in Figure 5.3 and 5.4

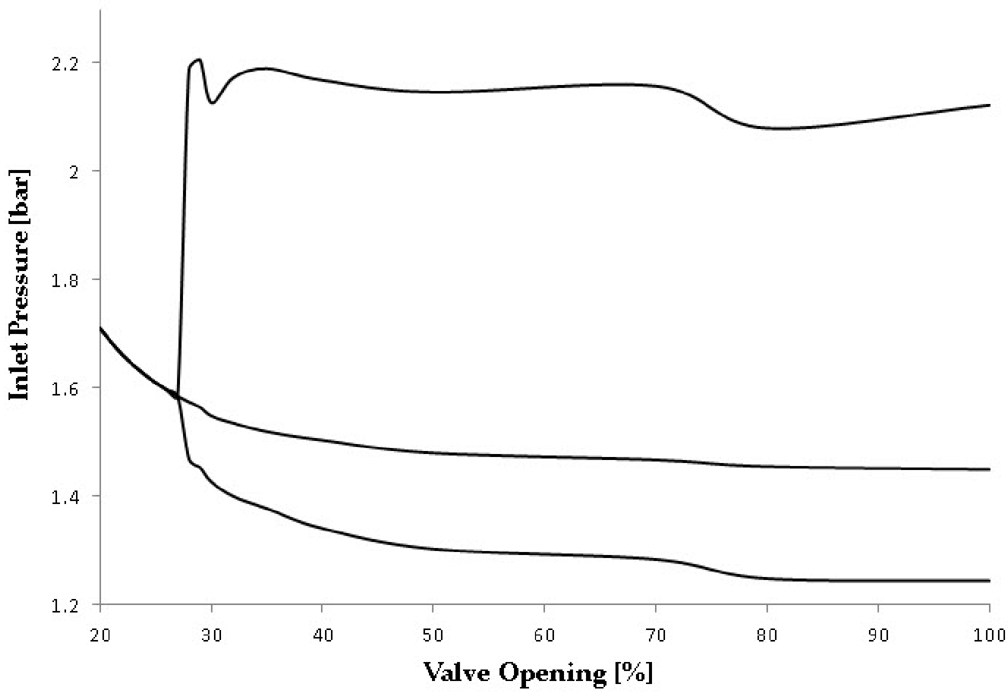

Figure 5.3: Bifurcation diagram made with simulation data from OLGA showing the variations in inlet pressure over a range of choke valve openings

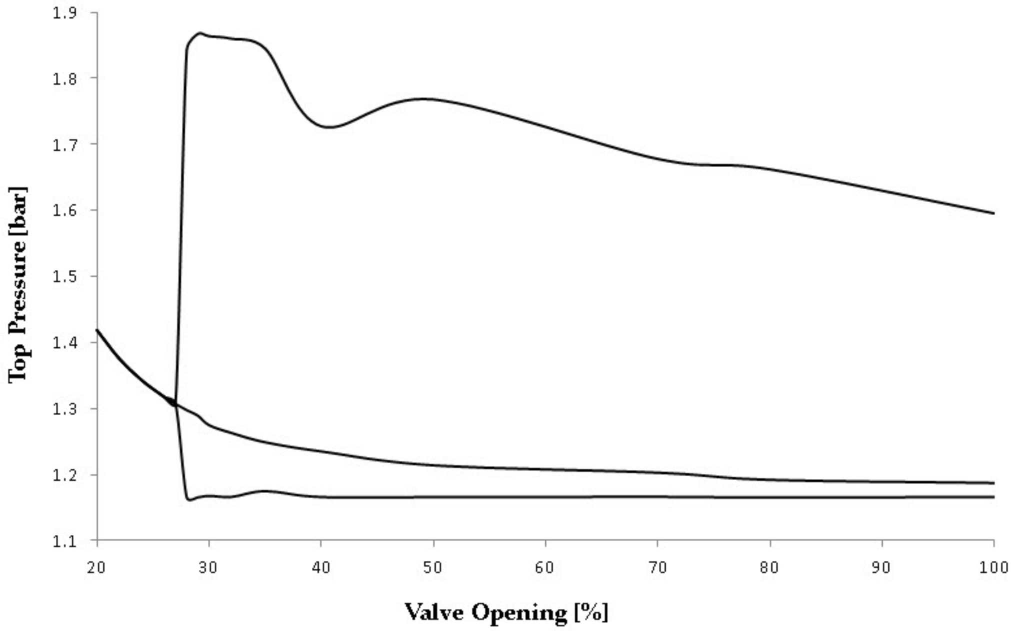

Figure 5.4: Bifurcation diagram made with simulation data from OLGA showing the variations in top pressure over a range of choke valve openings

5.2 Laboratory Experiment

5.2.1 Stability map

The stability map was made in order to compare the MATLAB model to the OLGA model over a large range of inflow rates. The resulting stability map can be seen in Figure 5.5 where the red ring indicates values used to make the bifurcation diagrams.

