NTNU
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Stabilization of two-phase flow in risers from reservoirs

Robust anti-slug control strategies

Knut Åge Meland

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Supervisor: Sigurd Skogestad, IKP

Norwegian University of Science and Technology
Department of Chemical Engineering

Preface

This thesis was written as a part of my M.Sc degree in Chemical Engineering from the Norwegian University of Science and Technology (NTNU) in 2011. There is a lot of people deserving credit for helping me finish this thesis.

First I would like to thank my professor and supervisor Sigurd Skogestad for his good guidance and encouragement. A special thanks goes to my co-supervisor Esmaeil Jahanshahi who was very helpful and supporting. I also would like to mention Erik Langørgen and Stein Skånøy for their support at the multiphase flow laboratory.

Thanks to my fellow students at the Process control group for their great spirit and uplifting atmosphere at the office. Finally, I would like to thank Christin Berndtsson for helping me find mistakes in my thesis.

Enclosed are the Matlab files used to generate the figures in this thesis in addition to a digital copy of the safety evaluation for the experimental setup.

Declaration of Compliance

I hereby declare that this is an independent work in compliance with the exam regulations of the Norwegian University of Science and Technology.

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Abstract

This thesis is an experimental study of robust anti-slug control strategies for riser systems. The main objective of this thesis was to develop a robust anti-slug control scheme to increase the stability of riser systems. Similar research has been done previously, but is repeated in this thesis using a new closed loop tuning method by Skogestad et al.[25]. Using this systematic approach ensures that the results from the different experiments are comparable.

A number of experiments have been carried out using a small scale two phase flow riser loop. The robustness of the different control schemes was compared by slowly increasing the choke valve opening (setpoint) of the closed loop system until instability was reached. A robust control scheme can maintain system stability in a large range of conditions. The control scheme with highest robustness was thus the one which was stable at the largest choke valve opening. Mainly, single loop control schemes were tested successfully. The general trend was that the best controllable variables, with respect to robustness, are measurements upstream the riser low point. The best control scheme was able to stabilize the riser system until a choke valve opening of 27 % from an open loop stability of 12 %.

Top side measurements were in general difficult to use in anti-slug control schemes. Density measurements using an optical slug sensor was able to stabilize the riser system, but no tuning method could be implemented. Measuring the topside flow rate using a venturi tube and a DP-cell installation was tested with no success. The equipment used in the experiments was oversized and resulted in no signal output. Since no systematic tuning method could be implemented to the topside control schemes, no cascade anti-slug schemes were tested. Inspired by the density valve action, a square wave signal was used as an input to the choke valve. The experiments proved that the riser system stability region was extended when using a square wave as input.

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Chapter 1

Introduction

Experiments to limit the effect of slugging have been run for decades. Small scale control experiments were run during the late 70's[18]. In the late 80's, larger scale experiments with PI controllers were used to control the pressure at the bottom of the riser in two-phase systems[13]. One of the first known industrial implementations of a slug controller was done by Total at the Dunbar pipeline in 1994. The Dunbar pipeline is a 16 inch multiphase pipeline connecting the Dunbar field to the Alwyn platform located at the British side of The North Sea.[6] A few years later ABB developed a feedback control algorithm for stabilizing terrain induced slug flow at the Hod Valhall pipeline. The algorithm was tested on site in 1999 and showed good results. The experiments proved that active control on the choke valve could stabilize the flow at conditions where slug flow was expected. Stabilizing the flow provided smoother operation of pipelines, wells, separators and compressors.[12] Statoil has also been active in the development of slug limiting technology and completed in 2001 their first slug control installation at the Heidrun oil platform[24]. In addition to the mentioned installations, there is a installation for preventing terrain induced slugging at the Tor-Ekofisk pipeline[1].

Norway has played an important role in developing new technology for the offshore oil industry. In particular the Norwegian University of Science and Technology has done research for developing of new technology to stabilize slugging in riser systems. Storkaas et al.[29][30][31], Sivertsen[21][23][22], and numerous master students guided by Skogestad[32][3][35][33][9][16] at the Department of Chemical Engineering have done work in modeling and controlling of riser systems.

Many simple non-linear models[15][7][30] have been developed in the aid of foreseeing slugging behavior. Companies like ABB[12][1], Statoil[24] and Total[6] have all researched prevention of slugging and built installations at offshore locations. Siemens is also involved in slugging research, and fund a PhD program, which this thesis is connect to.

Pipelines carrying multiphase flow are today common on offshore production facilities in the North Sea[12]. Offshore pipelines consist of two main types, infield pipelines and export pipelines. Export pipelines transports oil-water or gas-condensate to shore for further processing. Infield pipelines transports wellstreams to the platforms[11]. The pressure drop from subsea wells to the platforms is large, and will create gas-condensate multiphase flow for gas fields and oil-gas-water multiphase flow for oilfields. The latter leading to one of the biggest challenges in offshore operations, which is control of disturbances in the feed to separation process[12]. Control and transport of multiphase flow entering the separation process is often referred to as flow assurance. Research and development of flow assurance technology is of high importance to the oil industry. The increasing number of multiphase pipelines being built will only increase the importance of flow assurance in the future.[12]

There are different types of slugging, depending on the environment in which the slugging occur. The slugging type which can occur in the transport of multiphase flow from the seabed to the platforms are called riser slugging. This type of slugging will often become an issue at the tailproduction in oilfields, due to changes in operating conditions. Riser slugging induces large disturbances which could trip production. Preventing riser slugging, by increasing the non-slugging region with the use of active control can increase the well lifetime and oil recovery. Active control will reduce the disturbance and as a consequence increase the production uptime.[12]

In this thesis the different control strategies will be tested with experiments to find the most robust solution. High robustness will be obtained if the system can maintain stability at large deviations from original conditions, thus extending the non-slugging region. Similar research have previously been done by Sivertsen et al.[23][22], Bårdsen[3], Jalal[9], Søndrol[33] and Hyllestad[16] but will be repeated using a more systematic procedure for tuning the controllers to make the different control strategies comparable. Experiments will be executed in a small scale system located at the Norwegian University of Science and Technology. The original scope was to perform experiments in three different rigs, but because one rig is not available and another is lacking risk assessment, only one rig will be used. Experimental equipment connected to experiments executed in this thesis is financed with the help of Siemens.

