NTNU
Norges teknisk-naturvitenskapelige universitet

Fakultet for naturvitenskap og teknologi
Institutt for kjemisk prosessteknologi

SPECIALIZATION PROJECT 2012

TKP 4550

PROJECT TITLE:

Studies on slug flow in S-risers: LedaFlow simulations and experiments

By

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Date: 07 Dec 2012

Acknowledgments

I would like to acknowledge my co-supervisor Esmaeil Jahanshahi who has helped me a lot in doing my specialization project. He has always been available for questions and really did help me in all experiments and simulations.

Abstract

Anti-slug control could have an important role in preventing sever slugging in S-risers. The one that leads to serious problems in production facilities. Applicability of acoustic signal as a device for detection and monitoring of sever slugging in S-riser has been evaluated before. In this report its application as an input signal for controller (PV signal) has been studied.

Slugging in S-risers has been simulated in LedaFlow simulator.

Two detailed flow pattern map for steel S-riser containing air-water flow have been constructed. One is based on experiments, done in multiphase flow lab and the other is based on simulations done with Ledaflow. The results are compared.

Two bifurcation diagrams explaining the open loop behavior of S-riser system have been also made, one with experiments and the other with simulations in LedaFlow. The results have been compared.

Contents

1 Introduction

Connection between subsea pipelines and surface facilities is often made by S-shape risers with the aim of reducing mechanical stresses.

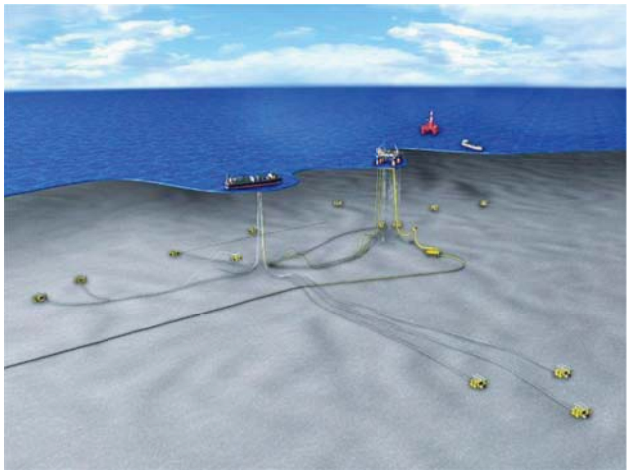

Figure 1: Floating gas production platforms, (Source: [1])

A common problem in this S-risers carrying oil and gas mixtures is severe slugging phenomenon. It includes liquid accumulation and blockage in the bends, its propagation through the riser and finally blowing out after back pressure overcomes the static head of the rising liquid column. It causes damage and flooding of operating surface facilities. Therefore finding new solutions correspondent to up to date technology is very important. Using slug catchers or gas lift in the risers has been considered as traditional solutions to mitigate this problem. However they are not the best solutions. A gliding traditional solution including using a top side choke valve has been studied in many projects and papers. Active control of this choke valve using an appropriate control variable can be very insightful. It has been shown previously that passive acoustic signals can monitor the type of flow regime, very well. The first part of this report investigates its application as an input signal for controller (PV signal). A right comparison between pressure signals and acoustic signals can be a good criterion to certify acoustic sensor applicability. The tests will be implemented in multi-phase flow Lab.
Severe slugging is a strong motivation for developing transient flow simulators [1]. LEDA is the new multiphase flow simulator with improved models and numeric [2]. In the second part of this report severe slugging in S-risers has been simulated in LEDA and the results are compared with the experimental one.

2 Theory

2.1 Multiphase flow regimes

Multiphase flow inside the pipeline can make different regimes of mixed or separated type depending on the fluid properties, phase velocities, pipe inclination and gas or liquid fraction. Figure 2 from [3] shows different flow regimes inside horizontal and vertical pipelines.

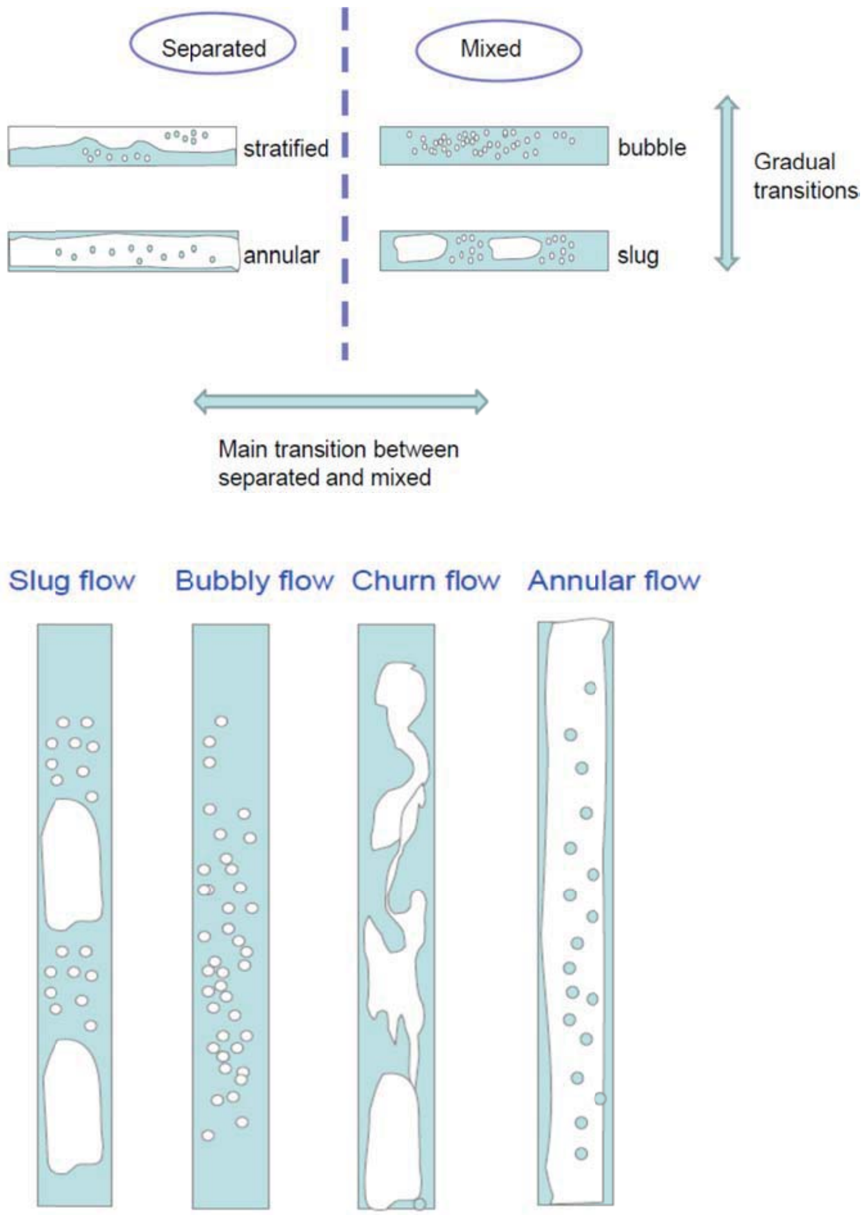

Figure 2: different flow regimes in horizontal and vertical pipelines

2.1.1 Slug flow

Slug flow is a dynamic flow containing sequence of bubbles and liquid slugs including two types of hydrodynamic slugging and terrain slugging. Hydrodynamic slugging is shown in figure 3.

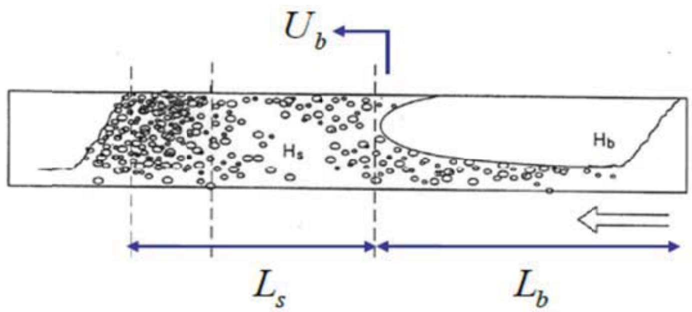

Figure 3: Hydrodynamic slugging

If the condition is true, hydrodynamic slugging, the small scale slug flow, would lead to severe (terrain) slugging, the large scale slug flow, which is an operational problem. A riser system (S-riser or L-riser) provide this condition very well.

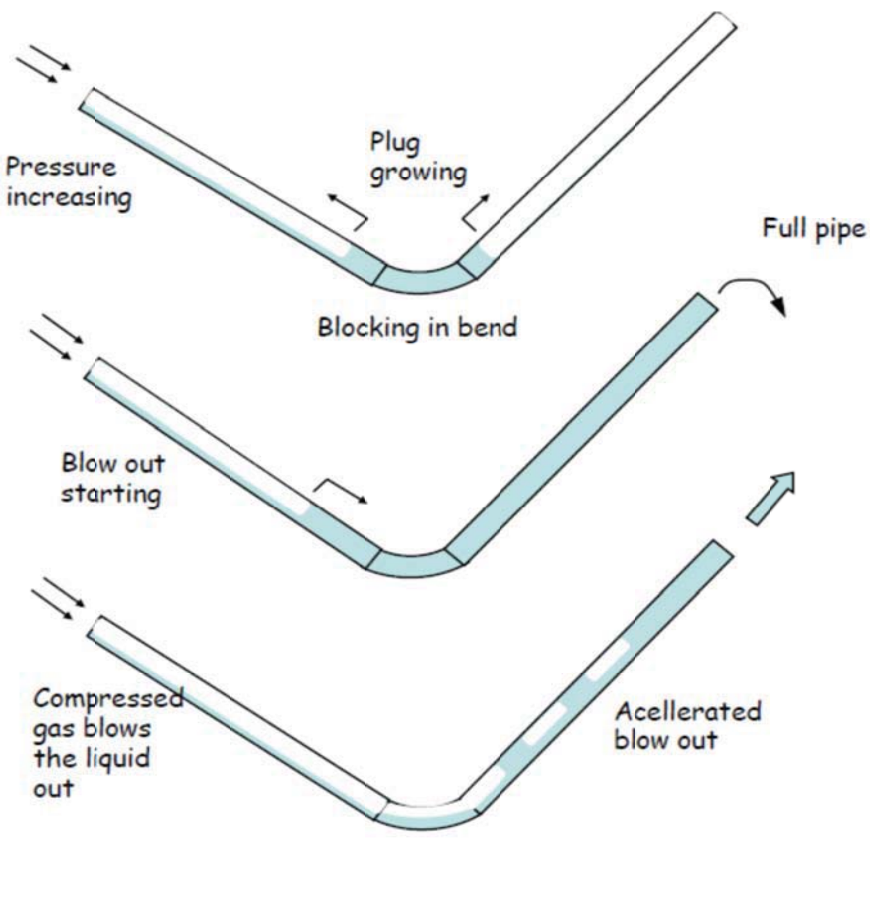

Figure 4: Severe slugging principle (Source: [4])

As it is seen in figure 4, this phenomenon occurs as regular liquid buildup and blow out of large liquid slugs in riser systems. There are two modes of severe slugging: I and II, with the following characteristics [3]:

Severe slugging I
Full liquid blockage in bend
Pressure oscillations reflect static head of the rising liquid column
Large oscillations in pressure
Accelerated blow out

Severe slugging II
Partial blockage at bend: gas passes through
Small pressure oscillations, but flow oscillations can be large

In figure 5 [3], an example of unstable flow from recordings of flow on offshore platform in the North Sea is indicated. Liquid slugs are exceeding 900m in length.

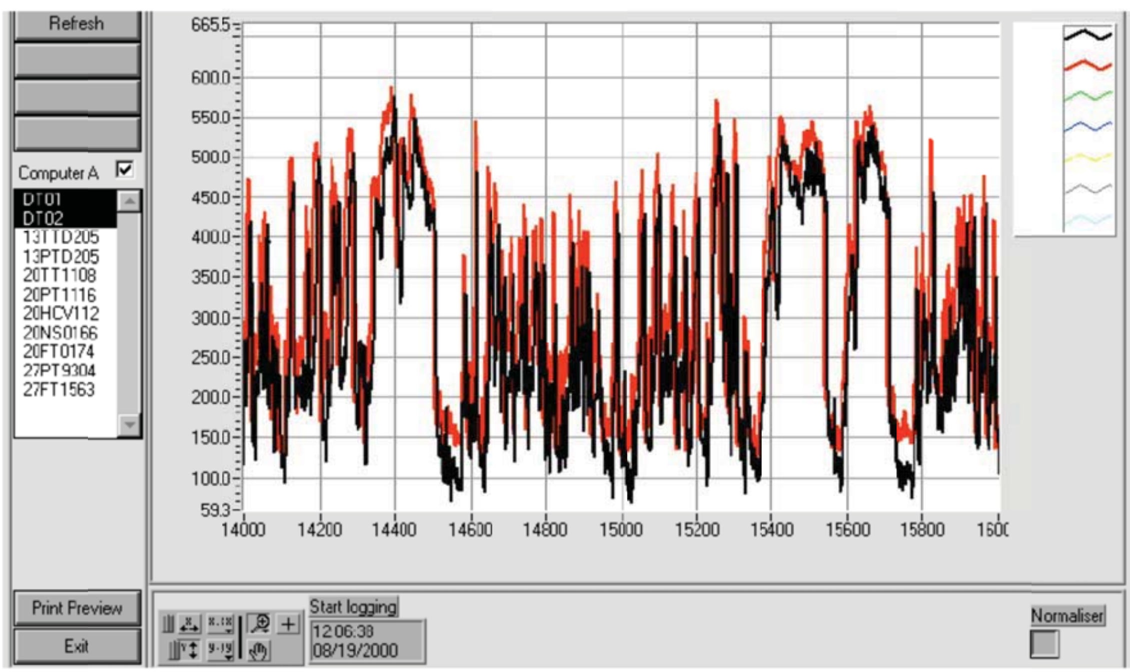

Figure 5: Recording of Severe-slugging in North Sea

2.1.2 Dynamic modeling of severe slugging

Flow simulators like OLGA and LEDA use fundamental physics and empirical correlations to model severe slugging. These simulators are very good tools to dynamic modeling and simulation of severe slugging. They can predict all issues related to unstable flow inside the pipeline, including where and when the flow becomes unstable and also the characteristics of the unstable flow. Moreover, they can give remediation strategies to stabilize the flow. Generally, when doing operational transients including production changes, shut-down, blow-down, restart, cooling during shut down, pigging and hydrate plugs there is a high requirement to dynamic models [3]. These dynamic models solve a set of conservation equations while considering closure relations (friction and/or slip relations) and using numerical methods.

In such simulators user chooses the pipeline profile, discretizes it in computational grid with desired grid length and sets the fluid properties, boundary conditions (pressure or flow) and initial conditions as input. Time evolution of pressure, temperature and gas (liquid) fraction along the pipeline will be predicted by the simulator as the output.