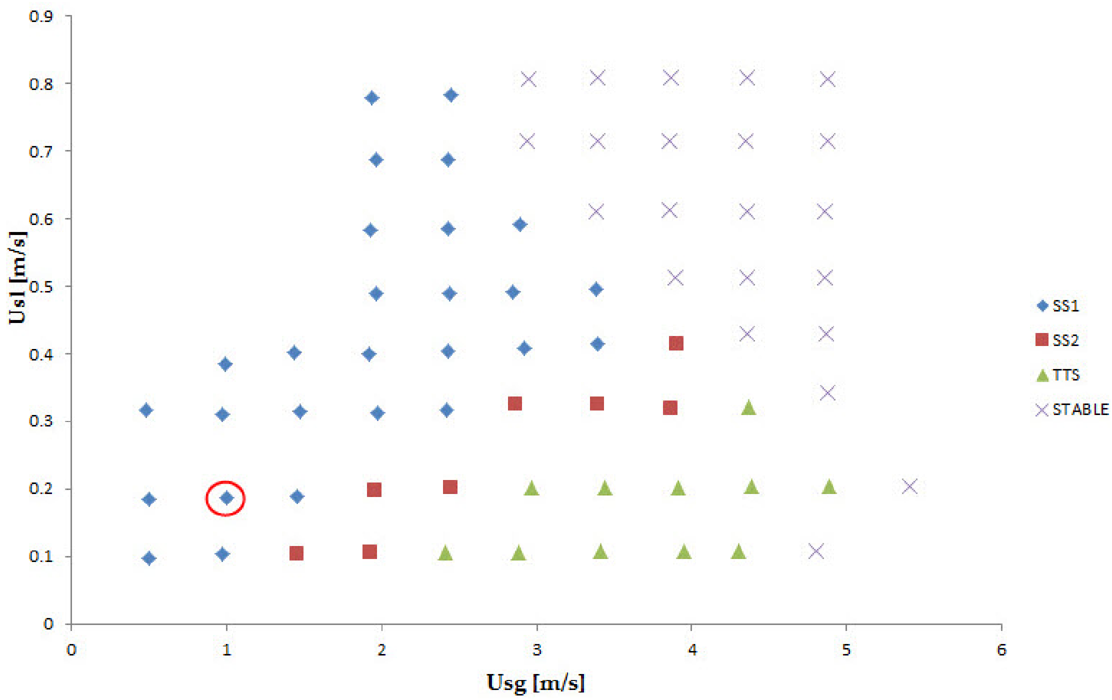

Figure 5.5: Stability map from laboratory experiments

5.2.2 Bifurcation diagram

The bifurcation diagrams were made in the laboratory by starting out with a small opening of the choke valve. It was waited until the system had stabilized, then data were logged before the valve opening was increased to the next step. The first bifurcation experiment only contained data from the buffer tank pressure as the top measurement device was yet to be installed. The resulting bifurcation diagram can be seen in Figure 5.6.

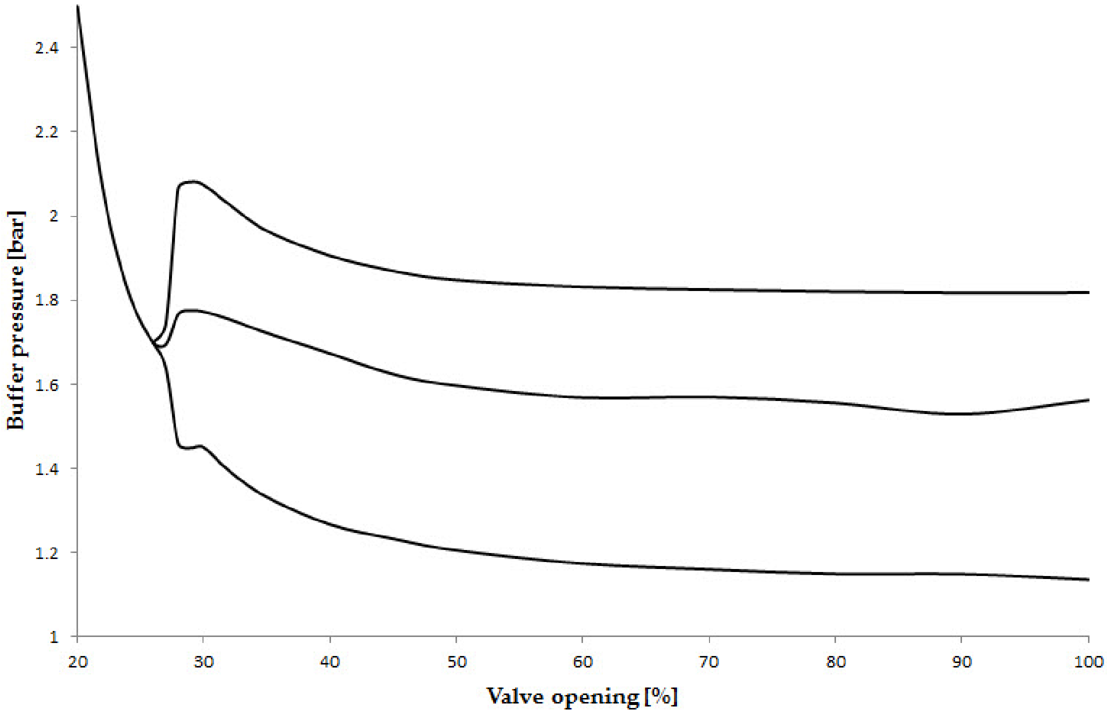

Figure 5.6: Bifurcation diagram from the first set of laboratory experiments

It should be noted that the curve in the middle is not the steady state values, but the average pressure. Therefore when comparing with the other simulation data this line is located at a higher pressure than the steady state pressures.