Chapter 2

Background

2.1 Multiphase flow

Multiphase flow can be defined as the transport of two or more distinct phases (usually a combination of liquid, gas and/or solids) inside a pipe. An example would be the flow from an oil well which produces oil and gas. Traditionally the different phases were separated before long transports, but recently it has become more economically viable to transport the phases in the same pipeline.[28]. The stability of multiphase flow can be visualized in a stability map, as illustrated in Figure 2.1[34].

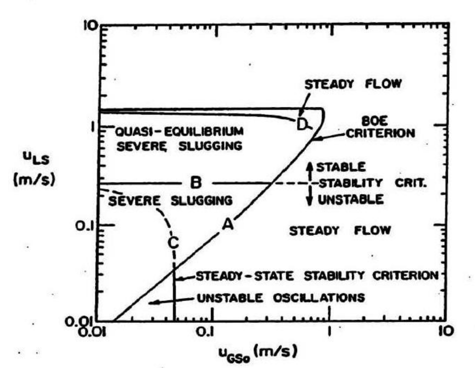


Figure 2.1: Stability map for multiphase flow.[34]

Unstable multiphase flow can be divided into multiple regions, where the instability is caused by several different phenomena (discussed in more detail in section 2.2).

2.2 Definition of slug flow

When oil, gas and water flows inside a pipeline simultaneously, the three phases can be distributed in many configurations due to density differences. How these phases are distributed in pipelines are dependent on operating conditions, such as phase velocities and pipeline angle. The possible configurations are called flow regimes, and the main categories are: stratified flow, annular flow, bubble flow, slug flow and churn flow. In this thesis slug flow has been the main focus area. Slug flow can also be divided into multiple categories[11][29]:

- **Hydrodynamic slugging**, develops in the horizontal parts of the pipeline. Liquid waves grows on the liquid-gas phase boundary and creates slugs when the waves gets large enough to close the cross-section.
- **Terrain slugging**, develops in pipelines at rough seafloor terrain, where liquid accumulates in the inclined sections.
- **Transient slugging** develops in pipelines connected to processing facilities in response to changes in operating conditions. Typical examples are change in flow rates and pressure. During startup and shutdown, transient slugging is a typical problem.
- **Riser slugging**, occurs when liquid blocks the low-point of a downsloping pipeline which is connected to a riser. The liquid slug will grow until the pressure builds up upstream, and gets large enough to blow the slug out of the riser.

2.3 Definition of a riser

Risers are long pipes connecting the reservoirs to surface facilities for oil production. There are essentially two kinds of risers, flexible and rigid risers.

Risers come in different shapes and configurations. Common riser shapes are the J-shaped risers (free hanging catenary) and the S-shaped risers(S type (supported by seafloor installations) and wave (supported by buoys)), see Figure 2.2.

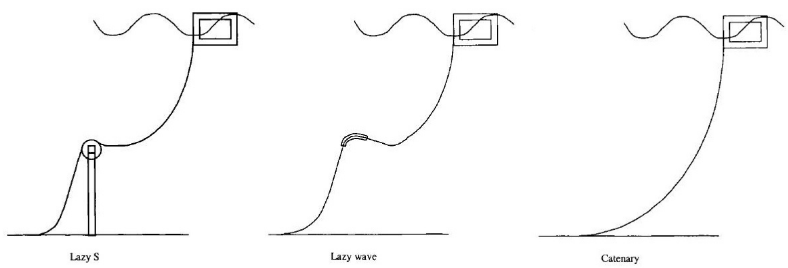


Figure 2.2: Common riser configurations used in the oil and gas industry [4]

2.4 Riser slugging

2.4.1 Problems caused by slugging

The most serious type of slugging for oil/water systems are riser slugging, possibly combined with or initiated by terrain slugging. Riser slugs can be several hundred meters long, and can fill up the entire riser. Separators on receiving downstream facilities are not large enough to receive slugs of this magnitude. This could cause overfilling which could trip the production. Other consequences could be unwanted flaring and reduced operating capacity for separation and compression units. The reduced capacity is caused by the need off larger operating margins to handle the larger disturbances. Larger disturbances requires a larger backoff from the optimal operation point, and thus reducing the throughput. Small slugs could also be problematic, as it could lead to poor separation, varying compressor load and wear on equipment.[12][29]

2.4.2 Mechanism of riser slugging

The cyclic behavior of riser slugging can be broken down into four parts. These steps are illustrated in the Figure 2.3. Gravity causes liquid to collect in the low point of the pipeline and causes blockage (step 1). This will only happen if the gas and liquid flow rates are low. The liquid slug will continue to grow as long as the hydrostatic liquid head increases faster than the pressure drop (step 2). When the pressure forces overcomes the force generated by the liquid column in the riser, the liquid slug is pushed upwards by the pressure difference (step 3). Gas starts to penetrate the liquid slug, and eventually the driving force is to low to push the remaining liquid out of the riser. The remaining liquid will flow back down the riser (step 4) and the accumulation of liquid starts again.[29]

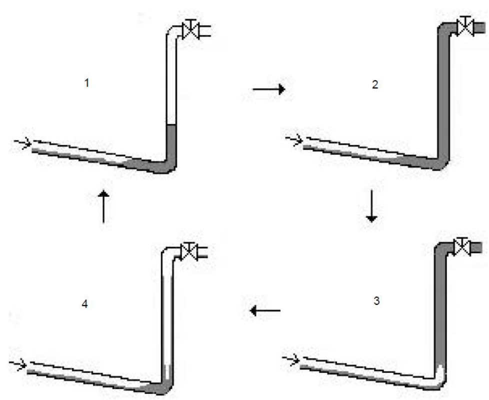


Figure 2.3: Cyclic behavior of riser slugging[29].