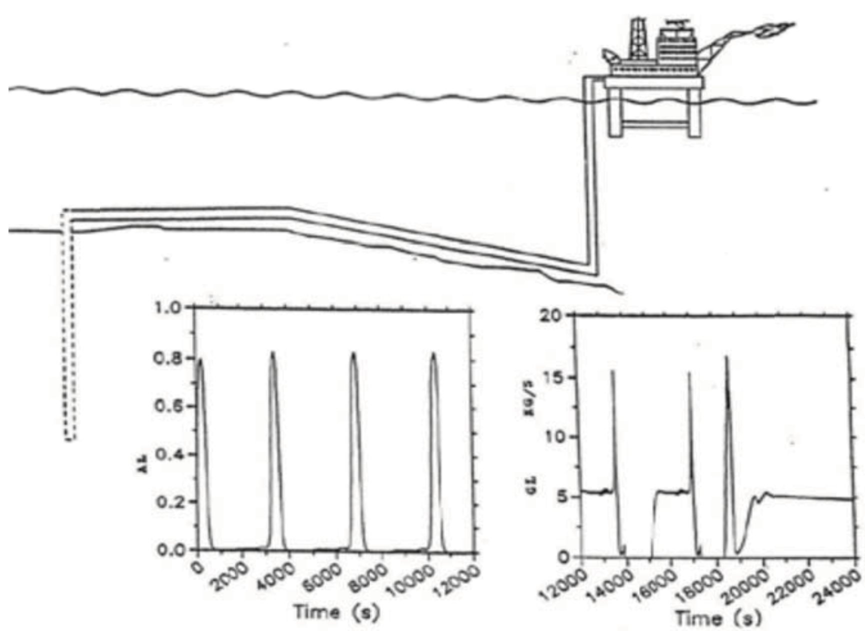

Figure 6: Steady flow after severe slugging, (Source: [3])

2.2 LedaFlow simulator

New dynamic flow simulator, LedaFlow, has been developed, progressed at SINTEF.

Figure 7: SINTEF Multiphase Flow Laboratory, Trondheim (Source: [3])

LedaFlow uses a multi-fluid multi-field approach for modeling multiphase flow [4]. The principles are shown in figure 8.

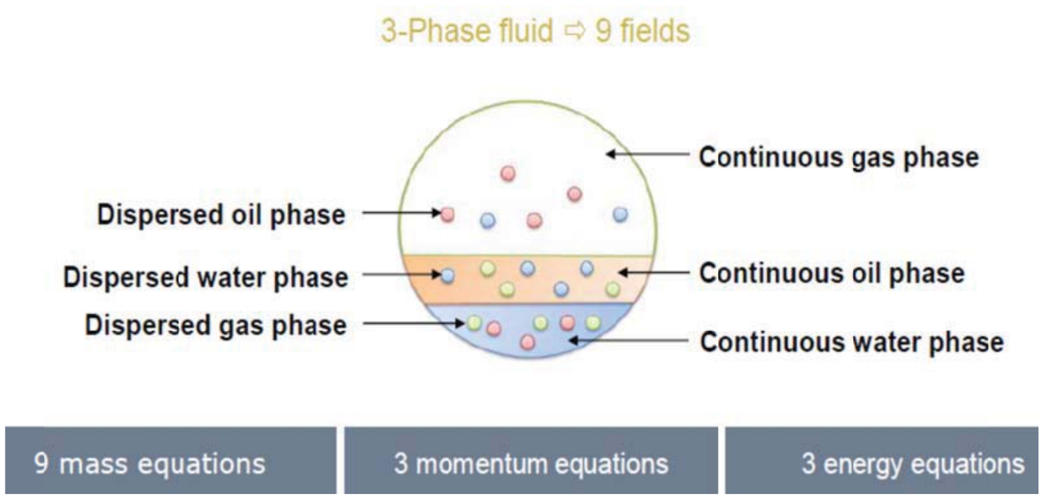

Figure 8: Conservation equations in LedaFlow (Source: [4])

In this project, LedaFlow was used for simulating severe slugging in S-riser, making the stability map of two phase flow and making the bifurcation diagram of pressure oscillations in different valve opening percentages.

The LedaFlow interface shown in figure 9 was developed over the ongoing simulations with different gas and liquid velocities and also different gridding numbers.

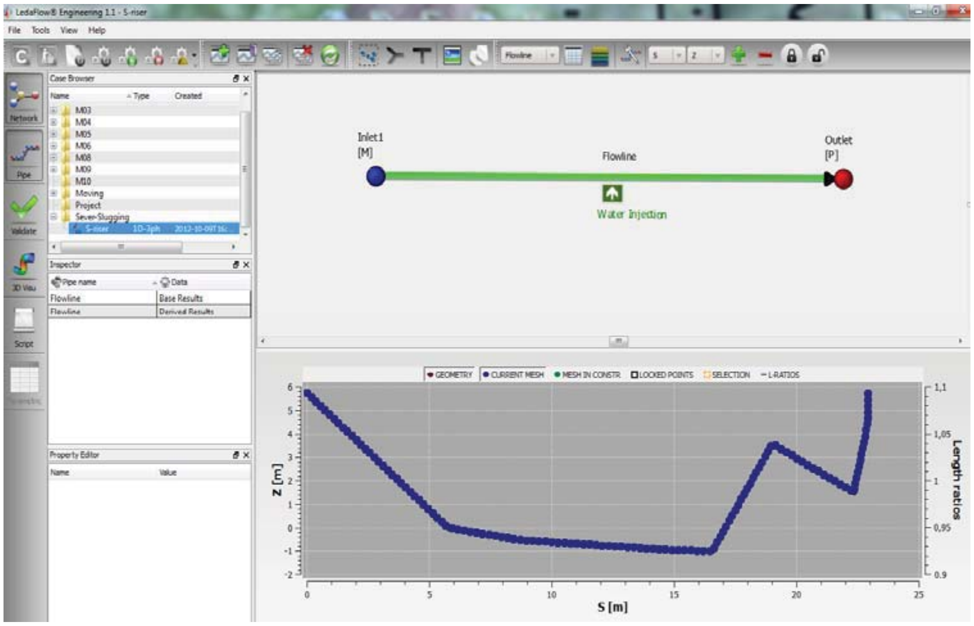

Figure 9: Operating screen for the simulations

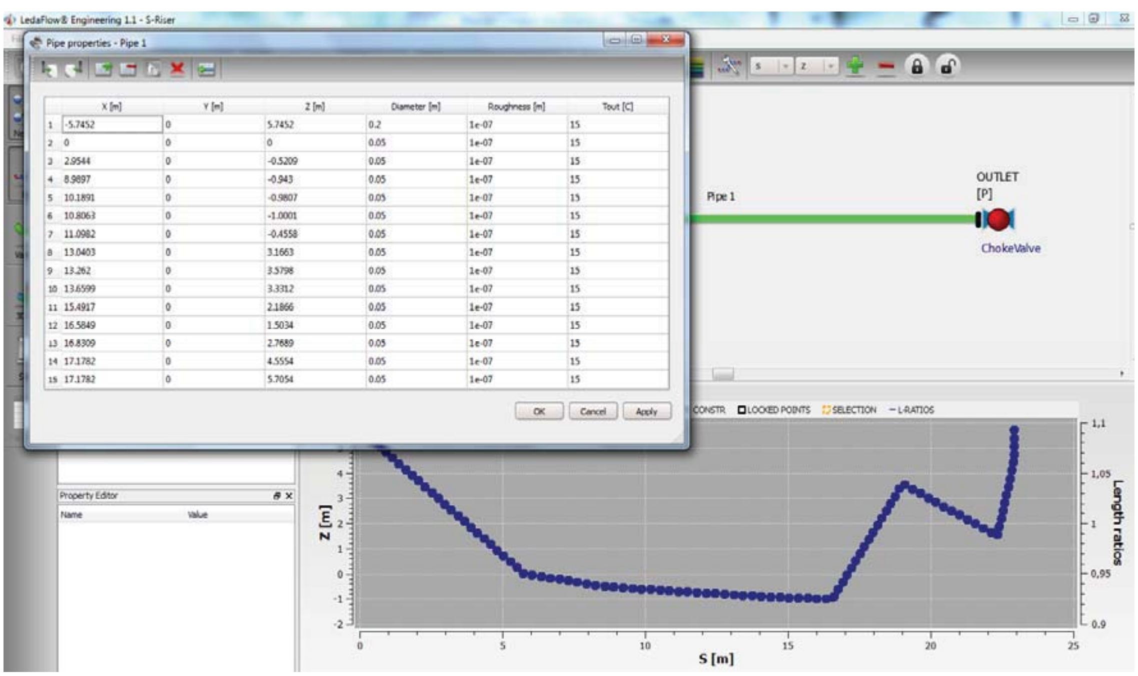

Figure 10: Riser system geometry fed to the simulator

According to the experimental setup in multiphase flow laboratory, it was decided to send only gas to the inlet and then inject water from a source to the midway of the pipeline before the riser. The gas and water Source points are illustrated in figures 11 and 12.

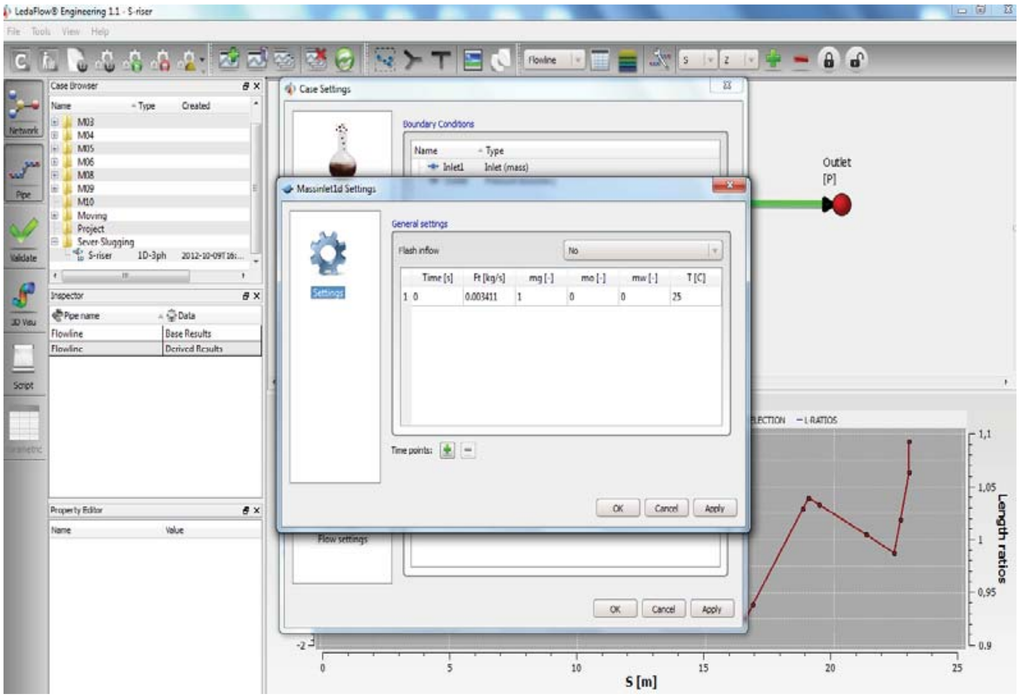

Figure 11: Gas source position

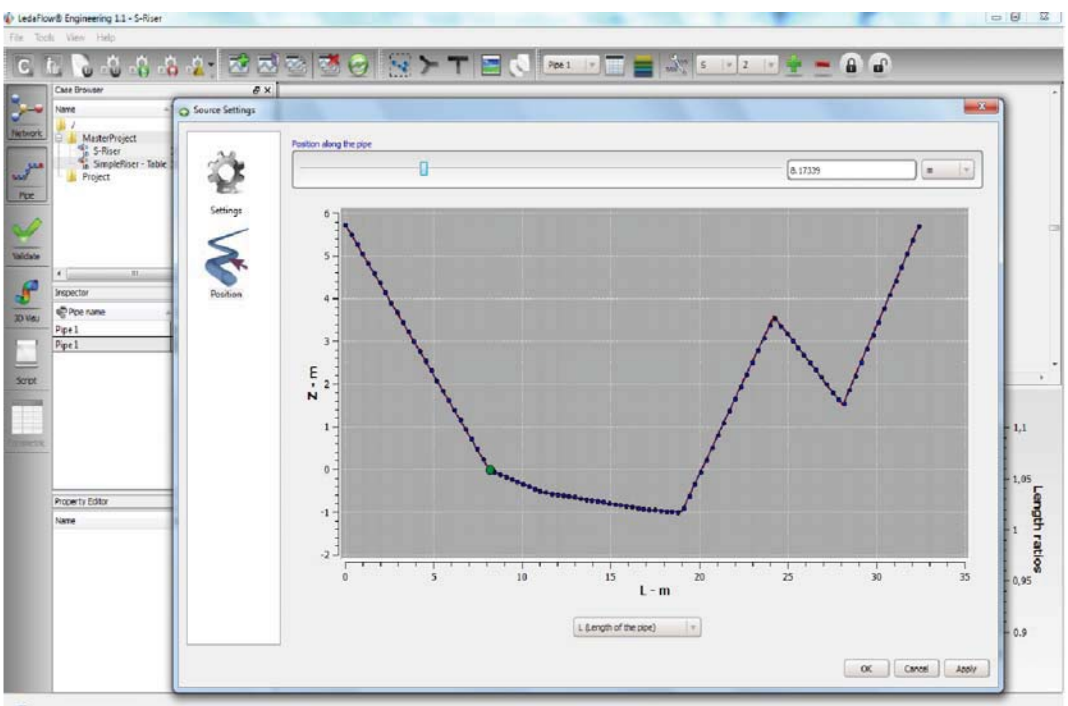

Figure 12: Water source position

2.3 Acoustic signal

Although a good modeling and simulation can be very useful in prevention of severe slugging, still using a simple control system can produce a more stable flow. A choke valve on top of the riser is used as manipulated variable. Like many other control systems, selecting a good control variable is a vital issue and signals produced by pressure or acoustic sensors mounted on different parts of the riser system could be suitable candidates.

Applicability of pressure signals related to different parts of mixing point, topside and buffer tank has been previously studied at NTNU [5]. This project focuses on acoustic signals.

Acoustic signal detects the type of flow regime very well. Depending on the flow regime, it shows different behavior. In a severe slugging region, it shows a cyclic behavior. Figure 13 [6] indicates the results of acoustic and pressure sensor for the severe slugging region.