When the second set of bifurcation diagrams were made the top pressure measurement device was installed and it therefore also includes a bifurcation diagram for the top pressure. It is the results from the last bifurcation diagrams that is used to compare the experimental results to the simplified model. The bifurcation diagram for the buffer tank pressure can be seen in Figure 5.7 whereas the bifurcation diagram for the top pressure can be seen in Figure 5.8.

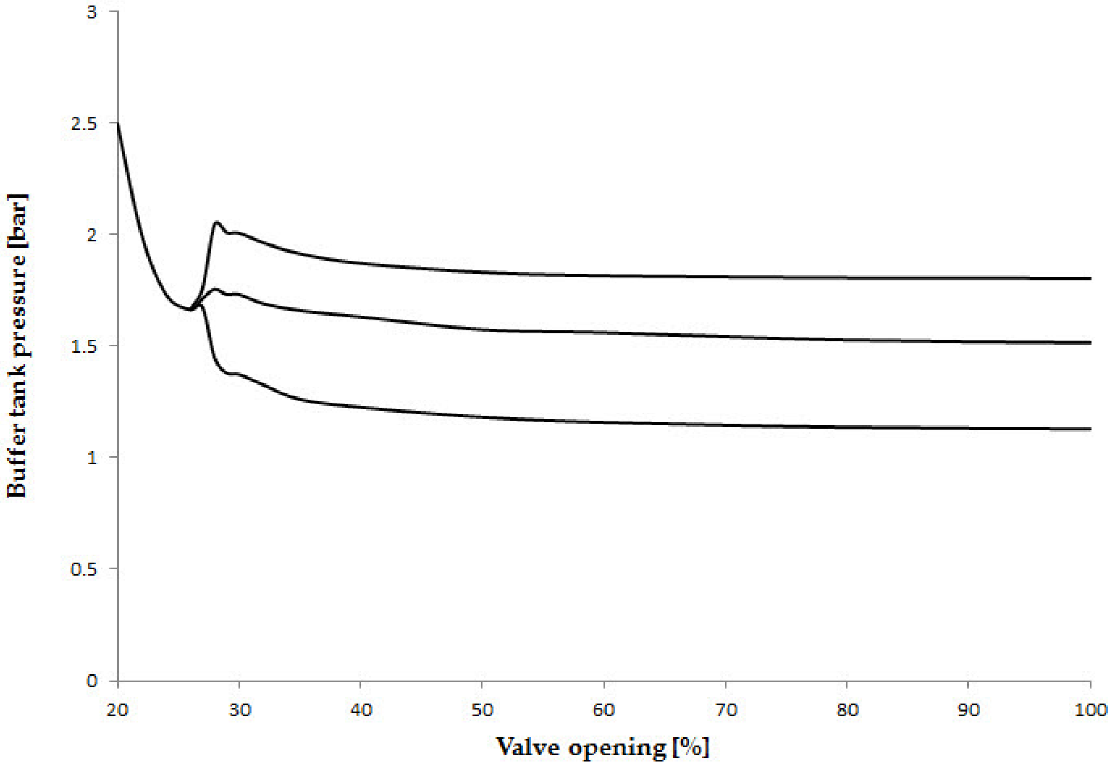

Figure 5.7: Bifurcation diagram showing how the buffer tank pressure changes with valve opening