2.4.3 Definition of severe slugging

Schmidt et. al[19] divided slugging into two different types. In type I slugging, the liquid slug length should exceed the riser height at low liquid and gas velocities. Type II slugs are characterized by having the same flow pattern as a type I, but having slightly aerated liquid slugs and a slug length smaller than the riser height. Slugging was characterized as severe if the length of the liquid slug was larger than the riser height, thus type I slugging. Type II slugging are usually not so critical for a stable operation.

2.5 Anti-slug control

Pipelines are designed such that slugging are prevented to some extent. Due to changes in operating conditions, slugging often becomes a issue towards the end of the well lifetime. Redesigning the riser/pipeline system is often not profitable, and other measures should be used. In this section, the most commonly used methods for stabilizing and preventing slugging are shortly described.

2.5.1 Choking

Riser slugging may be avoided by choking the flow, using the valve at the top of the riser. This phenomenon can be explained by considering a pipeline-riser system which initially is non-oscillatory. Increasing the liquid flow will cause the liquid to collect in the low point of the riser. This results in an increased pressure drop over the riser, due to compression of the gas upstream and decreased cross-section due to liquid blockage. The increased pressure drop results in less gas going through to the riser. The gas in the riser will expand, and result in reduced pressure in the top of the riser. The increased pressure upstream the low point will push the liquid slug to the top of the riser. If the choke valve opening is larger than a critical value, the liquid outflow rate will be larger than the liquid flow to the riser. This leads to a negative deviation in the liquid holdup, larger than the positive perturbation, and will result in growing oscillations and unstable slug flow. Valve opening lower than the critical value will result in less liquid leaving the system, and a liquid holdup deviation smaller than the perturbation resulting in a stable non-slugging system.[29]

2.5.2 Active control

Use of active control by controlling the topside choke valve can be used to prevent slugging. The valve position can be controlled using a simple feedback loop, measuring for instance the upstream pressure at the low point of the riser or the top pressure before the choke valve. The latter have been proven difficult in practice.

2.5.3 Gas lift

Another commonly used method is the use of gas lift. Slugging is prevented by injecting gas into the riser, and thereby preventing pipe blockage.[2]

2.5.4 Slug catchers

A solution for minimizing the effect of slugging could be to install slug-catchers. These are large tanks installed on the platform with the sole purpose of receiving slugs. Installing such large devices are often not economically viable on offshore installations, where space is limited.[35]

2.6 Proportional-integral-derivative (PID) and proportional-integral (PI) controllers

One of the most commonly used controllers today are the PI and PID controllers. The controllers consists of a proportional term (P), a integral term (I) and a derivative term (D) as shown in the equations 2.1 and 2.2.

$$c = K_c(1 + \frac{1}{\tau_I s}) \tag{2.1}$$

$$c = K_c(1 + \frac{1}{\tau_I s} + \tau_d s) \tag{2.2}$$

Where K_c, τ_I, and τ_d are the respective tuning parameters for the P, I and D terms.

2.7 The SIMC method for closed-loop systems

The Skogestad Internal Model Control (SIMC) method was developed by Skogestad. The method contains a set of tuning rules for finding near optimal parameters for PI controllers or PID controllers using a systematic procedure. It aims to be simple and easy to memorize while giving near optimal performance. The starting point is the Internal Model Control (IMC) tuning rules by Rivera et al.[17], from which the SIMC tuning rules can be analytically derived. As a basis, the SIMC tuning rules uses a first order approximation plus delay model for PI control, and a second order plus delay model for PID control. Most stable higher order processes can be approximated to a first or second order model, using the half rule[27]. For tuning, a general set of rules, given in the equations 2.3 and 2.4, are used.

The SIMC method can be broken down into two main steps:

1. Approximate the system with a lower order model (first or second order model, depending on which type of controller (PI or PID control) to be used).
2. Determine tuning parameters using a general set of rules. For PI control, the equations 2.3 and 2.4 can be used to tune the PI controller. These equations are derived by finding the expression for the controller in a cascade feedback arrangement, shown in Figure 2.4.

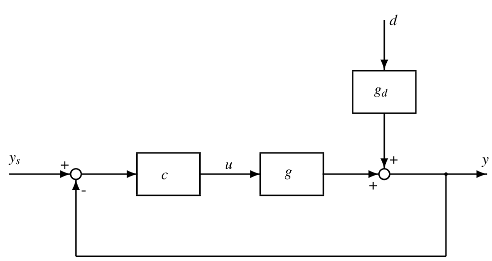


Figure 2.4: Cascade configuration of the controller structure [25].

$$Kc = \frac{1}{k}\frac{\tau_1}{\theta + \tau_c} \tag{2.3}$$

$$\tau_I = min(\tau_1, 4(\theta + \tau_c)) \tag{2.4}$$

Where τ_c is the only unknown tuning parameters, if the process could be approximated by a first or second order plus delay model. In the paper by

Skogestad[27], it was recommended to use $\tau_c = \theta$ as a good compromise between performance and robustness.

Not all systems are originally stable in open loop, or the open loop response could in some cases be difficult to obtain. For such cases an improved SIMC method called 'The setpoint overshoot method' was constructed by Shamsuzzoha et al. [20]. This method was designed for finding similar parameters as the SIMC method, but for closed loop setpoint experiments using only a proportional (P) controller. Skogestad et al.[25] developed this method further into a two step closed loop procedure. The latter procedure was used in this thesis for finding the appropriate tuning parameters.

Underneath is a step by step description of the two step closed loop SIMC method.