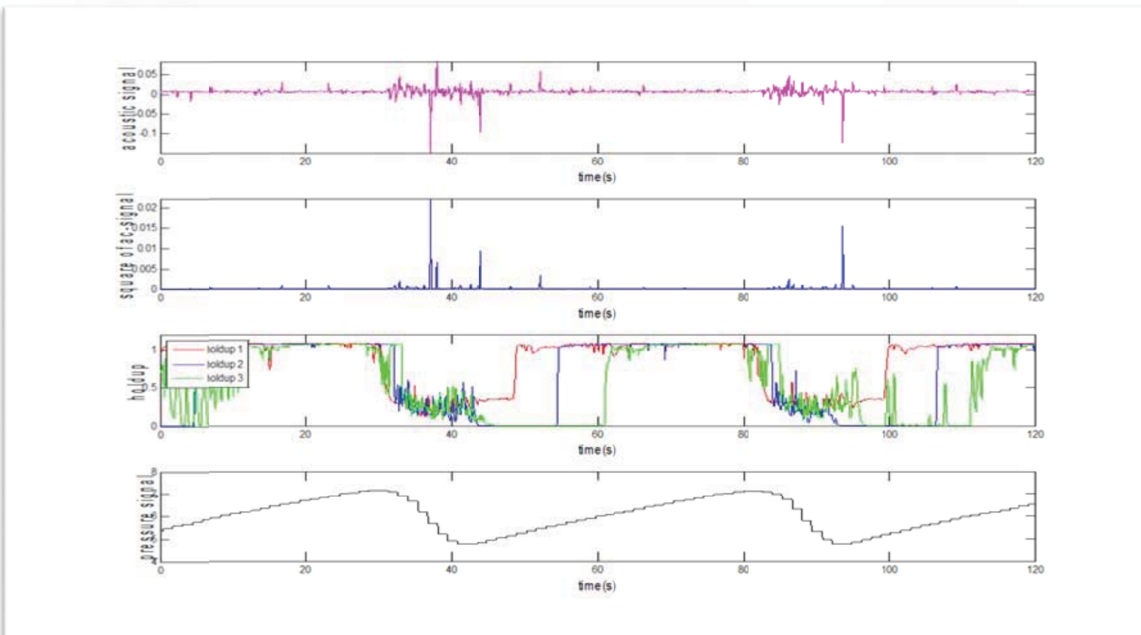

Figure 13: Acoustic, Holdup, and Pressure Signals for SS1. (Source: [6])

As it is clear in the figure, there is no sound when the riser is filling with water. But, after penetration of gas into liquid and blow out of the slug, acoustic sensor produces a noisy signal.

For a stable flow, the inlet pressure remains constant and no quiet period is found in acoustic signal. Figure 14 from [6], shows a stable flow related signals.

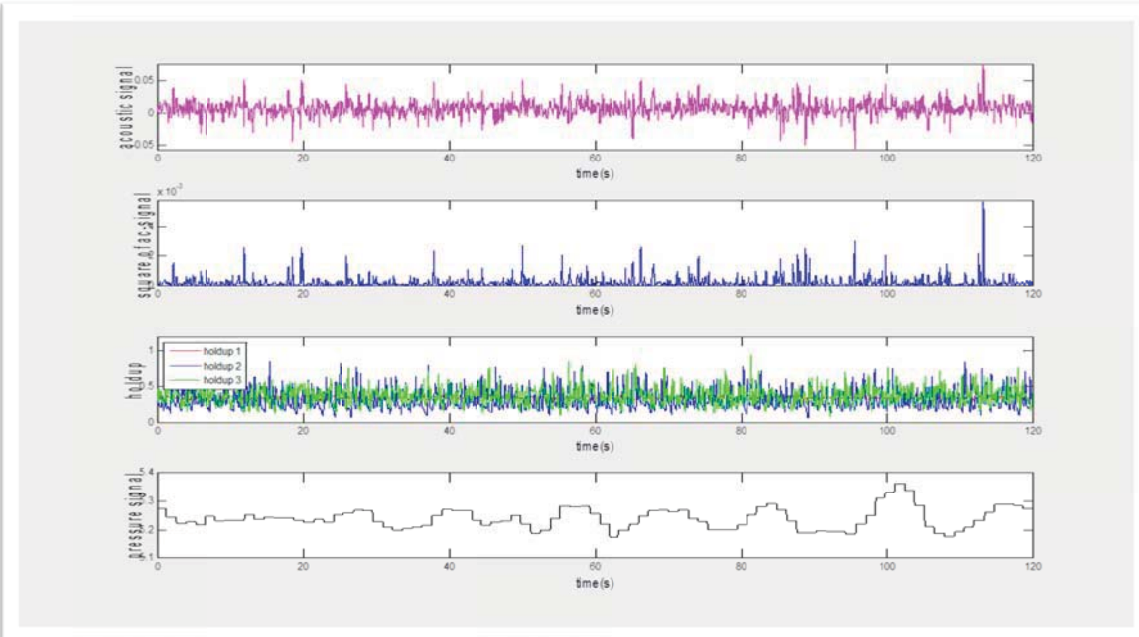

Figure14: Acoustic, Holdup and Pressure Signals for Stable Flow. (Source: [6])

The latter acoustic signal from stable region has been in the point of interest in this project to be tested if it can be a good measurement candidate for anti-slug control. This signal has been investigated by signal processing evaluations using Fast Fourier transform (FFT) algorithm.

2.4 Fast Fourier Transform (FFT) functions

FFTs are used for measuring and presenting the frequency content of signals over the entire time that the data have been logged and signal has been acquired. In signal processing, when the signal is noisy, it may be difficult to identify the frequency contents by looking at the original signal. Therefore, transferring it to the frequency domain by using FFT makes it easier to identify the dynamic contents of signal in a special frequency. In this project, the resulting acoustic signals from step tests have been evaluated in frequency domain.

3 Experimental

The experimental part of this project includes three sections. First the step change test in stable region is performed and the results from top and bottom pressure sensors and acoustic sensor are evaluated and compared. Second, a series of tests with different Usl's and Usg's are performed to make flow regime map for presenting different flow regimes. Finally, the last series of tests with different valve positions are implemented to make the bifurcation diagram. The experiments are implemented on steel S-riser in Multi-phase Flow laboratory at NTNU.

3.1 Setup

The experimental setup and the geometry of steel S-riser are indicated in figures 15 and 16 respectively. The PLC S-riser with the same geometry has been previously used in several other slugging experiments at NTNU [7], [8] and [9]. The objective is to perform the slugging phenomena in a small scale.

Air and water were used as components of the flow and experiments are carried out in standard temperature and pressure. In order to include the compressibility effects in the experiments, a buffer tank is located in the upstream of the pipeline so that it operates as a large pipeline. The volume effect of this buffer tank is considered in simulations as an approximately 8.125 meters of a pipeline with a diameter of 200 mm. The diameter of riser is 50 mm. An acoustic sensor is enclosed to pipeline before the first bend and two absolute pressure sensors are installed on the buffer tank and top side of riser. The buffer pressure is approximately equal to hydrostatic pressure of the riser. The reason is that there is an over flow tank at the top of the riser, which is open to the atmosphere. Water is injected to the connection point (start of the riser) and circulated through the flow line. Adjusting the flow rates, running the experiments and logging the data are all done by LabVIEW. A choke valve is installed on the riser and plays an important role in providing different flow regimes. This valve can be manipulated by LabVIEW.

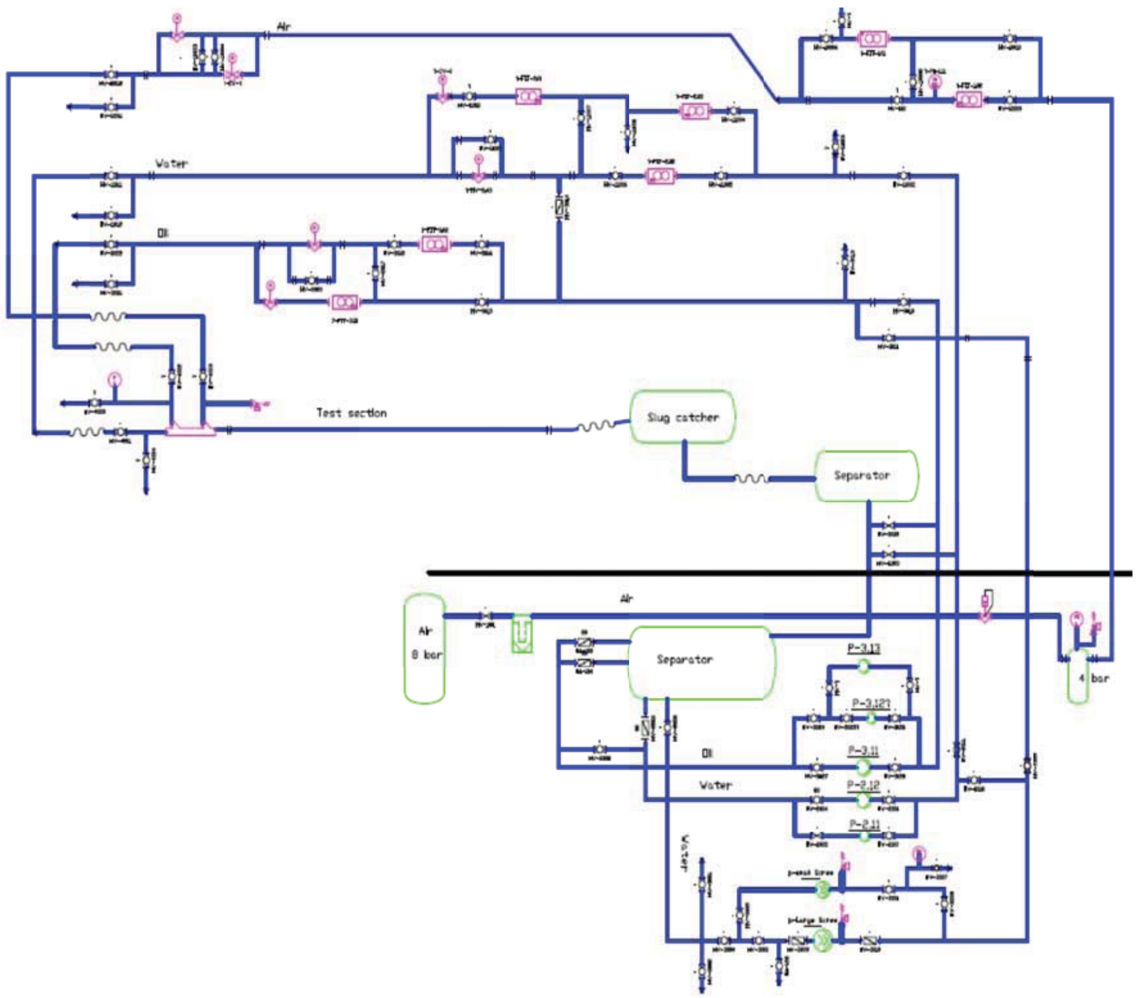

Figure 15: Schematic illustration of experimental setup

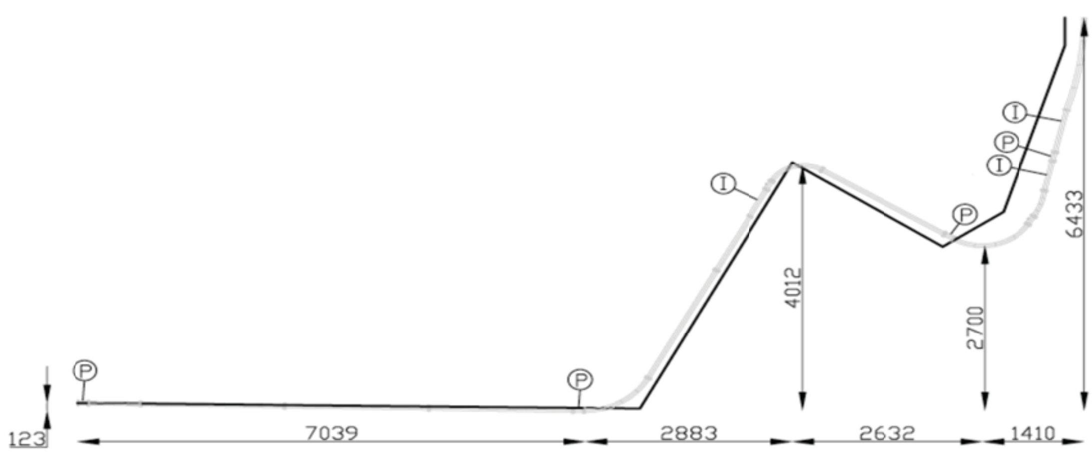

Figure 16: S-riser geometry (lengths are in millimeters). (Source: [10])

3.2 Equipment

Water Pump

A large centrifugal pump is pumping water to the system.

Figure 17: Water Centrifugal Pump

Pressure sensors

Pressure sensors from Siemens are used for measuring top side and buffer pressures. They are mounted on riser topside and buffer tank respectively.

Figure 18: Pressure sensor

Acoustic sensor

Acoustic sensor from Siemens is used. It is placed in the first S-riser bend, the optimal place for detecting slug flow.

Figure 19: Acoustic sensor

Flow meters

Liquid inlet flow rate is measured with flow meter from FISCHER & PORTER Company.

Figure 20: Liquid flow meter; Model: COPA XM

Gas inlet flow rate is measured with flow meter from MICRO MOTION Company.

Figure 21: Gas flow meter; Model: Elite CMF025

Software

LabVIEW from National instruments has been used for controlling the pumps and valves and also monitoring and logging the pressure and acoustic signals. The labVIEW interface used in the experiments, is indicated in figures 22 and 23.