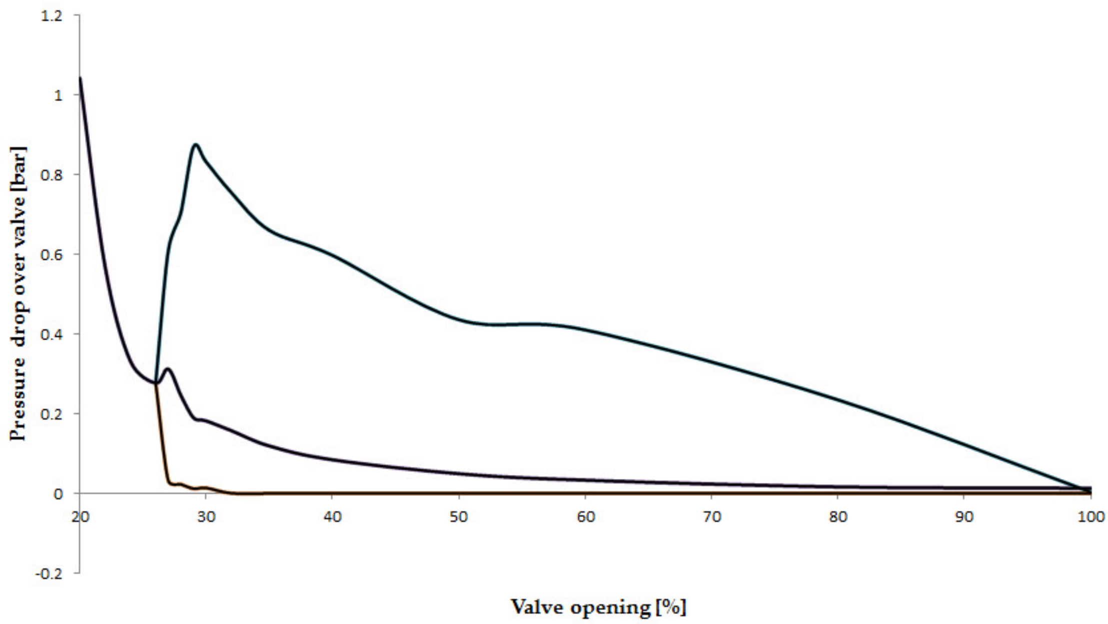

Figure 5.8: Bifurcation diagram showing how the pressure drop over valve changes with valve opening

In order to see the reproductive properties of the experiment (since it is a strongly non-linear system) the resulting buffer pressures from the different experiments were plotted in the same diagram. This result can be seen in Figure 5.9.

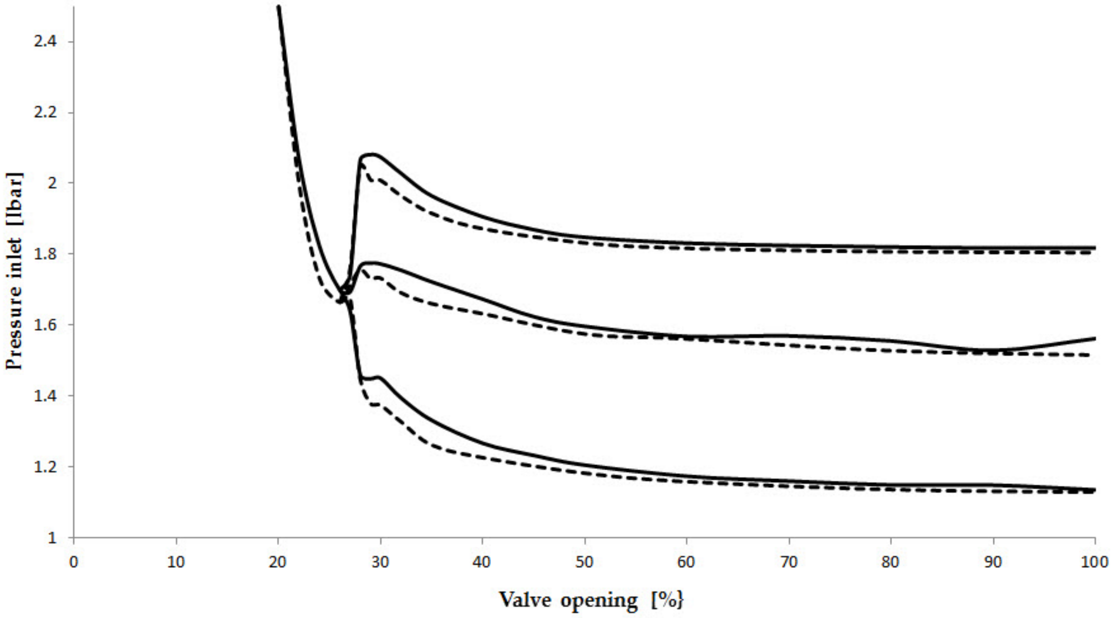

Figure 5.9: Comparison of the results from the two parallels of the experiment. The solid line denotes the first set of experiment while the dashed line denotes the second set of bifurcation diagrams

It is the second set of experimental results (dashed line) which is the one compared to the OLGA case and the simplified model. It can be seen from the figure that the results from the two parallels where satisfactorily close, which means that the experiment is reproducible.

5.3 MATLAB Model Compared with Results from OLGA Simulations and Laboratory Experiments

A comparison of the data from simulations performed with a S-shaped riser case in OLGA and the simple model of an L-riser can be seen in Figure 5.10