1. Use a P controller and make a setpoint change, Δy_s.
2. Record the closed loop step response. Tune the P controller gain (K_{c0}) such the overshoot (D) is approximately 30 %, see Figure 2.5 for a graphical illustration and equation 2.6.
3. Record the following values from the graphical step response.
   - Time to first peak (t_p).
   - Maximum output change (Δy_p).
   - Relative steady state output change ($\Delta y(\infty)$) or alternatively the output change at first undershoot (Δy_u), from which an estimate $\Delta y(\infty)$ could be calculated using equation 2.5.

$$\Delta y(\infty) = 0.45(\Delta y_p + \Delta y_u) \tag{2.5}$$

4. Calculate the following parameters:
   - If not recorded earlier, calculate the relative steady state output change ($\Delta y(\text{inf})$), using equation 2.5.
   - Overshoot (D) using equation 2.6.
   - Steady state offset (B) using equation 2.7
   - The parameter (A) using equation 2.8.

- the parameter (r) using equation 2.9.

$$D = \frac{\Delta y_p - \Delta y(\infty)}{\Delta y(\infty)} \tag{2.6}$$

$$B = \left| \frac{\Delta y_s - \Delta y(\infty)}{\Delta y(\infty)} \right| \tag{2.7}$$

$$A = 1.152D^2 - 1.607D + 1 \tag{2.8}$$

$$r = \frac{2A}{B} \tag{2.9}$$

5. Calculate the first order plus delay model parameters:

   - Steady state gain (k) from equation 2.10.
   - Time constant (τ_1) from equation 2.12.
   - Delay (θ) from equation 2.11.

$$k = \frac{1}{K_{c0}B} \tag{2.10}$$

$$\theta = t_p(0.309 + 0.209e^{-0.61r}) \tag{2.11}$$

$$\tau_1 = r\theta \tag{2.12}$$

6. Calculate the PI controller tuning parameters (Kc and τ_I). Any tuning method could be used, but in this thesis the previously described SIMC method was used. A first order plus delay model are found in steps 1-5, corresponding to the SIMC method first step. In this last step, corresponding to the second SIMC method step, the tuning parameters are found using the general tuning equations (equations 2.3 and 2.4).

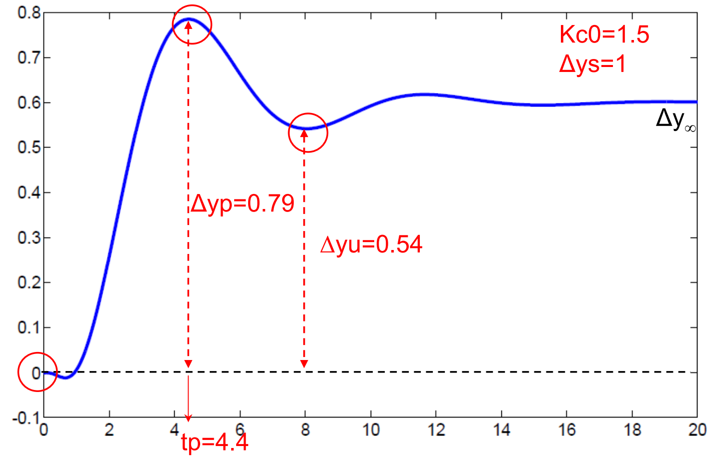


Figure 2.5: Closed loop setpoint response with P controller only [25].

Chapter 3

Experimental

In this thesis, experiments on three experimental setups were to be performed originally. However, only one small scale experimental setup was used. A similar setup was in the process of being constructed during the time of writing, but did not become ready to run experiments. Some time was invested to get this experiment working, but due to delivery delay and equipment breakdown, it became evident that it was not possible to get it running in the time frame set for this thesis. Both the working small scale setup and the third medium scaled experimental setup were missing a safety certification. A new policy in the laboratory required a thorough study of hazards related to the experiments. Because of this extra work, it was not time to run experiments at the medium scale setup. The Health Safety and Environment (HSE) evaluation for the small scale setup was done in cooperation with the HSE supervisor according to laboratory guidelines to ensure a safe and non hazardous working environment. A copy of this safety evaluation is enclosed as a digital attachment.

In the following sections the layout, operating procedure and the main components are explained, including a procedure for calibration of sensors. Calibration is important to ensure that the experiments are operated using correct the flow regime.

3.1 Experimental overview

The experiments were executed in a small scale setup, called Mini-loop. This particular experiment was located in the Multiphase Flow Laboratory at the department of Energy and Process Engineering. Previously, other master and project students at NTNU also had been using this experimental setup for their thesis[3][33][9][16]. The main idea behind the Mini-loop is to emulate the slugging phenomena in a small scale. The Mini-loop is easy to operate and quickly reaches steady state, thus reducing the time between each single experiment. Slugging can, as explained in the theoretical part of this thesis, occur when mixing oil and gas at certain individual flow rates. Instead of using oil and gas, water and compressed air was used because of availability and handling issues. The difference with respect to control would indeed be small, as the same slugging phenomena occur also for this fluid mixture.

Figure 3.2 shows a schematic overview of the experimental setup used to perform the series of experiments in this thesis. In Figure 3.3 a real picture of the experiment can be seen. The liquid (water) was stored locally in a water tank (T2). Pressurized air from the laboratory high pressure air supply was mixed with water from the storage tank and the multiphase flow was forced up the riser tube. For slugging to occur, it is important that the air volume is large enough to force the liquid up the riser. To increase this volume and emulating a long pipeline, an air buffer tank (T1) was installed upstream the mixing point. For preventing water flowing into the air buffer tank, the connection between the mixingpoint and buffertank was elevated. The coke valve (C)(mounted at the top of the riser) was used for manipulating the back pressure and thus the flow rate up the riser tube. Pressure transmitters (P1, P2, P3 and P4), venturi with DP-cell (DP) and a slug sensor (SS) were installed at various places in the setup, and were used to construct a number of different control structures. Finally, air and water were separated in the separation unit (T3). Water was recycled back into the water tank, while the air was released into the atmosphere.

The most essential dimensions of the experimental setup are listed in Table 3.2.

The Laboratory Virtual Instrumentation Engineering Workbench (LabVIEW) software from National Instruments was used for instrumentation control and data logging. Figure 3.1 shows the user interface. Directly from the interface it is possible to monitor pressures, flow rates and valve position. In addition it is possible to manually set choke valve opening, or set tuning parameters for PID/PI/P controllers. A previously program used by Hyllestad[16] was used as a basis, but this program did undergo heavy modifications. Custom parts were added for additional sensors, signal processing and a setpoint decrease schedule.