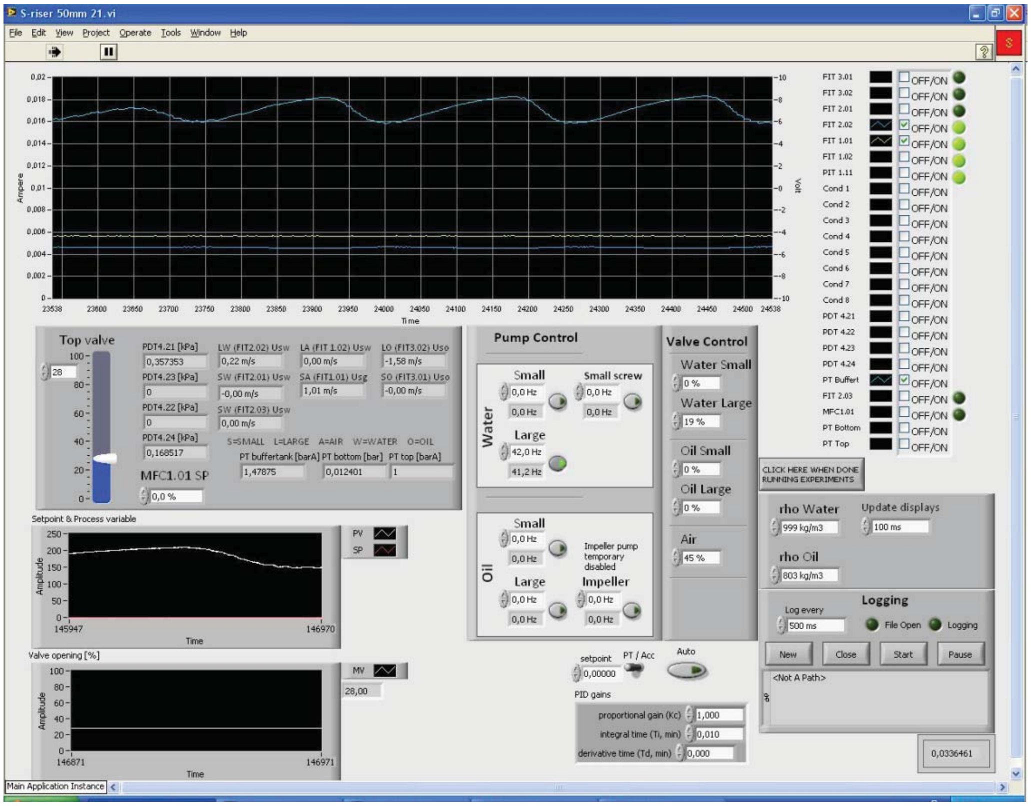

Figure 22: Operating screen for the experiments

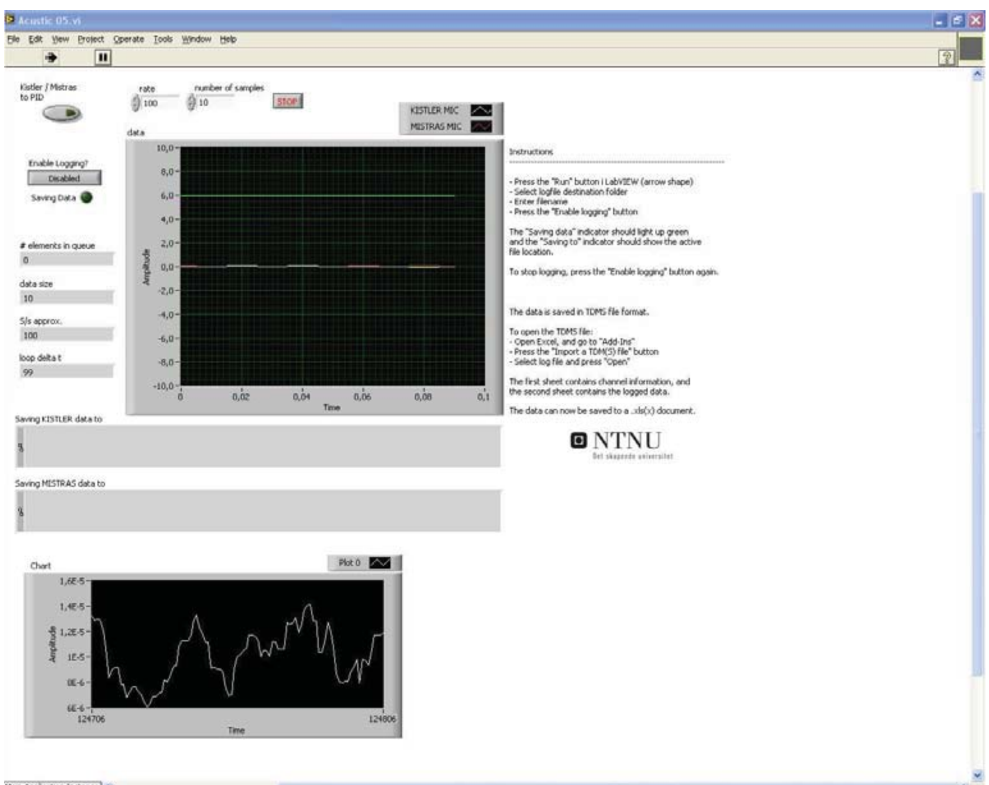

Figure 23: Acoustic logging screen

3.3 Experiments

The first thing before starting experiments is checking different valves in the path of water and air from the storage up to S-riser starting point. This is done according to the check box available for the rig, in the laboratory. Then LabVIEW must be run and the screen shown in figure 22 comes up. From this moment on, the experiments' settings are all done through LabVIEW. The starting point is turning the large centrifugal pump on by LabVIEW. In order to avoid liquid flow rate oscillations, the pump has been run by a relatively high frequency, about 45, while the maximum is 50. The liquid flow rate for getting different flow regimes has been adjusted by setting the control valve opening, in LabVIEW. However, the manual choke valve has been also used for generating different flow regimes and implementing step change test. The air flow rate is set in LabVIE and the data of flow rates, pressures and acoustic signals are logged.

3.3.1 Step change test

Step change test is done in order to evaluate the performance of acoustic signal both in time and frequency domain and compare it to pressure signal. In order to implement the step change test, the stable region is achieved by adjusting liquid and gas flow rates and the valve opening percent. The superficial velocities are Usl = 0.2 [m/sec] and Usg = 1 [m/sec]. Then the step change is implemented on valve opening (one time from 20 percent into 25 and another time from 25 to 20 percent) while the stable region is retained. Data from acoustic sensor, top and buffer pressure sensors are logged and analyzed in results.

3.3.2 Flow regime map

A flow regime map for the steel S-riser has been made by logging data for about 70 points of different gas and liquid superficial velocities. Choke valve was fully opened (100 percent of valve opening). Therefore, the only reason affecting the type of flow regime has been superficial velocities of gas and liquid. The experiments include all available operating points for the steel S-riser setup. The map includes four different regions of Severe Slugging I, Severe Slugging II, Transitional flow and Stable flow. Brief descriptions of the four related regions are in the following.

Severe Slugging I (SSI)

This regime occurs with relatively low gas flow rates (velocities) for almost all available liquid flow rates (velocities). In such a region the bend is completely blocked with liquid accumulation and the length of slug is as long as one or several riser height. There are large pressure oscillations for this flow regime.

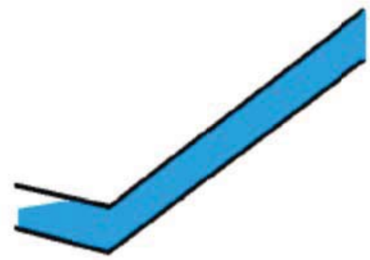

Figure 24: Illustration of SSI. (Source: [11])

Severe Slugging II (SSII)

This flow regime is observed by increasing gas flow rate in SSI region. The physical explanation of this phenomenon is that the gas in the downward pipe penetrates the liquid column, before the slug length reaches to the height of the riser. By further increasing of gas velocity, the gas penetration occurs continuously and the liquid column in the riser contains many bubbles. The bend is neither completely blocked by liquid. This regime contains short periodic pressure oscillations.

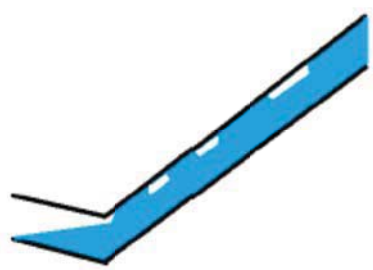

Figure 25: Illustration of SSII (Source: [11])

Transitional flow (TTS)

Irregular small pressure fluctuations are the clearest characteristic of this region. Continuous gas transport through the riser causes even more bubbles and slugs in the riser.

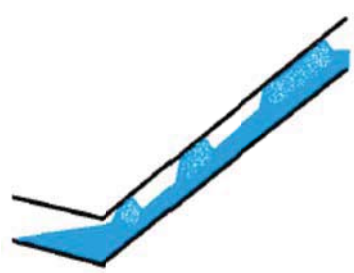

Figure 26: Illustration of TTS (Source: [11])

Stable flow

This flow regime is a desired one for the riser containing small hydrodynamic slugs. There is no liquid accumulation in the bend and the slugs are transported continuously through the riser. The pressure is containing very small oscillations and almost stable.

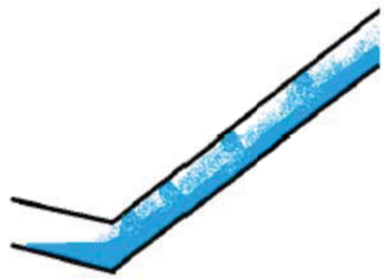

Figure 27: Illustration of Stable flow (Source: [11])

3.3.3 Bifurcation diagram

A bifurcation is a fundamental change in the nature of a solution and a bifurcation diagram is a plot that shows the value of the changing parameter on one axis and the solution to the system on the other axis. A bifurcation diagram is an appropriate way of illustrating the appearance of slug flow in a pipeline-riser system due to moving through different valve openings.

In order to make the experimental bifurcation diagram in this project, the experiments were set to a fixed Usl = 0.2 [m/Sec] and Usg= 1 [m/Sec]. The experiments were then started with a valve opening percent of 20. In each step the valve opening percent was increased until it was fully open. The results of buffer tank pressure were logged and the related bifurcation diagram was plotted.

4 Simulations in LedaFlow

Simulation part of this project includes three sections. First slug flow is simulated. Then it has been tried to make the same flow regime map by simulations in LedaFlow. The conditions for the simulations were set according to the experimental flow regime map: The same Usg’s and Usl’s were used for different points. The objective is to make the stability margin in the flow regime map through simulations. Finally the bifurcation diagram has been obtained by changing valve position in different simulations with a fixed Usl and Usg. The simulations were started with a valve opening percent of 1.

5 Results

5.1 Step response test

Results from step change test are presented below. The superficial velocities of gas and liquid are fixed on Usl = 0.2 [m/sec] and Usg = 1 [m/sec]. The related flow regime is stable. Then the step change is implemented on valve opening (one time from 20 percent into 25 and another time from 25 to 20 percent) while the stable region is retained. Figures 28 and 29 are based on data obtained from acoustic sensor, top and buffer pressure sensors.

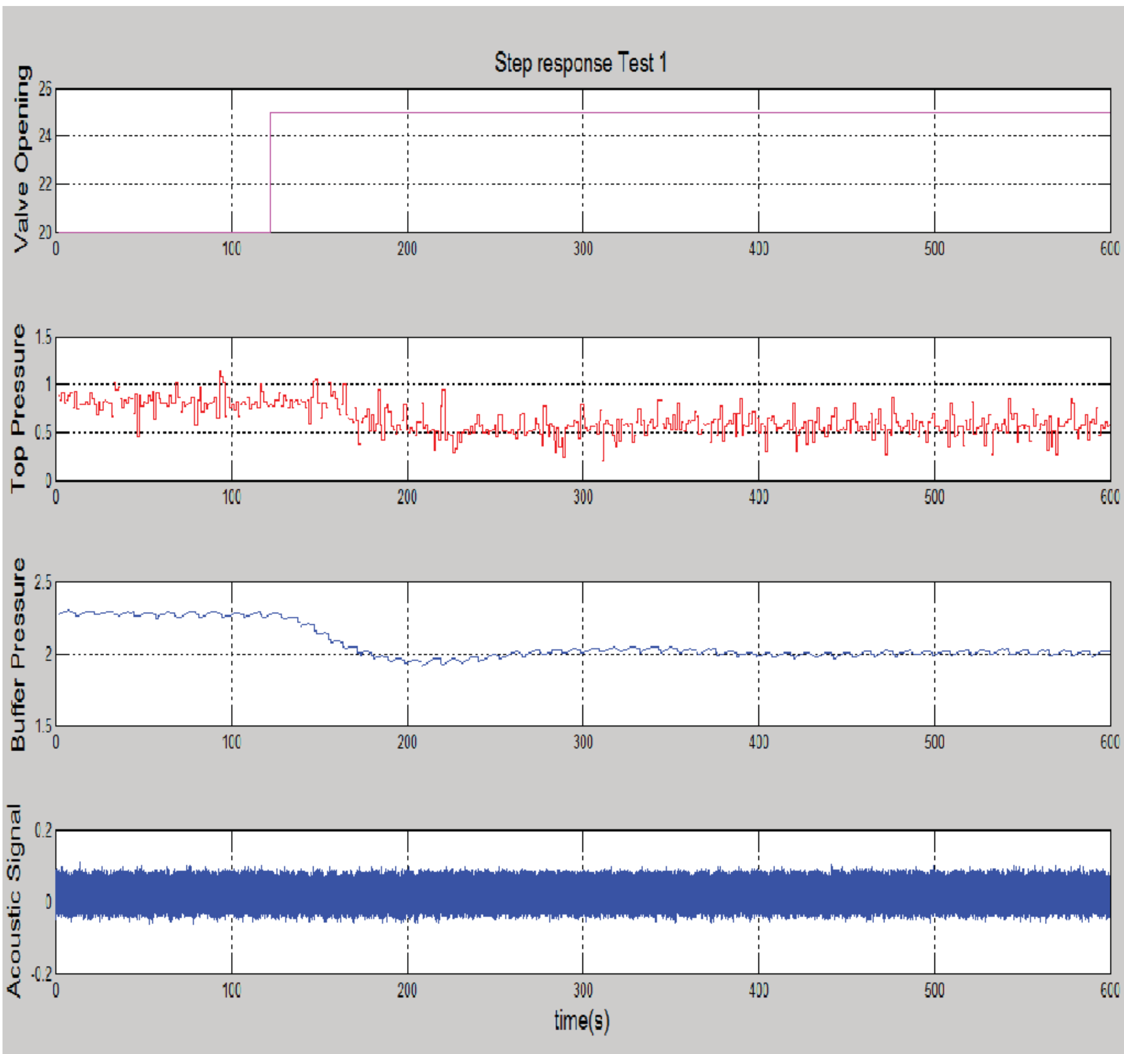

Figure 28: Step response of pressure and acoustic sensors with a step change in valve opening from 20 to 25 percent

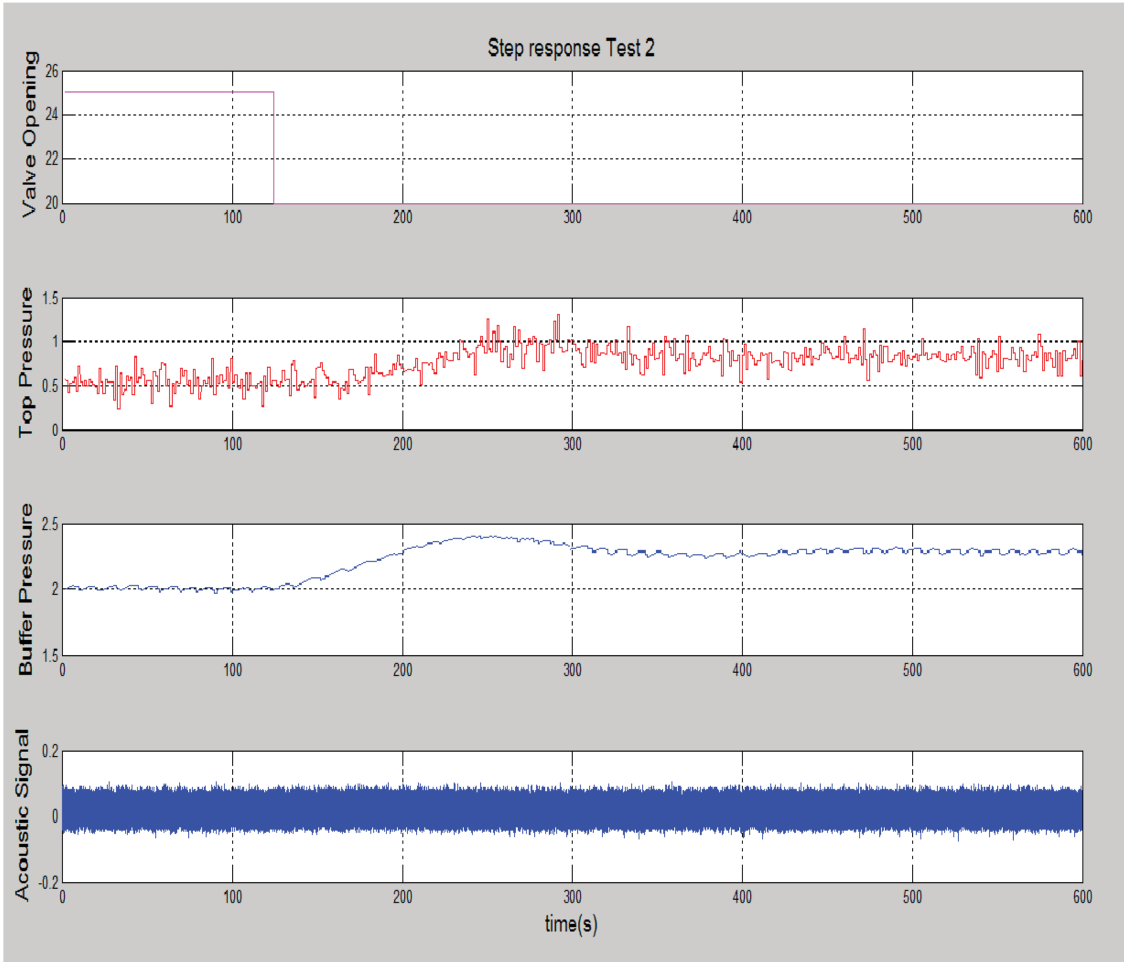

Figure 29: Step response of pressure and acoustic sensors with a step change in valve opening from 25 to 20 percent

As it is clear in the figure, the step response of the buffer pressure is very fast and clear. The one related to Top pressure is a bit slower and it also has measurement noise. Acoustic signal does not show any clear response to the valve opening step change. The frequency of data logging for the pressure sensors has been 100 per seconds and for the acoustic sensor has been 1000 per seconds (1 kHz).