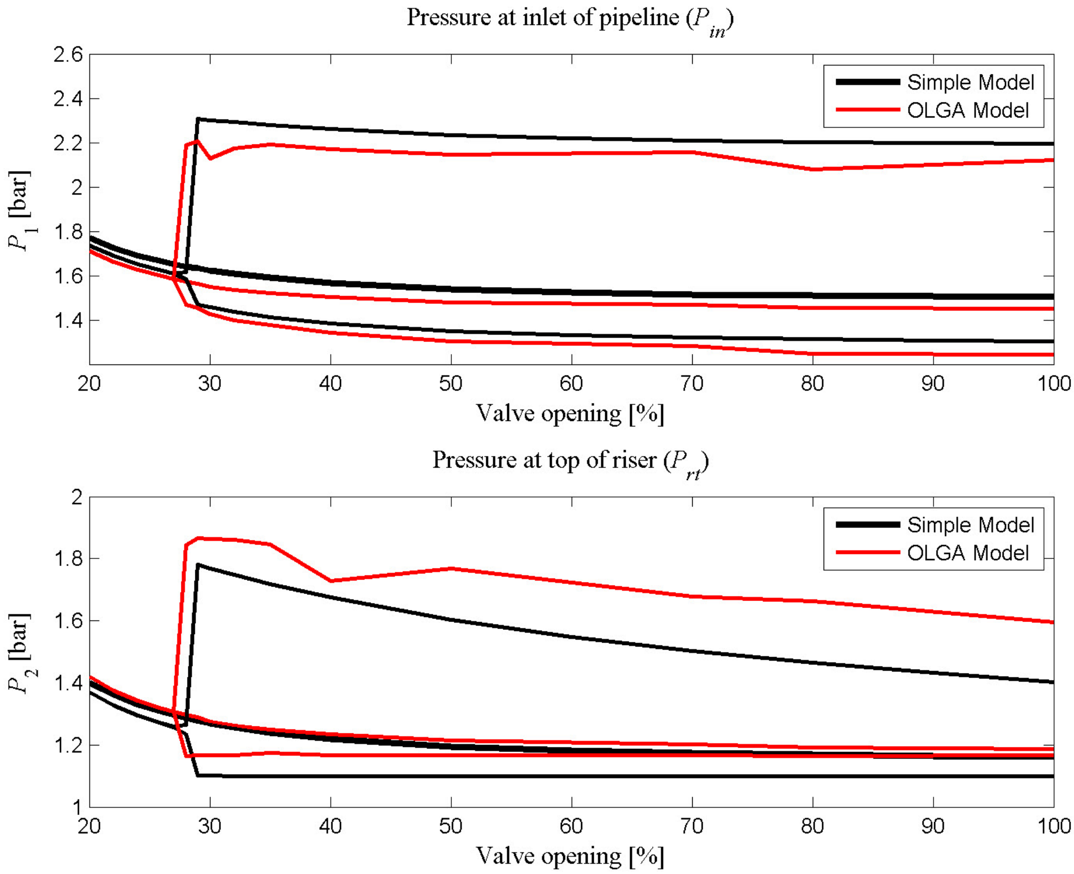

Figure 5.10: Simulation data from S-shaped riser case in OLGA compared to the simple model for a L-riser

It can be seen from the figure that the simple model match very well with the results from the OLGA simulations.

A comparison of OLGA simulation data and the experimental data can be seen in Figure 5.11