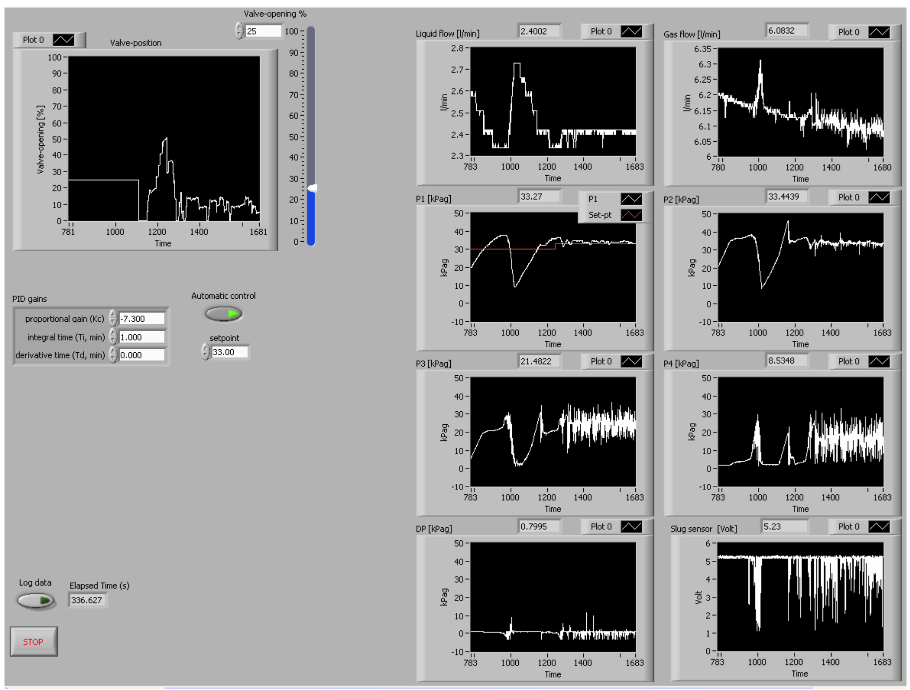


Figure 3.1: LabVIEW user interface.

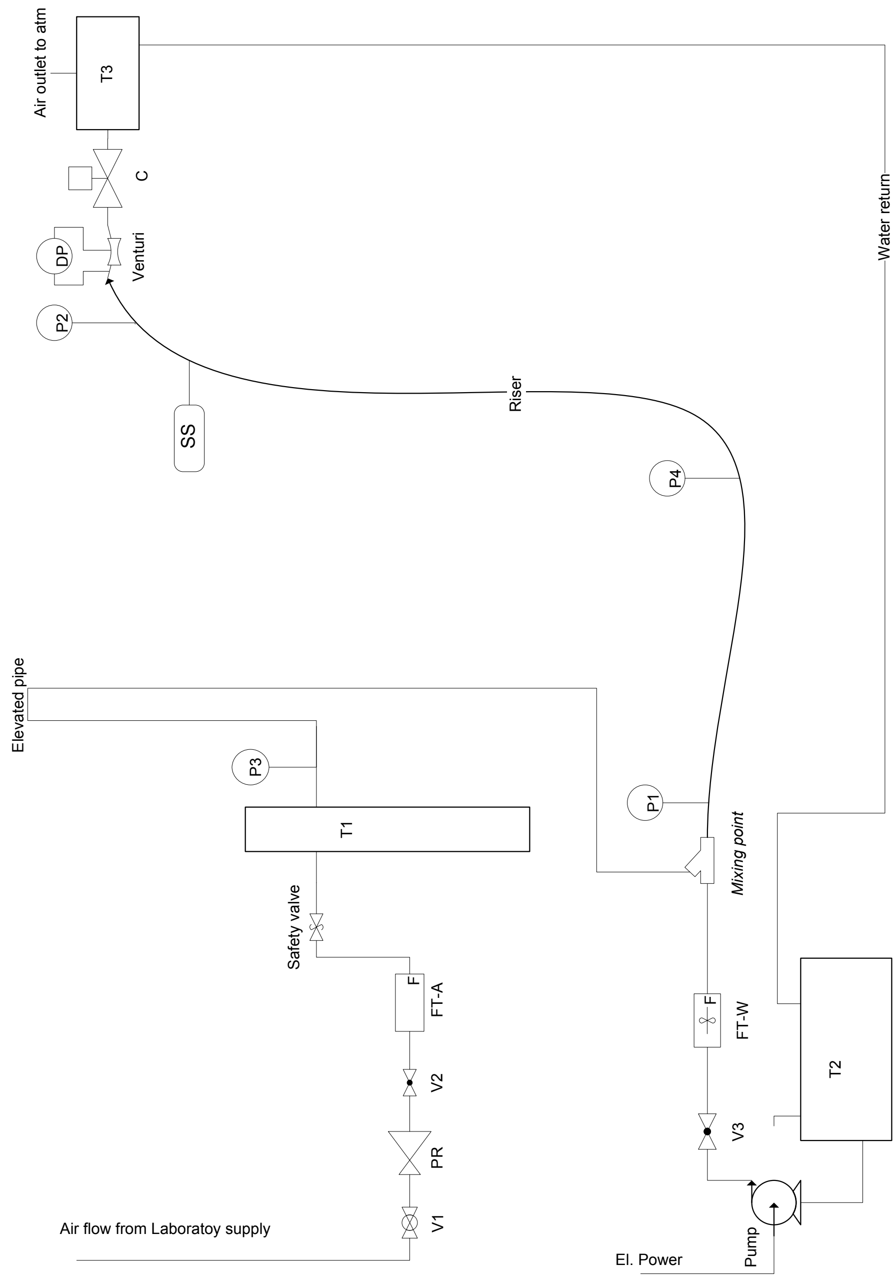


Figure 3.2: Mini-loop layout. An small description of the components are given in Table 3.1.