It has been also tried to evaluate the acoustic signal in frequency domain in order to be clarified if the acoustic signal contains information about the dynamics of the system and if it can be used as an input signal for controller. FFT only can be used for periodic signals, so the acoustic signal has been divided into 6 smaller periodic sub-signals. Figures 30 and 31 indicate Fast Fourier Transforms of acoustic signals related to two step change tests.

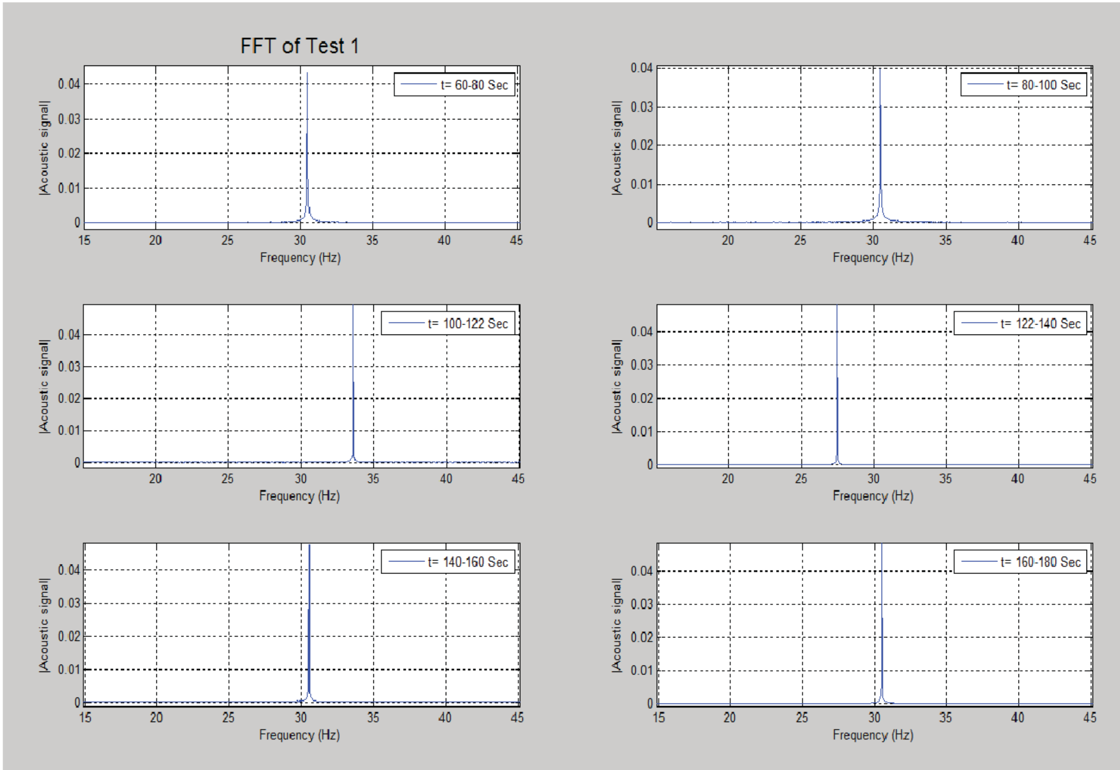

Figure 30: Fast Fourier Transform of acoustic signal with a change in valve opening percent from 20 to 25

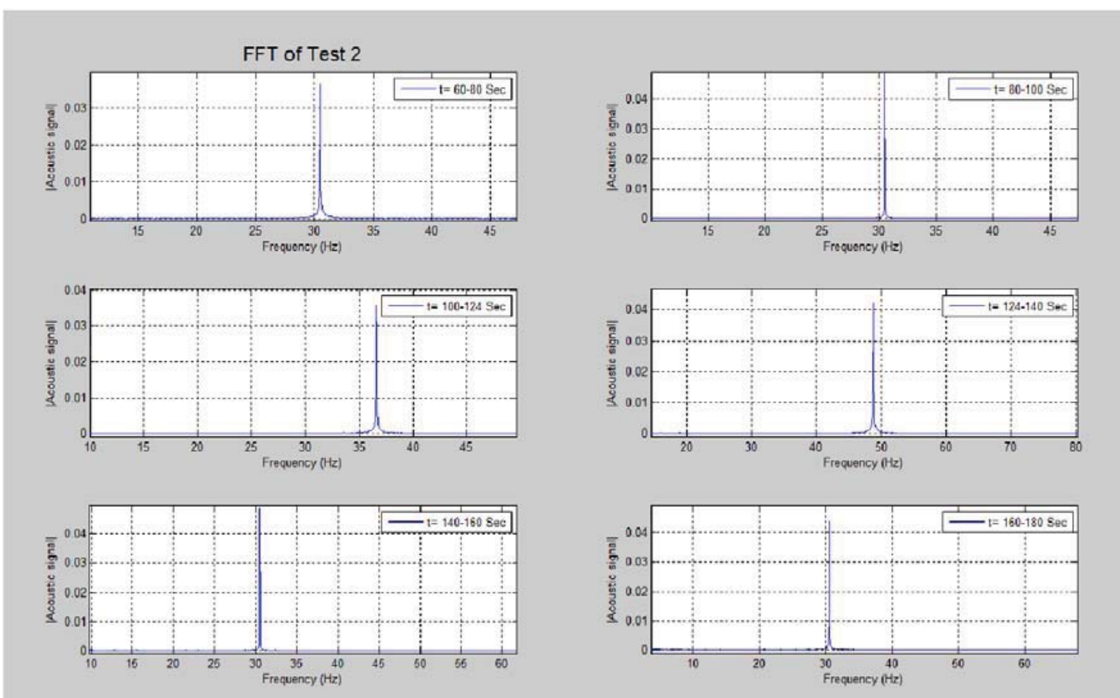

Figure 31: Fast Fourier Transform of acoustic signal with a change in valve opening percent from 25 to 20

The step change has occurred at t=122 sec in first test and at t=124 sec in second test. Figures indicate that after happening of step change, the frequency pick has a small change to a new value for a while and then it goes back to its previous state. This small change in frequency components means that the signal can be useful for detection and monitoring but not useful for control.

5.2 Simulation of slug flow in LedaFlow

It was tried to obtain four different flow regimes from simulations in LedaFlow. The same S-riser was modeled with the same geometries and conditions. Unfortunately, the model did not match with experiments very well in the case of stability. At least for the Usl's and Usg's covered the flow regime map, stable region was not clearly obtained by model simulated in LedaFlow. There are many oscillations for the Buffer pressure even in the stable region. The results of flow regime map will be discussed in the following. Four different types of flow regimes were resulted from doing simulations in related Usg's and Usl's.

Figure 32 illustrates the buffer pressure resulting from simulation with Usl=0.1 [m/s] and Usg= 1 [m/s]. As it is clear in the figure, it is in Severe Slugging I (SSI) region.

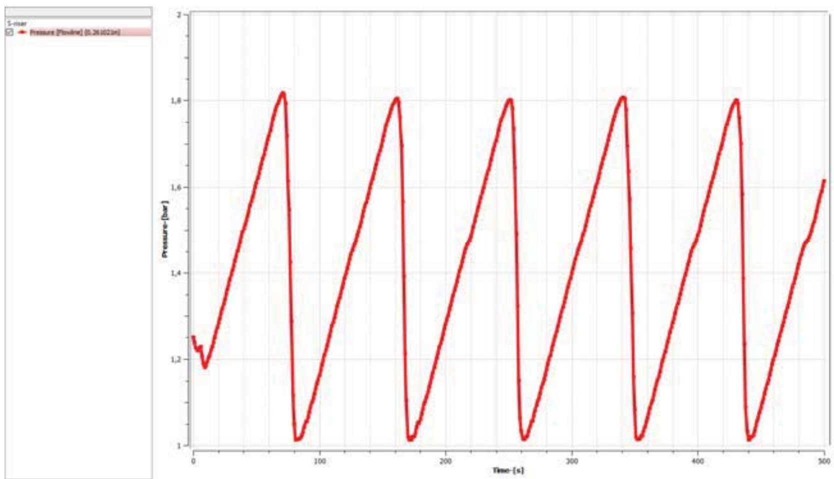

Figure 32: Pressure Oscillations in Severe Slugging I (SSI) region

Figure 33 illustrates the buffer tank pressure with Usl= 0.1 [m/s] and Usg = 2 [m/s]. As it is clear in the figure, it is in Severe Slugging II (SSII) region.

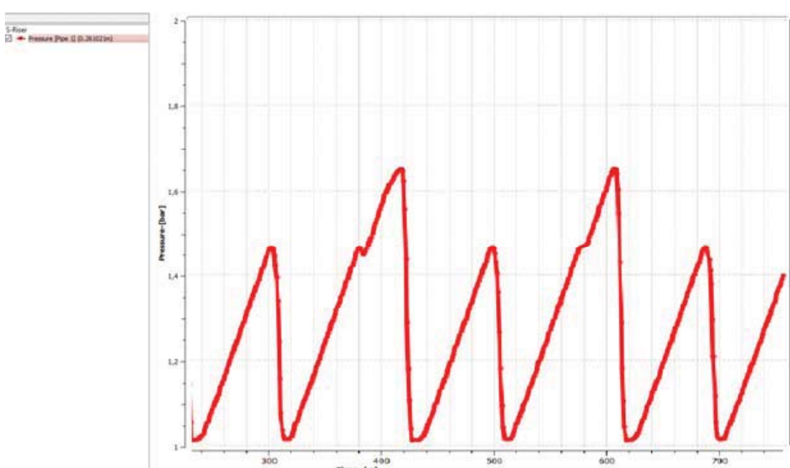

Figure 33: Pressure Oscillations in Severe Slugging II (SSII) region

Figure 34 illustrates the buffer pressure with Usl= 0.1 [m/s] and Usg = 4 [m/s]. It is in the Transfer region.

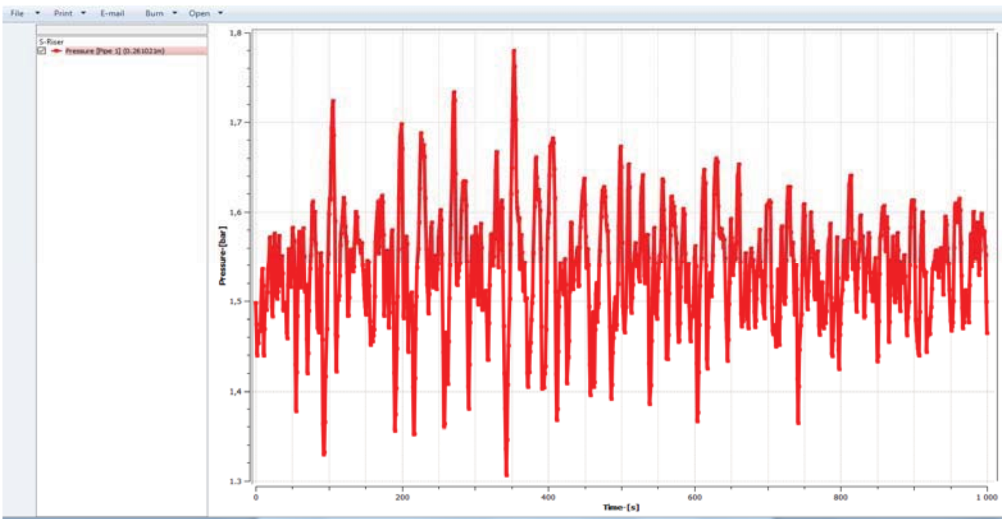

Figure 34: Pressure trend in Transfer region

Figure 35 shows the buffer pressure trend resulting from simulations with Usl= 0.2 [m/s] and Usg = 100 [m/s]. It is in Stable region. Although such superficial velocities seem impossible in reality, they were used to obtain a quite smooth pressure trend.

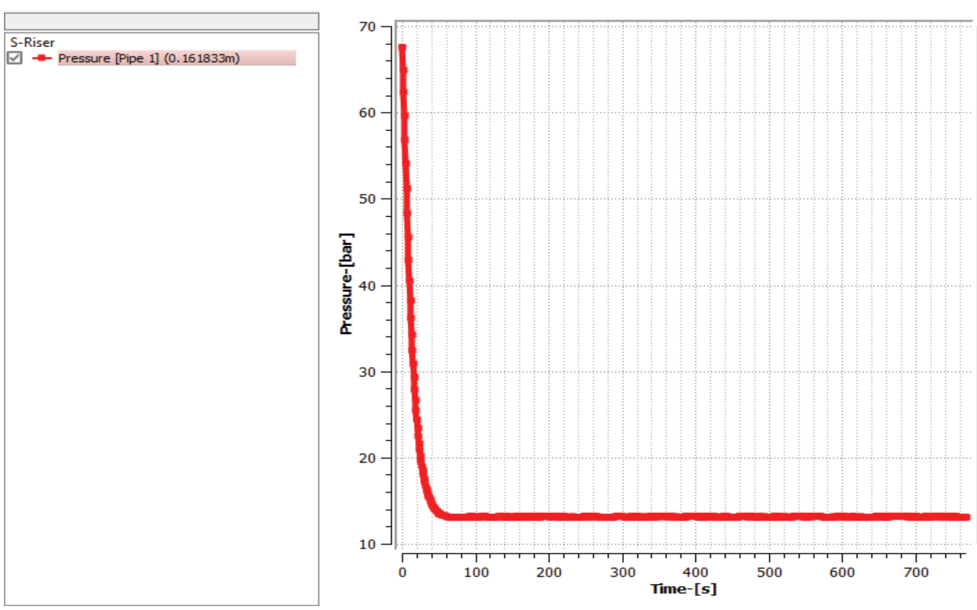

Figure 35: Pressure trend in Stable region

5.3 Flow regime map

-Comparing stability margin in flow regime map based on experiments and based on LedaFlow simulations.