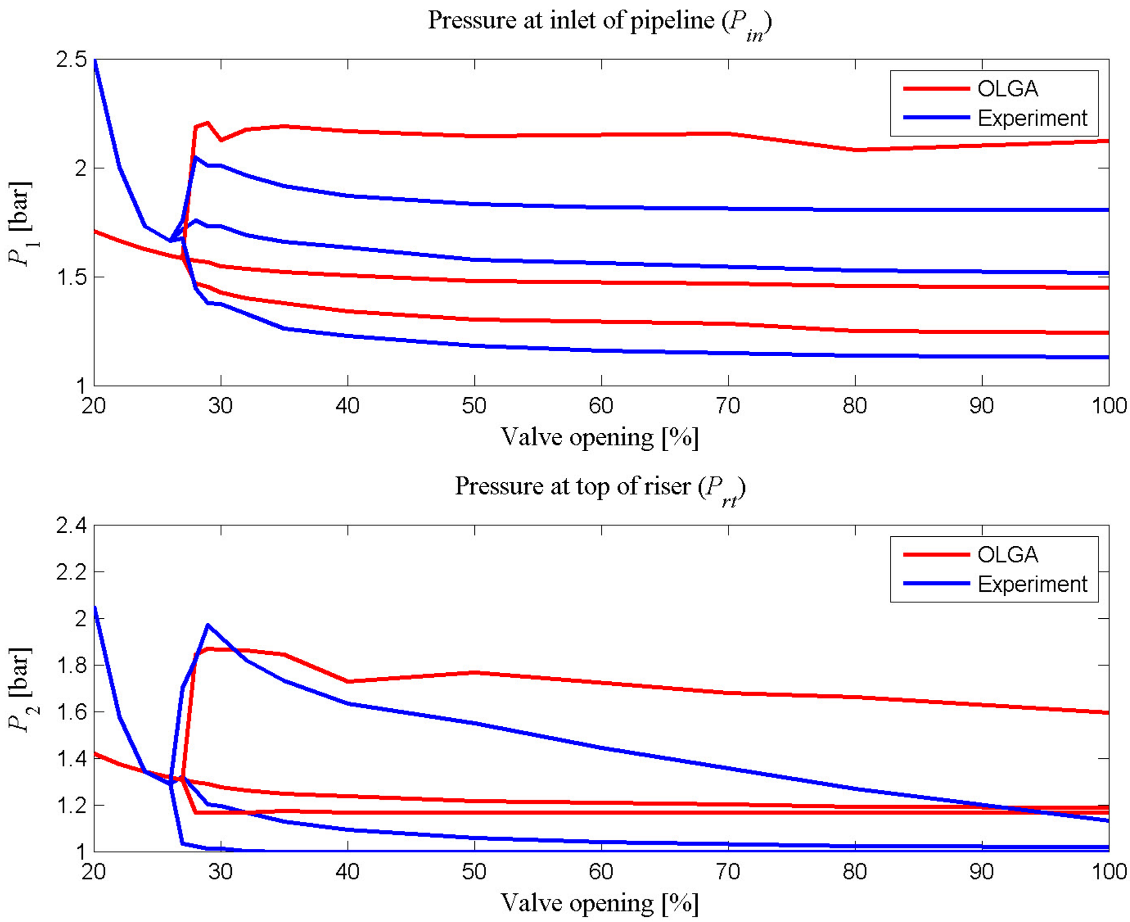

Figure 5.11: Simulation data from S-shaped riser case in OLGA compared with experimental results from a S-shaped riser

The two models deviate slightly from each other. The maximum of the oscillations are at a higher pressure for the OLGA simulations than for the experiment. The trends however, are the same and can not said to be a fair match.

A comparison of experimental data and the simple model can be seen in Figure 5.12

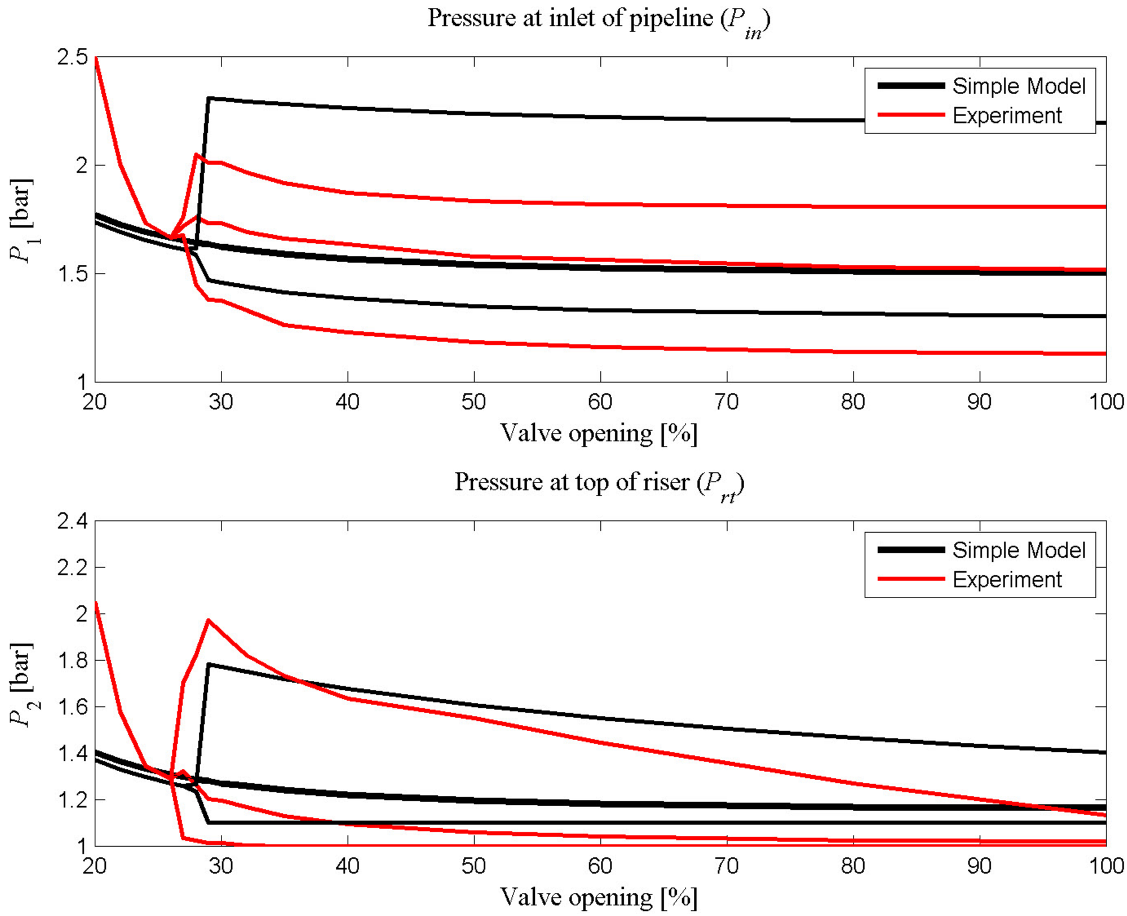

Figure 5.12: Simulation data from the simple L-shaped riser model compared with experimental results from a S-shaped riser

The top pressure for the simple model and the experiment match to a certain degree. The maximum of the oscillations however, deviates relatively much.

5.4 A Comparison of Parameters from the Simulation Results with the Experimental Results

To further compare the OLGA case with the simple model from MATLAB and the experimental results two tables were constructed containing their respective periods, and their maximum and minimum pressures in the oscillations. The resulting parameters from the experiment and simulations for a fully open valve are presented in Table 5.1.