Figure 3.3: Overview of the Mini-loop experiment. The inlet is in the lower left corner. The riser starts in the lower right corner and goes up to the upper right corner. On the horizontal top section, the DP-cell, pressure sensor and choke valve are installed. The separator is located in top after the horizontal top section.

Table 3.1: Equipment list

Label	Description
C	Choke valve
DP	Differential pressure transmitter
FT-A	Flowmeter for the air supply
FT-W	Liquid flow transmitter
P1	Pressure transmitter
P2	Pressure transmitter
P3	Pressure transmitter
P4	Pressure transmitter
PR	Pressure regulator for air
Pump	Water pump
Riser	Riser made of flexible tube
Safety valve	1 barg safety valve
SS	Slug sensor
T1	Air buffer tank
T2	Water storage tank
T3	Separator
V1	Master valve for air supply
V2	Globe valve for controlling air flow rate
V3	Globe valve for controlling water flow rate
Venturi	Venturi for inducing pressure difference

Table 3.2: Dimensions of the Mini-loop.

Description	size [cm]
Riser height	291
Tube diameter	0.2
Length inclined pipe section	210
Angle inclined section	18 (degrees)
Length horizontal feed pipe	28
Horizontal top section	110
From choke valve to separator	55
Separator length	25
Separator diameter	10.5
Air buffer tank height	77.5
Air buffer tank diameter	14

3.2 Components

In this section properties and purpose of the main components and sensors are given.

3.2.1 Water reservoir tank

The water reservoir tank is used to store water to ensure that the water pump gets a continuous feed of water. After going through the riser and into the topside separator, the water is recycled to the water tank. The tank is made of transparent Plexiglas and has a cylindrical shape. A picture of the tank can be seen in Figure 3.4.

Figure 3.4: The water storage tank.

3.2.2 Air buffer tank

The air buffer tank is made of transparent Plexiglas with an cylindrical shape. A picture of the tank can be seen in Figure 3.5. To make slugging possible, a large pipe volume for pressure buildup is necessary. The buffer tank increases this pipe volume, which can be adjusted by filling the tank partly with water. The maximum pressure the buffertank can withstand is limited. For safety, the tank has been equipped with a safety value, to ensure that the pressure not will exceed 1 barg.

Figure 3.5: The air buffer tank.

3.2.3 Separator tank

Just like the air buffer tank and the water reservoir tank, the separator tank is made of transparent Plexiglas. The shape is also similar. The separator is situated at the top of the riser, after the choke valve. A picture of the separator is shown underneath in Figure 3.6. The outlet on top releases the air from the riser. The bottom outlet is used for the water recycle, returning the water to the water storage tank.

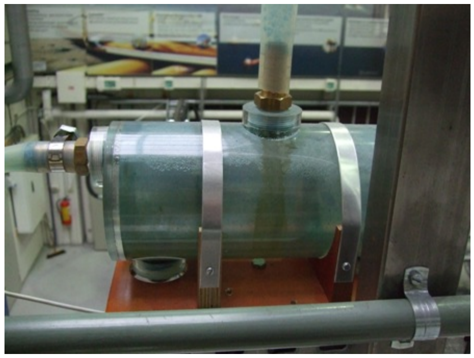


Figure 3.6: Water and air separator.

3.2.4 Water circulation pump

The water circulation pump is used to increase water pressure before the mixing point to force water up the riser. The pump has three levels of power. For most of the experiments in this thesis, the lowest power level was sufficient. The pump is located between the water tank and the mixing point. It is important that the water level in the water tank is above the water outlet to avoid air getting into the pump and potentially damage the pump. The Figure 3.7 shows a picture of the water circulation pump.

Figure 3.7: Water circulation pump

3.2.5 Tubing

The tubes used in the pipeline and riser sections are made from transparent silicon-rubber hoses with an inner diameter of 20 mm. Figure 3.8 shows such a pipe.

Figure 3.8: Transparent rubber tube, 20 mm inner diameter

3.2.6 Air flow meter

The air flow meter, manufactured by Palmer Cole, is located upstream the air buffertank and downstream the pressure regulator. The principle of through-flow measurement is used to measure the mass of air flowing through the device. Figure 3.9 shows the air flow meter.

Figure 3.9: Air flow meter.

3.2.7 Water flow meter

Figure 3.10 shows the water flow meter. The water flow meter, located upstream of the mixing point, is manufactured by Gemü. This flow meter utilizes turbine flow measurements with a low pressure drop to measure the water flow rates.

Figure 3.10: Liquid flow meter

3.2.8 Pressure regulator

A manual pressure regulator is used at the air inlet to ensure that the pressure will not exceed the upper limit of the air buffertank, see Figure 3.11.

Figure 3.11: Manual pressure regulator.

3.2.9 Pressure transmitters

Simple and cheap pressure transmitters manufactured by Motorola were used to measure the pressure relative to the atmospheric pressure. The transmitters have a working range of 0-1 barg. Signals are linear and in the range 0.2-4.5 V. Figure 3.12 shows one of the transmitters used in the Mini-loop.

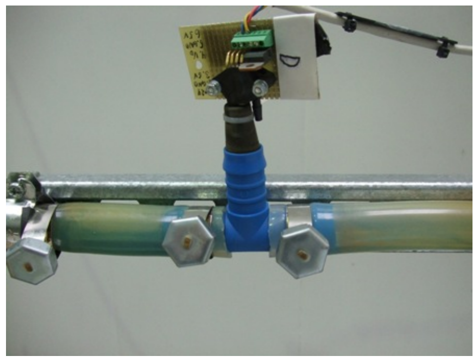


Figure 3.12: Pressure transmitters type MPX 1500DP from Motorola.

3.2.10 Choke valve

The choke valve is an angle seat valve manufactured by Gemü. Located upstream of the separator on the top of the riser, the valve is operated by pressurized air (4-8 bar) supplied from the pressurized air system in the laboratory, through the valve positioner. A picture of the choke valve and the valve positioner are shown in the Figure 3.13 underneath.