A flow regime map for the Plexiglas S-riser has been made previously [11]. One for "steel" S-riser was made in this project by logging data for about 70 points of different gas and liquid superficial velocities. Choke valve was fully open (100 percent of valve opening). Therefore, the only reason affecting the type of flow regime has been superficial velocities of gas and liquid. The experiments include all available operating points for the steel S-riser setup.

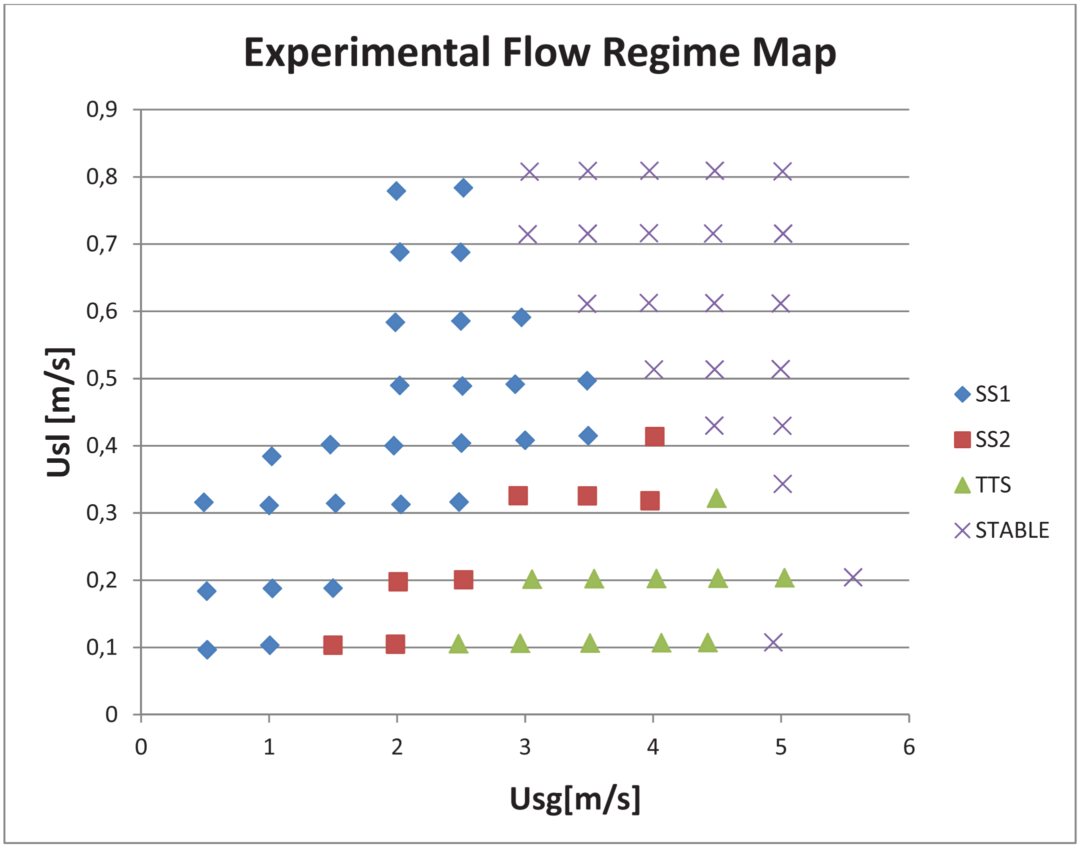

Figure 36: Obtained Flow regime map for Steel S-riser based on Experiments

It is clear in the figure that in lower liquid flow rates, the transition from severe slugging into stable region is more gradually compared to higher liquid flow rates. This means that it is more difficult to distinguish the transition in low liquid velocities. It was even more difficult in the case of simulations, since pressure oscillations never disappeared and the only way to identify flow regime type was to compare results of pressure trend for all simulations together.

It was tried to make the same flow regime map by simulations in LedaFlow. The conditions for the simulations were set according to the experimental flow regime map: The same Usg's and Usl's were used for different points. The objective is to make the stability margin in the flow regime map through simulations. The simulator LedaFlow performed well in the case of unstable regions (SSI, SSII and TTS). But when moving to stable region the results of simulations were not inspiring and the pressure oscillations were never stopped even at very high gas flow rates. A rule from [12] was used to distinguish the stability margin. The rule says that if the range of pressure oscillations is up to 10 percent of the maximum pressure, then the region could be called stable.

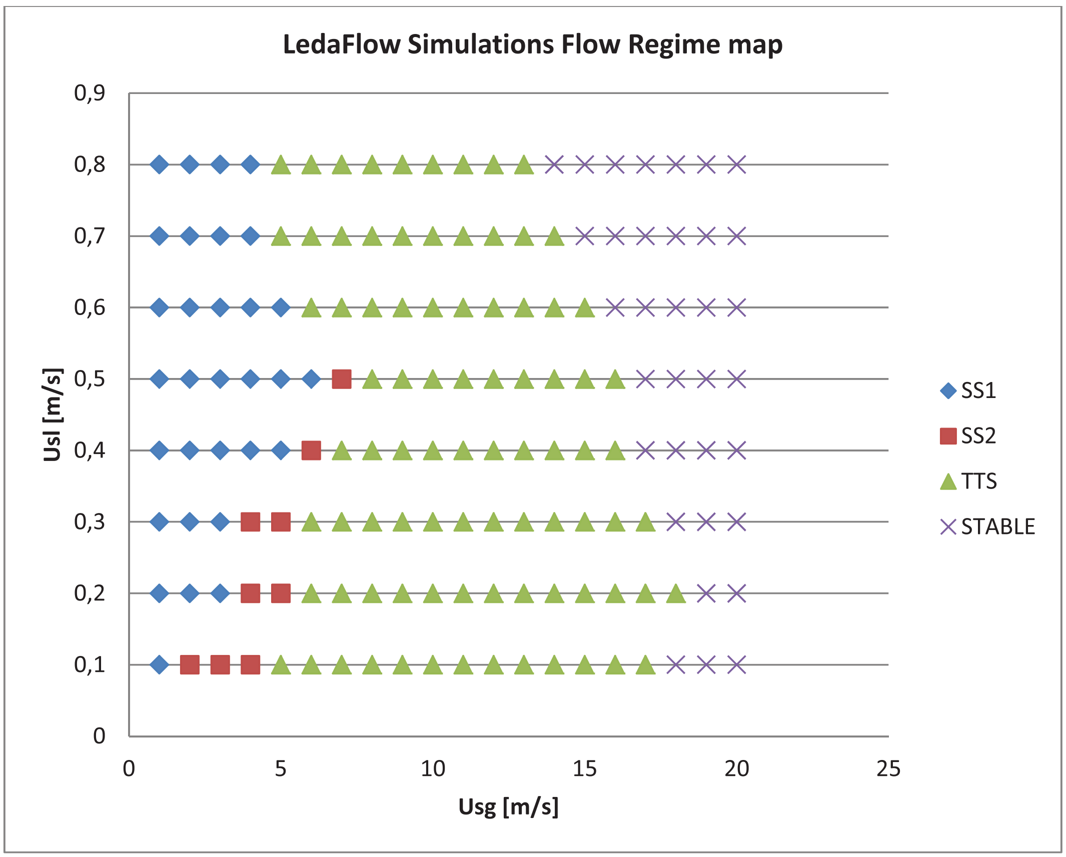

Figure 37: Obtained Flow regime map for Steel S-riser based on LedaFlow Simulations

As it is indicated in figures 36 and 37, the stability margin in LedaFlow has appeared in quite higher gas flow rates compared to experiments. The most stable flow belongs to Usl = 0.8 [m/s] in which the stability starts at Usg = 3 [m/s] in experiments, but at Usg = 15 [m/s] in LedaFlow simulations. The most unstable flow belongs to Usl = 0.2 [m/s] in which the stability starts at Usg = 5.5 [m/s] in experiments, but at Usg = 19 [m/s] in LedaFlow simulations.

5.4 Bifurcation diagram

In this project, the open loop behavior of the S-riser system has been evaluated using bifurcation diagrams made with experiments and simulations in LedaFlow. The base is keeping flow rates constant and changing choke valve position.

The experiments and simulations were set to a fixed Usl = 0.2 [m/sec] and Usg= 1 [m/sec]. The experiments were then started with a valve opening percent of 20. In each step the valve opening percent was increased until it was fully open. The results of buffer tank pressure were logged and the related bifurcation diagram was plotted.

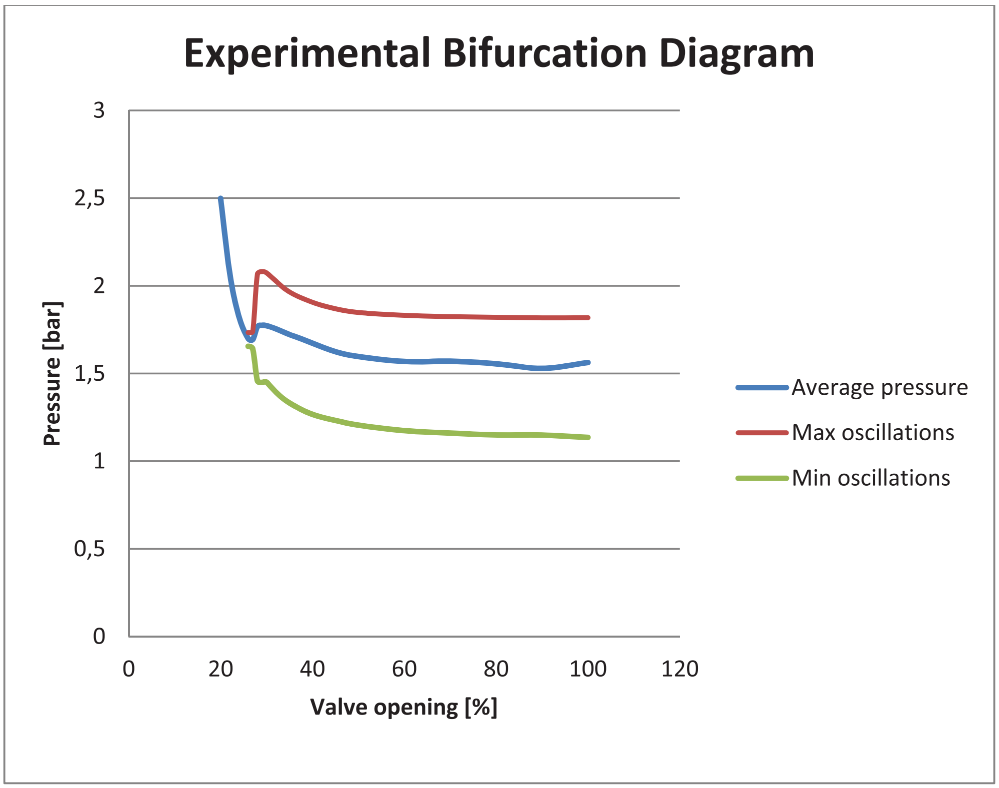

Figure 38: Bifurcation diagram of Buffer pressure- based on Experiments

The blue trend shows the average pressure trend and the red and green ones show the maximum and minimum of buffer pressure oscillations after the onset of instability. The instability starts at 27 percent of valve opening.

The same bifurcation diagram with the same conditions of experiments was tried to be made with simulations in LedaFlow, however the simulations were started at a valve opening percent of 1. The resulted bifurcation diagram from simulations is presented below.

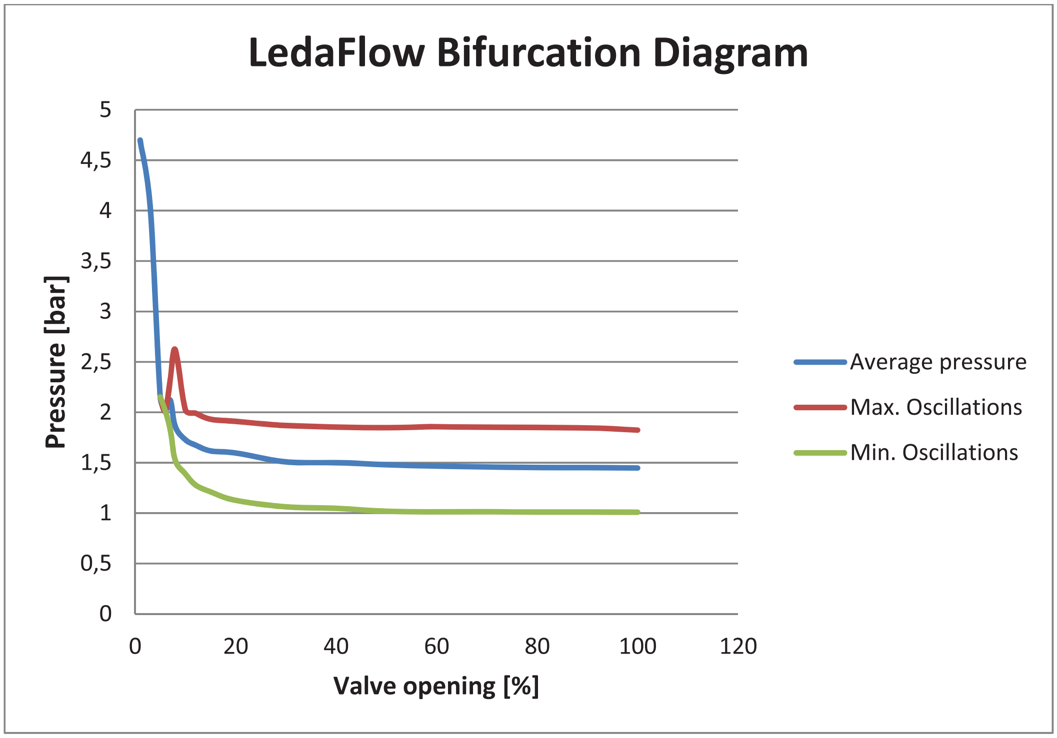

Figure 39: Bifurcation diagram of Buffer pressure- based on LedaFlow Simulations

As illustrated in the figures, the bifurcation point occurs at 6 percent of valve opening while simulating the same conditions of experiments. This expresses that the dynamic model we made in LedaFlow is mostly unstable.

6 Discussion

6.1 Results of step test

Implementing step response test and evaluating the resulted acoustic signal in frequency domain showed that acoustic signal is not a good control variable. However it is good for detection of flow regime inside the riser.