Table 5.1: Different parameters from the three results with a valve opening of 100 %

Parameter	OLGA	MATLAB	Experiment
Period [s]	88	755	91
Max inlet pressure [bar]	2.13	2.22	1.79
Min inlet pressure [bar]	1.25	1.35	1.13
Max top pressure [bar]	1.58	1.44	1.08
Min top pressure [bar]	1.17	1.15	1.0

The resulting parameters from the experiment and simulations for a 50% valve opening are presented in Table 5.2.

Table 5.2: Different parameters from the three results with a valve opening of 50 %

Parameter	OLGA	MATLAB	Experiment
Period [s]	97	798	103
Max inlet pressure [bar]	2.14	2.28	1.83
Min inlet pressure [bar]	1.33	1.39	1.23
Max top pressure [bar]	1.75	1.63	1.55
Min top pressure [bar]	1.17	1.15	1.0

The periods of the slugging cycles in the simplified model is very different from the results of the experiment and the OLGA simulation. This can be achieved by doing some further adjustments to the simple model, but due to time issues it was rather put focus on matching the simple model to the critical valve opening and the pressures instead. Aside from the fact that the periods does not match it can be seen that the pressures achieved for the simple model and simulations in OLGA match very well. The pressures found in the experimental set-up is a bit lower than the simulation pressures.

6 Discussion

From the results it can be seen that the manipulated L-riser model did fit adequately to the simulation results from OLGA. However, the simplified L-riser model did not fit very well with the experimental results. However, as the simulation results in OLGA came out so different for the two simulation cases the question can be raised to which of the three tools used in this research is the most trustworthy.

Two stability maps were created in OLGA. The stability map created with the "complex"-case in OLGA presented in Figure 5.1, is the one that imitates the results from the experimental stability the best. In fact it has almost identical regions of stability. This may indicate that the OLGA case reflects the real conditions relatively well. However, the manipulations done to make OLGA converge may have resulted in untrustworthy results. This is be seen when the stability map created with the simple version, Figure 5.2, is compared to the experimental results. The region of stability is shifted 2 m/s to the left even if the same inflow rates are used. The manipulations performed in OLGA, such as changing the valve coefficient and increasing the initial pressure conditions in the outlet is probably the reason for this change. However, the accuracy of the experimental data can not necessarily be trusted either. The measurement instruments at the experimental set-up is not of the best quality and the results from these may be inaccurate. Also, in the simple model the valve is assumed to have a linear characteristic, however this may not be the case for the valve used in the experiment.

These experiments and simulations are performed with air and water as the fluids and not the oil and gas which would be present in real systems. Therefore, even if the simple model fits to the experimental data it does not mean that it can be extended to count for real system. If so it is dependent on good real test data to build on so that it can be tuned to fit the specific system. The bends of the s-riser in the laboratory also was very sharp which not necessarily will be the case in a real system, although it does fit well with the OLGA data. Also it needs to be mentioned that the s-riser that is used for the experiment is of the rigid kind. Its bends are rather sharp and not very similar to those used in today's offshore fields.

7 Concluding Remarks and Suggestions to Further Work

The objective of this study was to investigate the dynamics of S-shaped risers relative to the dynamics of L-shaped risers. It was found that by changing parameters in the simplified model for an L-riser, a model is achieved which imitates the behavior of a S-shaped riser reasonably if compared with simulation data from OLGA. The case is somewhat different when compared to experimental results. It can not be stated that the simplified model imitates the dynamics of the S-shaped riser experiments well, but it is a fair match. But the dynamics of S-shaped and L-shaped risers are not that different and adequate dynamics for an S-shaped riser can be achieved with a model designed for L-shaped risers.

Further research should be done to fit the simple model better to the experimental data. The simple model should be extended to a S-shaped riser model and this should be compared to the simple L-shaped riser model. Also, the numerical problem with OLGA at low superficial velocities should be solved.

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Appendices

A Matlab Model in State Space

A.1 State equations

The state equations are essentially just the mass balances of the system and is presented below.

$$\dot{m}_{G1} = w_{G,in} - w_{G,lp}$$

$$\dot{m}_{L1} = w_{L,in} - w_{L,lp}$$

$$\dot{m}_{G2} = w_{G,lp} - w_{G,out}$$

$$\dot{m}_{L2} = w_{L,lp} - w_{L,out}$$

The subscripts G and L denotes Gas and Liquid, and 1 and 2 means the pipeline and the riser respectively. The subscript lp denotes the low point of the riser.