Figure 3.13: The choke valve used before the separator

3.2.11 Choke valve positioner

A valve positioner is used to keep a valve in a given position. The positioner utilizes pressurized air to open and close the valve and is mechanically connected to the valve, such that the valve position is always known. A picture of the choke valve postioner can be seen in the Figure 3.13.

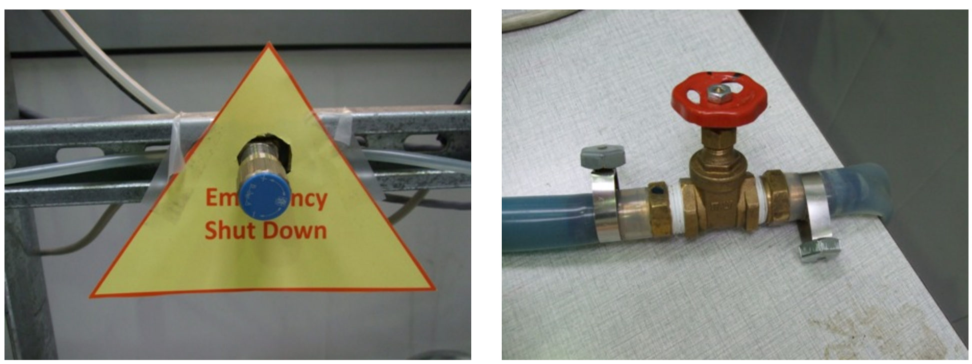
3.2.12 Slug sensor

For measuring the slugs a fiber optic sensor manufactured by Omron is used. The sensor measures the amount of light transmitted through a fiber optic cable (connected to a light source) to a receiving fiber optic cable. These cables (sensors) are attached to the riser tube near the top. When a liquid slug is passing the sensor, less of the transmitted light goes through to the receiving cable than when the tube is filled with air. To increase the contrast between air and water, a color substance (Vulcanosol Blue 684) was added to the water. A picture of the sensor setup can be seen in the Figure 3.14.

Figure 3.14: Fiber optic slug sensor by Omron.

3.2.13 Valves

Water and air flow rates are set using two globe valves (Figure 3.15). To control the water flow rate, the valve (V3), located between the pump and the mixing point, was used. The valve (V2), downstream of the pressure regulator, was used to set the air flow rate.



(a) Valve (V2). (b) Valve (V3).

Figure 3.15: Valves for setting water and air flow rates.

3.2.14 Venturi/DP-cell arrangement

Measuring a multiphase flow rate could often be a challenge and commercially available equipment specially designed for this purpose is often expensive.

A cheap and simple alternative method could be to use a venturi and a differential pressure cell (DP-cell) arrangement. A venturi, Figure 3.16, with an inner diameter of 10 mm was used to induce a pressure difference at the narrow point (orifice). A DP-cell (Figure 3.17) is designed for measuring small pressure differences accurately. Using the relations given in appendix A, the recorded pressure difference can be used to obtain an estimate of the velocity in the pipeline and the volumetric flow rate. An estimation of the mass flow rate can be found using an estimation of the density (could be found with the help of the slug sensor measurements).

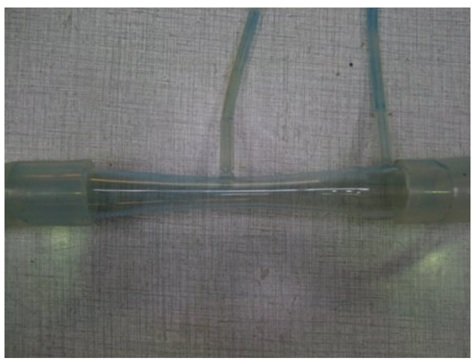


Figure 3.16: Venturi tube with a orifice of 10 mm.

Figure 3.17: DP-Cell manufactured by Fuji with working pressure range of 0-6 kPa.

3.2.15 I/O module

The I/O module is used to convert the measured signals into a signal the computer can handle. In general I/O modules consists of multiple analog or digital output and input modules mounted in a cabinet. In this setup, Field point analog modules from National Instruments, which can handle both voltage and current signal were used. The modules, four in total, were mounted in a closed cabinet (Figure 3.18). The module on the top left is handling the computer connection through the serial port. Next is the output module for setting the choke valve position, followed by two input modules for various sensors.

Figure 3.18: Field point modules from National Instruments

3.3 Calibration of sensors

Since the experiment had not been in use for a while (at least one year), a calibration was executed to ensure that the pressure sensors and the liquid flow meter were giving the correct readings. The air flow meter should ideally also been calibrated, but because a time consuming and complicated calibration procedure it was decided not to prioritize this. A very accurate calibration of the equipment is not critical. Mostly, it is sufficient to only have an idea where in the flow regime you are, and use the same basis calibration throughout the series of experiments to make the results comparable.

Both the liquid flow meter and the pressure sensors use a linear relation (equation 3.1) for converting the corresponding current and voltage signals to the appropriate scales in LabVIEW. The constants a and b in equation 3.1 was found using a known reference connected to the system.

$$y = ax + b \tag{3.1}$$

3.3.1 Calibration of pressure sensors

When no mass was flowing into the system, the pressure sensors were not consistently having the same readings. Thus indicating that one or more sensors were not calibrated correctly. As a reference, a one meter long water manometer was used to measure the relative pressure precisely. For converting the water level in the manometer to pressure the following equation was used.

$$p_d = \rho g h \tag{3.2}$$

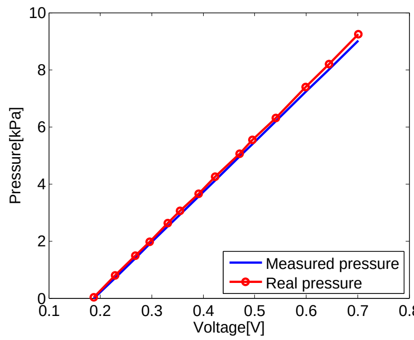
Where p_d is the gauge pressure, ρ is the water density, g is the gravity constant and h is the height of the liquid column.