6.2 LedaFlow simulations

The dynamic model simulated in Ledaflow didn't match with experiments very well in stable region. In most cases the stability was not obtained even the experiments showed a stable region. The dominant regime in most cases was transient flow regime (TTS). This could be because of some reasons. One reason may be that the simulations have been run in an isotherm condition without considering heat transfer effects. This could destabilize the simulations. One other reason may be the imperfect model for the case. It would be tried to do more investigations on the model in master thesis. Finally, the version used in this project to do simulations is 1.1. A new version of 1.2 has been recently published, which is told to be more stable.

One important thing to consider in simulations was grid cell number. Grid sensitivity test was done for some points in different regions of flow regime map in order to obtain the best performance of the simulator. Grid cell lengths of: 2D, 5D, 10D and 20D were simulated for each point. Grid sensitivity test showed that a grid length of 2D shows the best coincidence with the experiments. However the one used in our simulations is 5D and the reason was that with a grid length of 2D the simulator could not complete the simulation in most cases. It stopped calculations in the middle of simulating and the trend could not be completed. So a uniform algorithm with a cell length of 5D was chosen in mesh setting to perform simulations in LedaFlow in order to make the stability map and bifurcation diagram.

6.3 Experiments

There were some challenges during implementing Experiments in multiphase flow laboratory.

6.3.1 Gas and liquid flow rates

In order to have a specified Usl and Usg in each test it was important to have constant and consistent flow rates. It was a challenge to adjust the flow rates for each test at the exact required amount. Especially for the liquid, the centrifugal pump was oscillating and made it difficult to set the required Usl. It was tried to solve this problem by running the pump in a high frequency and set the flow rate by adjusting the control valve. Still as there were variations in the system, like occurring slugging, it varied and needed to be set again.

6.3.2 Water flow into the buffer tank

When the buffer pressure became lower than the pressure inside pipeline, water sometimes flowed back into buffer tank. This reduces the volume of buffer tank and therefore needed to be drained between each experiment that it happened.

6.3.3 Noise in top pressure

Top pressure measurement contains a lot of noise. It may have been because of choke valve which is connected close to the top pressure sensor. In this project, top pressure was only used in step change test in order to make a comparison between pressure and acoustic signals and only its trend was the point. Therefore these noises were not considered as a problem. However its step response is not as nice and fast as buffer pressure.

7 Conclusion and future work

Acoustic signal is not a good variable for control. Evaluating signals in frequency domain justifies previous result that it can be used for recognition of different flow regimes in S-riser. But the application to flow control is rejected. The dynamic information of signal is not as enough as to be used for control.

Flow regime maps show a wider range of stability in higher liquid flow rates. The stability margin shifts to right (higher gas velocities) when going from experiments into LedaFlow simulations.

Experimental bifurcation diagram presents a bifurcation point of 27 percent of valve opening, while simulations result in instability onset at 6 percent of valve opening.

The experiments in both conditions of fixed and changing valve position demonstrate that buffer pressure is a very good variable for control. Stabilizing control experiments using buffer pressure can be done as future work. Top pressure contains noise, but using top pressure combined with density can be tried for Control. Other further work on this subject includes testing online PID tuning rules on S-riser experiments and doing Control simulations using new version of LedaFlow.

8 References

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Appendices

A Acoustic sensor data sheet

R.45I Sensor

Very Low Frequency

High Sensitivity Acoustic Emission Sensor

Description and Features

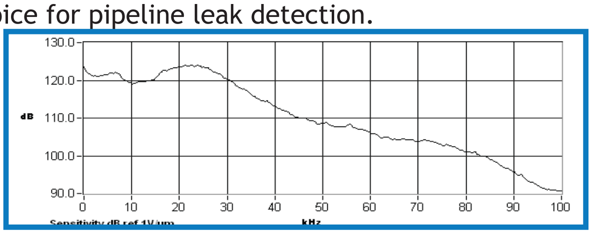
The R.451 is a very low frequency and High sensitivity, internally amplified AE sensor with a 20 kHz resonance frequency, 124 dB peak sensitivity and useful bandwidth from 1 to 30 kHz. The sensor has a standard BNC connector on the side of the sensor. The cavity is made from Stainless steel. It is approximately 2.0" (50 mm) high.

PAC's integral preamp sensors were specifically engineered to attain high sensitivity and have the capability to drive long cables without the need for a separate preamplifier. Incorporating a low-noise input, 40dB preamplifier and a filter all inside the sensor housing, these transducers are completely enclosed in metal stainless steel (or aluminum) housings that are treated to minimize RFI/EMI interference. Care has also been taken to thermally isolate the critical input stage of the preamplifier in order to provide excellent temperature stability over the range of -35° to 75° C.

Their integrated Auto Sensor Test (AST*) capability allows these sensors to pulse as well as receive. This feature lets you verify the sensor coupling and performance at any time before, during or after an AE test.

Applications

This sensor is normally selected for structural health monitoring of concrete and geologic structures. It is also a good choice for pipeline leak detection.



Frequency response of R.45I. Calibration based on ASTM E 1106

* AST -- Auto Sensor Testing feature allows AE systems to control the sensor as a pulser and a receiver at the same time. It can therefore characterize its own condition as well as send out a simulated acoustic emission wave that other sensors can detect, so the condition of the nearby sensors also can be tested.

Operating Specifications

Dynamic

Peak Sensitivity, Ref V/(m/s) .... 124 dB
Operating Frequency Range ....5 to 30 KHz
Resonant Frequency, Ref V/(m/s)............... 20KHz
Directionality................................. +/- 1.5 dB

Environmental

Temperature Range .... -35° to 75° C
Shock Limit .... 500 g
Completely shielded crystal for maximum RFI/EMI immunity

Physical

Dimensions............................ 1.125 OD X 2.0 H
Weight... 140 grams
Case Material........................... Stainless steel
Face Material.................................... ceramic
Connector...BNC
Connector Location ....side

Electrical

Input Voltage Range (VDC) 16-29
Operating/Max Current (mA) 20/120
Internal Preamp Gain ....40 dB
Noise RTI (referred to input µV) ....< 2.4

Ordering Information and Accessories

R.45I R.45I
Cable (specify cable length in meters)..............1234 - X
Magnetic Hold-Down MHR.45I
Amplifier AE2A

Sensors include
NIST Calibration Certificate & Warranty

MISTRAS
A World of NDT Solutions
Products & Systems Division

195 Clarksville Road, Princeton Junction, NJ 08550
Phone: 609-716-4000 • Fax: 609-716-0706 •
Email: sales.systems@mistrasgroup.com • www.mistrasgroup.com

ISO 9001

R1.5I Sensor

Very Low Frequency

High Sensitivity Acoustic Emission Sensor

Description and Features

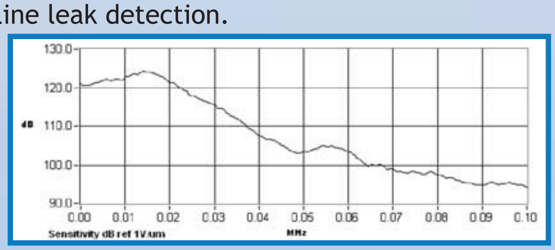
The R1.5I is a low frequency and High sensitivity AE sensor with 14 kHz resonance frequency, 124 dB peak sensitivity and useful bandwidth from 5 to 20 kHz. The sensor has a standard 1 meter RG58 cable and BNC connector on the side of the sensor. The sensor is made from stainless steel. It is approximately 1.55” (40 mm) high.

PAC’s integral preamp sensors were specifically engineered to attain high sensitivity and have the capability to drive long cables without the need for a separate preamplifier. Incorporating a low-noise input, 40dB internal preamplifier and a filter all inside the sensor housing, these transducers are completely enclosed in metal stainless steel (or aluminum) housings that are fabricated to minimize RFI/EMI interference. Care has also been taken to thermally isolate the critical input stage of the preamplifier in order to provide excellent temperature stability over the range of -35º to 75º C.

The integrated Auto Sensor Test (AST) capability allows these sensors to pulse as well as receive. This feature lets you verify the sensor coupling and performance at any time before, during or after the test.

Applications

This sensor is useful for structural health monitoring of concrete and steel structures. It is also a good choice for pipeline leak detection.



Frequency response of R1.5I. Calibration based on ASTM E 1106.

* AST -- Auto Sensor Testing feature allows AE systems to control the sensor as a pulser and a receiver at the same time. It can therefore characterize its own condition as well as send out a simulated acoustic emission wave that other sensors can detect, so the condition of the nearby sensors also can be tested.

Operating Specifications

Dynamic

Peak Sensitivity, Ref V/(m/s) .... 124 dB

Operating Frequency Range ....5 to 20 KHz

Resonant Freq. V/(m/s); [V/μbar] .... 14 kHz

Directionality................................. +/- 1.5 dB

Environmental

Temperature Range .... -35º to 75º C

Shock Limit .... 500 g

Completely shielded crystal for maximum RFI/EMI . Immunity

Physical

Dimensions........................... 1.125 OD X 1.55H

Weight... 130 grams

Case Material .... Stainless Steel

Connector......................1 meter cable with BNC

Connector Location ....side

Electrical

Input Voltage Range (VDC) 16-29

Operating/Max Current 20/120

Internal Preamp Gain 40dB

Noise RTI (referred to input μV) .... < 2.4

Ordering Information and Accessories

R1.5I R1.5I

Cable (specify cable length in meters) 1234-X

Magnetic Hold-Down..................................MHR.1.5I

Sensors include

NIST Calibration Certificate & Warranty

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Fax: 609-716-0706 • Email: sales@pacndt.com • Internet: www.pacndt.com

Rev. 12/07 #180-07

R1.5 Sensor

Low Frequency

High Sensitivity Acoustic Emission Sensor

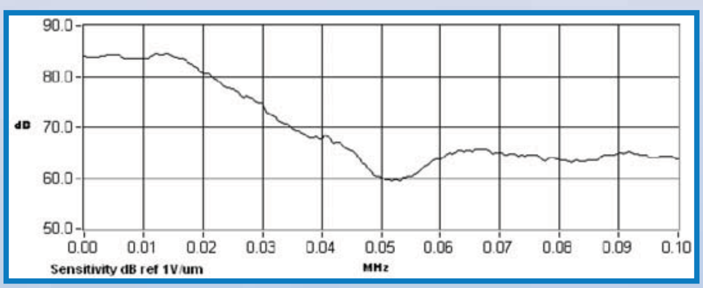
Description and Features

The R1.5 is a low frequency and high sensitivity AE sensor with 14 kHz resonance frequency, 85 dB peak sensitivity and useful bandwidth from 5 to 20 kHz. The sensor has a standard 1 meter RG58 coax cable and BNC connector on the side of the sensor. The cavity is made from stainless steel. It is approximately 1.55” (40 mm) high.

These transducers are completely enclosed in metal stainless steel housings, fabricated to minimize RFI/EMI interference.

Applications

This sensor is normally used in structural health monitoring of concrete and steel structures. It is also a good choice for pipeline leak detection.



Frequency response of R1.5I. Calibration based on ASTM E 1106.