A.1.1 Pipeline model

Liquid Mass of liquid in the pipeline:

$$\bar{m}_{L1} = \rho_L V_1 \bar{\alpha}_{L1}$$

level of liquid in the low-point is approximately

$$\bar{h}_1 \cong h_c \bar{\alpha}_{L1} \Rightarrow \bar{h}_1 = K_h h_c \bar{\alpha}_{L1}$$

where K_h is a correction factor around unity which can be used to tune the model. If liquid content in pipeline increases by Δm_{L1}

$$\Delta h_1 = \Delta L sin\left(\theta\right) \Rightarrow h_1 = \bar{h_1}\ \Delta L sin\theta$$

$$\Delta m_{L1} = \Delta L \pi r_1^2 \left(1 - \bar{\alpha_{L1}}\right) \rho_L \Rightarrow \Delta L = \frac{\Delta m_{L1}}{\pi r_1^2 \left(1 - \bar{\alpha_{L1}}\right)}$$

$$\Delta m_L = m_{L1} - \rho_L V_1 \bar{\alpha_{L1}}$$

Gas Volume of gas in the pipeline:

$$V_{G1} = V_1 - \frac{m_{L1}}{\rho_L}$$

Gas density in pipeline

$$\rho_{G1} = \frac{m_{G1}}{V_{G1}}$$

Pressure in pipeline (ideal gas):

$$P_1 = \frac{\rho_{G1} R T_1}{M_G}$$

Pressure loss due to friction (only considered liquid):

$$\Delta P_{fp} = \frac{\bar{\alpha_{L1}} \lambda_p \rho_L \bar{U_{sl,in}^2} L_1}{4 r_1}$$

where

$$\lambda_p = 0.0056 + 0.5 Re_p^{-0.32}$$

and

$$Re_p = \frac{2 \rho_L \bar{U_{sl,in}} r_1}{\mu}$$

and

$$\bar{U_{sl,in}} = \frac{w_{L,in}}{\pi r_1^2 \rho_L}$$

Riser Model Total Volume of riser:

$$V_2 = \pi r_2^2 (L_2 + L_3)$$

Volume occupied by gas in the riser:

$$V_{G2} = V_2 - \frac{m_{L2}}{\rho_L}$$

Pressure in the top of the riser (ideal gas):

$$P_2 = \frac{\rho_{G2} R T_2}{M_G}$$

where

$$\rho_{G2} = \frac{m_{G2}}{V_{G2}}$$

Average liquid volume fraction in riser:

$$\overline{\alpha}_{L2} = \frac{m_{L2}}{V_2 \rho_L}$$

Average density of the mixture in the riser

$$\overline{\rho}_m = \frac{m_{G2} + m_{L2}}{v_2}$$

Friction loss in the riser:

$$\Delta P_{fr} = \frac{\overline{\alpha}_{L2}\lambda_r\overline{\rho}_m\overline{U}_m^2\left(L_2+L_3\right)}{4r_2}$$

where

$$\lambda_r = 0.0056 + 0.5Re_r^{-0.32}$$

and

$$Re_r = \frac{2\rho_m\bar{U}_m r_2}{\mu}$$

The average mixture velocity in the riser is

$$\overline{U}_m = \overline{U}_{sl2} + \overline{U}_{sg2}$$

where

$$\overline{U_{sl2}} = \frac{w_{L,in}}{\pi r_1^2\rho_L}$$

and

$$\overline{U_{sg2}} = \frac{w_{G,in}}{\pi r_1^2\rho_{G2}}$$

Gas Low Point When $h_1 \geq h_c$ then $w_{G,lp} = 0$. When $h_1 < h_c$ then

$$w_{G,lp} = K_G A_G\sqrt{\rho_{G1}\Delta P_G}$$

where

$$\Delta P_G = P_1 - \Delta P_{fp} - P_2 - \overline{\rho}_m g L_2 - \Delta P_{fr}$$

Liquid Low Point

$$w_{L,lp} = K_L A_L\sqrt{\rho_L\Delta P_L}$$

where

$$\Delta P_L = P_1 - \Delta P_{fp} + \rho_L g h_1 - P_2 - \overline{\rho}_m g L_2 - \Delta P_{fr}$$

and

$$A_G \cong \pi r_1^2\left(\frac{h_c - h_1}{h_c}\right)^2 \qquad h_1 < h_c$$

$$A_L = \pi r_1^2 - A_G$$

A.1.2 Outflow conditions

$$\alpha_L = \frac{\frac{\alpha_{Lm}}{\rho_L}}{\frac{\alpha_{Lm}}{\rho_L} + \frac{(1-\alpha_{Lm})}{\rho_G}}$$

$$\bar{\alpha}_{Lm1} = \frac{w_{L,in}}{w_{G,in} + w_{L,in}}$$

$$\bar{\alpha}_{L1} = \frac{\bar{\rho}_{G1} w_{L,in}}{\bar{\rho}_{G1} w_{G,in} + \rho_L w_{L,in}}$$

$$\bar{\rho}_{G1} = \frac{P_{1,nom} M_G}{RT_1}$$

$$w_{mix,out} = K_{pc} f(z) \sqrt{\rho_t (P_2 - P_0)}$$

$$w_{L,out} = \alpha_{Lm,t} w_{mix,out}$$

$$w_{G,out} = (1 - \alpha_{Lm,t}) w_{mix,out}$$

A.2 Tuning Parameters

The simplified model uses four tuning parameters to fit the model to the system in question. These are the choke valve coefficient K_{pc}, the orifice coefficient for gas flow through the low point K_G, the orifice coefficient for liquid flow through low point and K_h which is the correction factor for the level of liquid in the pipeline.

B Matlab Scripts