Operating Specifications

Dynamic

Peak Sensitivity, Ref V/(m/s)......................85 dB

Operating Frequency Range ....5 to 20 KHz

Resonant Frequency, Ref V/(m/s)............... 14KHz

Directionality................................. +/- 1.5 dB

Environmental

Temperature Range ....-35º to 150º C

Shock Limit .... 500 g

Completely shielded crystal for maximum RFI/EMI immunity

Physical

Dimensions........................... 1.125 OD X 1.55H

Weight... 100 grams

Case Material........................... Stainless steel

Face Material............................ Stainless steel

Connector..........................1 m cable with BNC

Connector Locations ....side

Ordering Information and Accessories

R1.5 ....R1.5

Cable (specify cable length in meters)........... 1234 - X

Magnetic Hold-Down MHR1.5I

External Pre-Amplifier............................2/4/6 or IL

Amplifier Subsystems.................................... AE2A

Sensors include

NIST Calibration Certificate & Warranty

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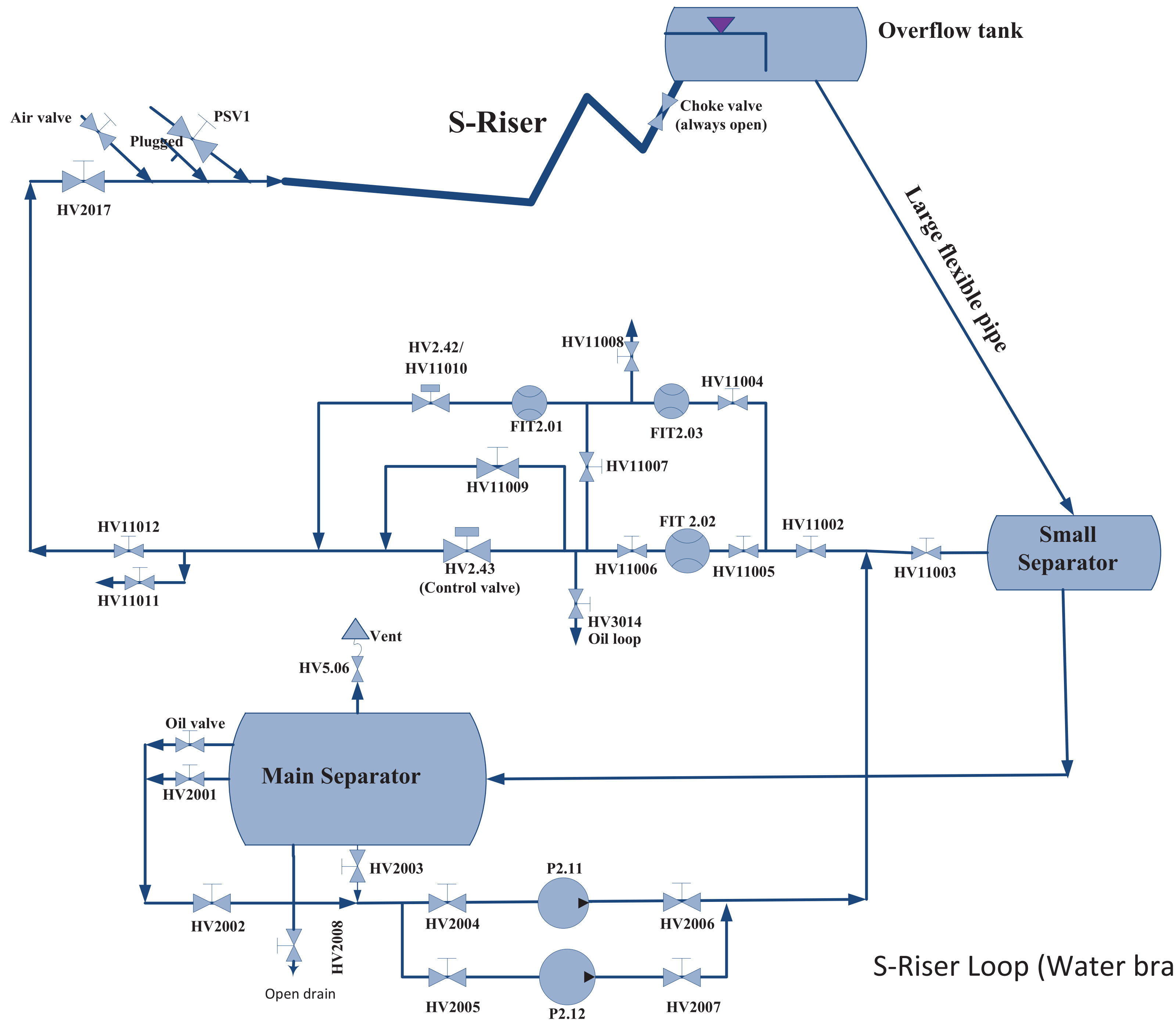
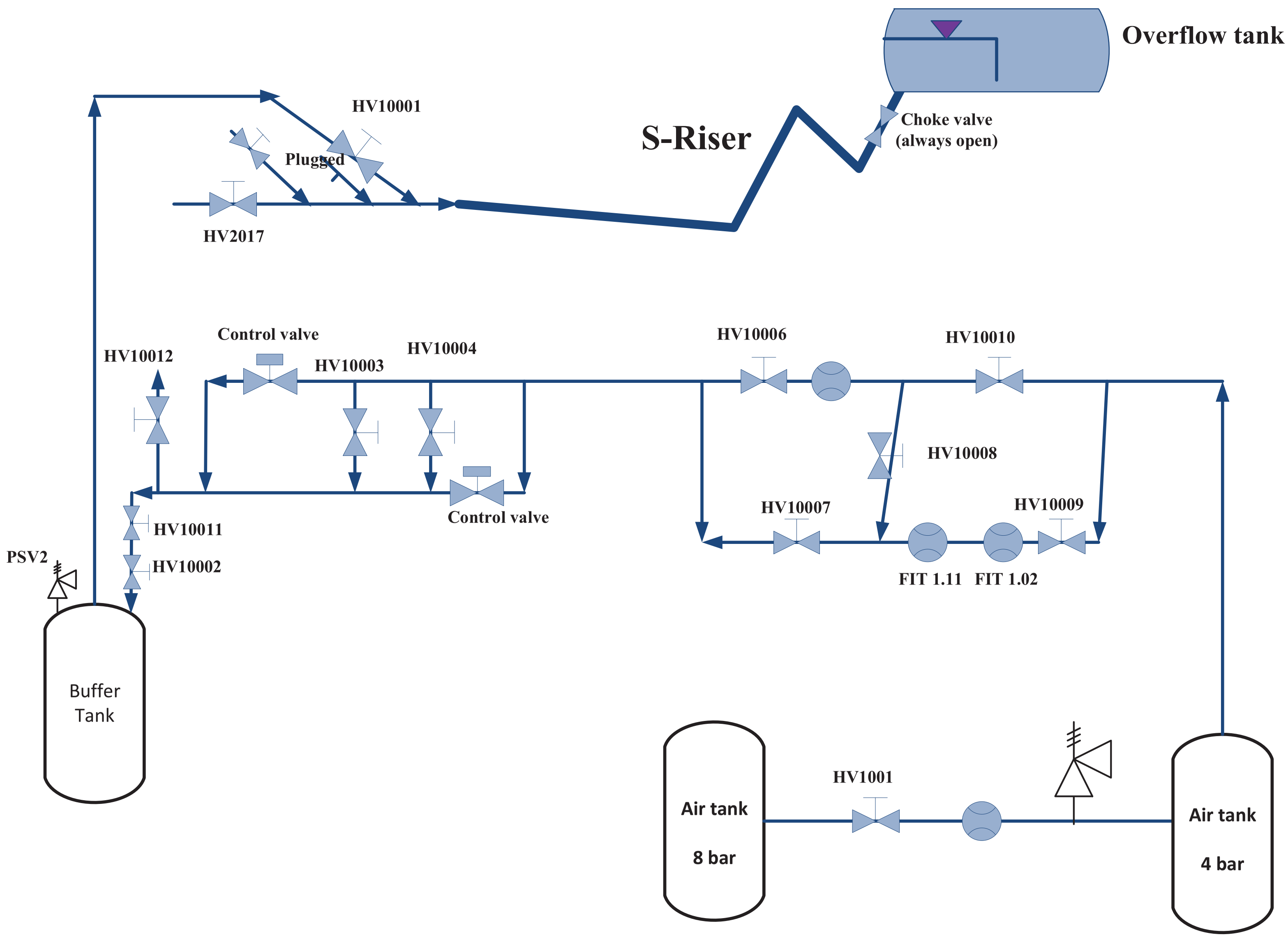
B Sketch of S-riser in multiphase flow laboratory



S-Riser Loop (Water branch)



S-Riser Loop (Air branch)

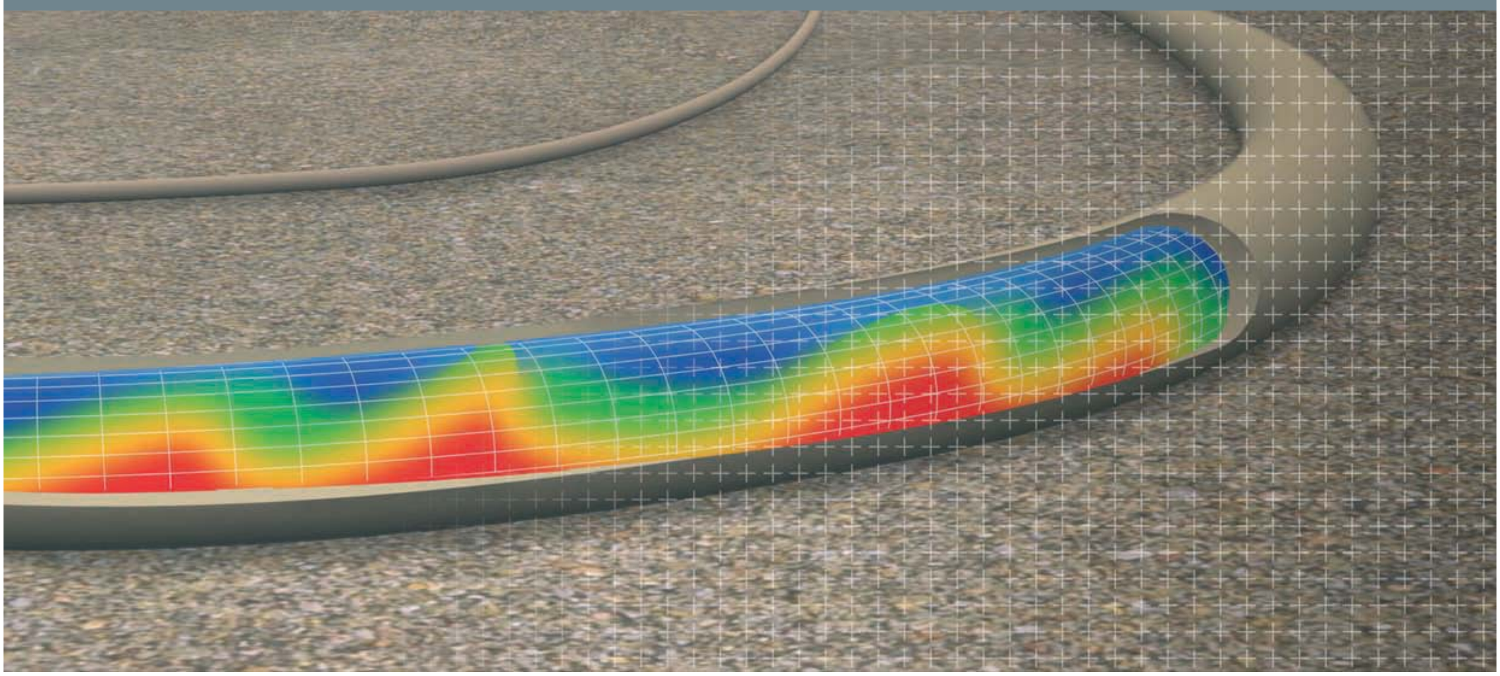
C LedaFlow brochure

Kongsberg Oil & Gas Technologies

KONGSBERG

LedaFlow®

Flow Assurance for 21st Century Oil & Gas Production



The New Generation Dynamic Multiphase Flow Simulator
The Key to a Step Change in Flow Assurance
Closer to the Actual Physics
Unique CFD Capabilities
Seamless Integration of Dynamic Process and Multiphase Flow Simulation

Multiphase Flow Solutions for the 21st Century

Oil & gas production is changing. Longer and larger diameter flowlines, deeper field developments and harsher environments are just some of the challenges we face today. In this context, accurate and powerful simulation tools are needed to assure the safest and most efficient production.
Kongsberg Oil & Gas Technologies has pioneered the development of integrated simulator systems, consisting of a dynamic process simulator interfaced with a dynamic multiphase flow simulator. The next step is the introduction of LedaFlow®, which demonstrates KONGSBERG's dedication to overcoming the challenges of 21st century oil & gas production.

LedaFlow® is a true next generation solution that meets significant market demand for a better dynamic multiphase flow simulator. It is the product of a decade of collaboration between Total, ConocoPhillips and SINTEF, and is further developed as a unique integrated tool for oil & gas engineers by the experts at KONGSBERG.

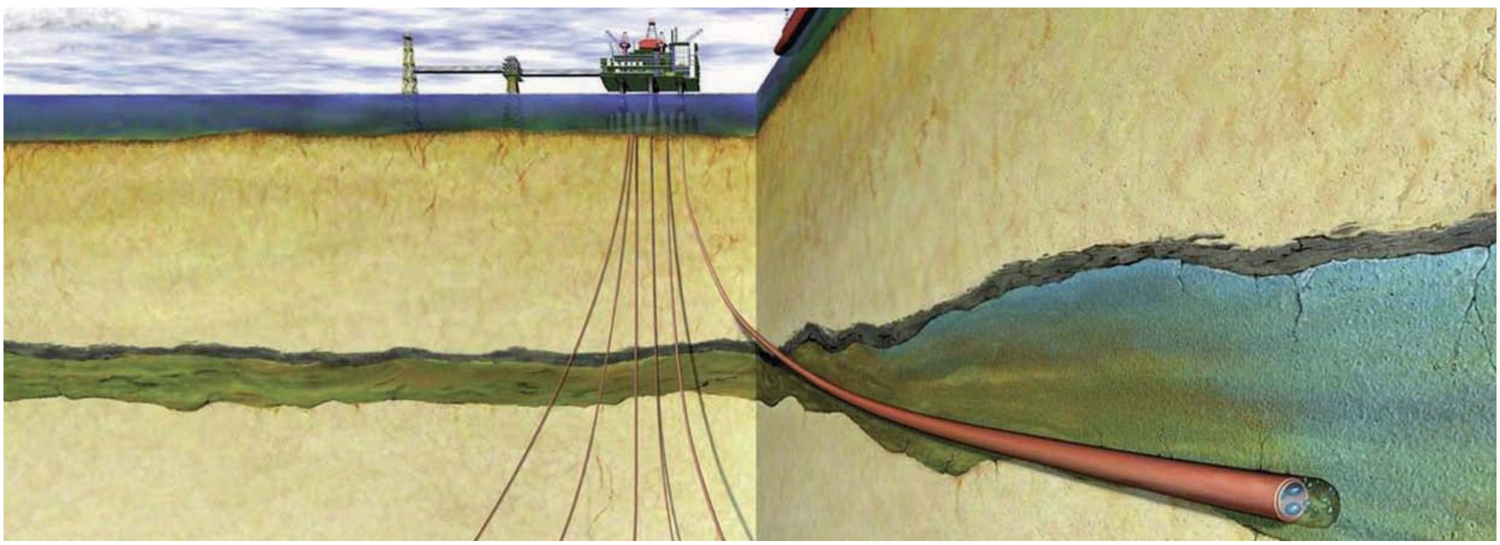


Illustration: StatoilHydro

Based on real multiphase flow models, LedaFlow® provides a step change in fidelity, quality, accuracy and flexibility over current generation multiphase flow simulation technology. It has been validated against the best available, most comprehensive experimental data.

LedaFlow® is an efficient and user-friendly stand-alone tool for transient multiphase flow analysis and flow assurance design in engineering studies. In addition, LedaFlow® is built to exploit the power of high-performance computing to support decisions in real-time. It is seamlessly integrated with the K-Spice® dynamic process simulation tool and suite of solutions for digital oil fields and Integrated Operations.

KONGSBERG is the only vendor currently able to provide a suite of proprietary tools including stand-alone transient multiphase simulations as well as integrated facility simulation systems and services. Support is given through all stages of the asset lifecycle – from feasibility studies to operation and maintenance, with flow assurance throughout every stage. KONGSBERG pioneered the delivery of integrated flow assurance systems and is market leader in supplying robust, accurate, field-proven systems – 80 solutions have so far been implemented world wide.

LedaFlow® Multiphase Flow Simulator

Product line
LedaFlow® is a flexible, modular dynamic multiphase flow simulator for single phase, 2-phase and 3-phase applications.

LedaFlow® Engineering	1D stand-alone engineering tool including the steady-state preprocessor and the 1D transient code
LedaFlow® Steady-state	Steady-state plug-in available for steady-state simulators
LedaFlow® Q3D	Q3D module which can be used as a stand-alone tool or in combination with LedaFlow® Engineering
LedaFlow® Profile	2D resolution of flow profiles that can be added to LedaFlow® Engineering or act as a self-standing module
LedaFlow® Integrated	LedaFlow® fully integrated with the K-Spice® dynamic process simulator
LedaFlow® Online	LedaFlow® running online with the process as a stand-alone tool or fully integrated in K-Spice® online systems

LedaFlow® Engineering
- Single, two and three phase flow
- Steady-state point model
- Steady-state pre-processor
- Fully transient model
- Thermal and compositional models
- Temperature, enthalpy and mass transfer modeled in each phase
- Flow transitions between separated and dispersed phases
- Fully compressible solution
- Slug capturing integrated in solver
- Gas lift for wells and risers, valves, controllers

Field Data Validations

ConocoPhillips and TOTAL have validated LedaFlow® against a large number of measured data from fields covering:
- both gas/condensate and oil dominated systems
- a large range of Gas-Oil-Ratio and Water Cut
- pipe diameters ranging from 2″ to 38″
- a large variation in operational pressures

Some selected examples:

Field type	*Type*	*Company*
Gas/oil 42 km offshore pipeline	Pipeline	Total
Offshore gas field	Pipeline	ConocoPhillips
Gas/oil 2 km onshore pipeline	Pipeline	Total
Onshore gas field	Pipeline	ConocoPhillips
Gas/condensate 20 km offshore pipeline	Pipeline	Total
Gas 81 km offshore pipeline	Pipeline	Total
Oil well with gas lift	Well	ConocoPhillips
Gas/oil 4 km offshore pipeline	Pipeline	Total
Gas/oil 16 km pipeline	Pipeline	Total

Right:
Left: LedaFlow® 1D simulation of liquid hold-up in an S-riser. Good agreement in amplitude, pressure drop and frequency.

Below:
LedaFlow® 1D simulation of liquid hold-up in an S-riser. Dynamic visual representation of liquid hold-up.