Having closed the choke valve to ensure that no mass was leaving the system, the system was pressurized by adding pressurized air. By combining the voltage signals from the pressure sensors and the measurements of the water level in the manometer, the Figure 3.19 was created. Deviation from the optimum values was not significantly large, and the original calibration of the pressure sensors was mostly satisfactory. The only exception was the P3 pressure sensor, where the new linear constants was somewhat different from the original values. Later, a additional pressure sensor (P4) was installed in the riser low point. This sensor was calibrated by comparing the P4 signal with the signals from the previously calibrated sensors. This test revealed that the P3 sensor had previously not been calibrated correctly. In Table 3.3 the scaling constants for the different pressure sensors are listed.

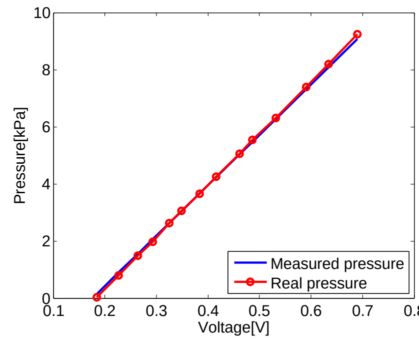
Table 3.3: Calibrated scaling constants for the pressure sensors.

Constant	P1	P2	P3[1]	P4
a	17.85	18.18	17.91	18.03
b	-3.30	-3.32	-3.09	-3.08

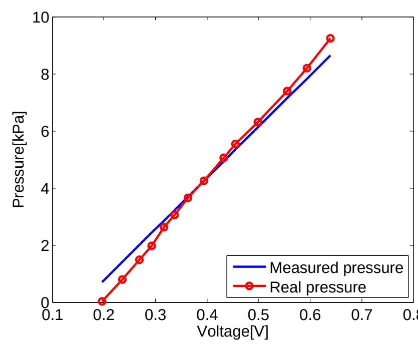
[1] Listed are the correct scaling constants found after the second calibration experiment. The constants found after the first calibration was a= 20.75, b=-4.01.



(a) Calibration of sensor P1.



(b) Calibration of sensor P2.



(c) Calibration of sensor P3.

Figure 3.19: This figure shows the original pressure calibration compared to the real measured pressure.

3.3.1.1 Comments

Some parts of the calibration could have been done better. A manometer with larger range should have been used to enable measurements at higher pressures. The current pressure range (0-10 kPa) was not large enough to cover the whole pressure range used in the experiments.

During the calibration experiments, it was found that the pressure was decreasing slowly when the system was closed. Despite extensive effort sealing the setup, it was not possible to make the setup completely sealed. Logging data was done manually, thus inducing a small time delay between each reading. The error caused by this time delay will also be influences by the decreasing pressure.

3.3.2 Calibration of the liquid flow meter

The liquid flow meter was also calibrated in the same manner as the pressure sensors. As a reference, the flow rate was measured by using the time needed to fill a bucket with water. The bucket was placed at a scale, and a fixed flow rate was set. After reaching steady state, the time and weight of the water in the bucket was logged. It was assumed steady state was reached in 10-30 seconds, depending of the flow rate. The time and weight was noted when the bucket was full. The difference between the original and measured flow rate from filling the bucket was very small as illustrated in Figure 3.20. The calibrated scaling constants for the liquid flow meter are listed in Table 3.4.

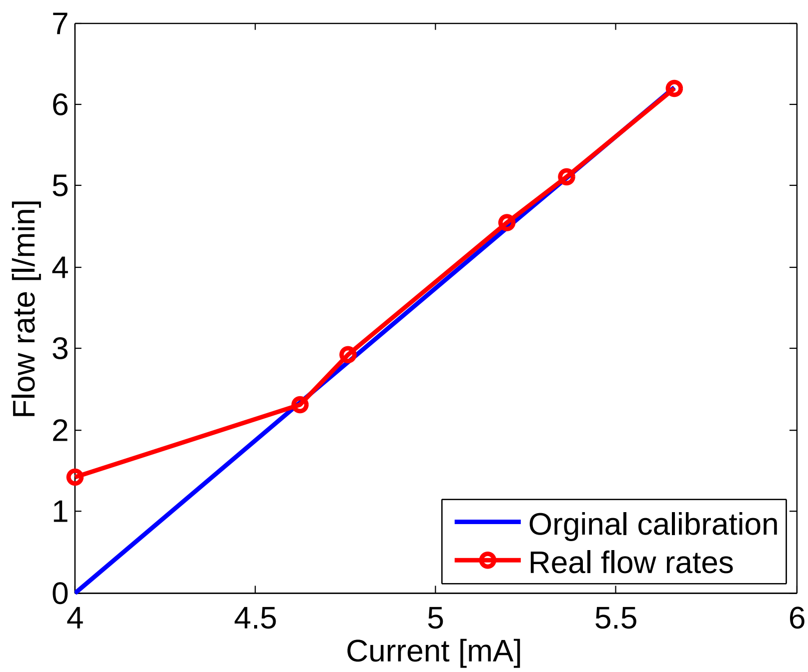


Figure 3.20: Calibration of the liquid flow meter.

Table 3.4: Calibrated scaling constants for the liquid flow meter.

Constants	Calibrated
a	3716.2
b	-14.81

3.3.2.1 Comments

Because the liquid flow meter was not able to measure flow rates below 1.6 l/min, there was a lower limit from where calibration data could be collected resulting in a deviation from the real flow measurements at very low flow rates, as seen in Figure 3.20.

During large flow rates the bucket was filling up very quick and induced some errors when logging the time and weight. This was because of the human factor (Time delay between readings). At increasing flow rates this error became more significant, and at the largest flow rates it was not an easy task to handle. The waiting time for reaching steady state was reduced to approximate 10 seconds at the largest flow rates of practical reasons (else the bucket would be filled before the experiments had started).

Chapter 4

Results

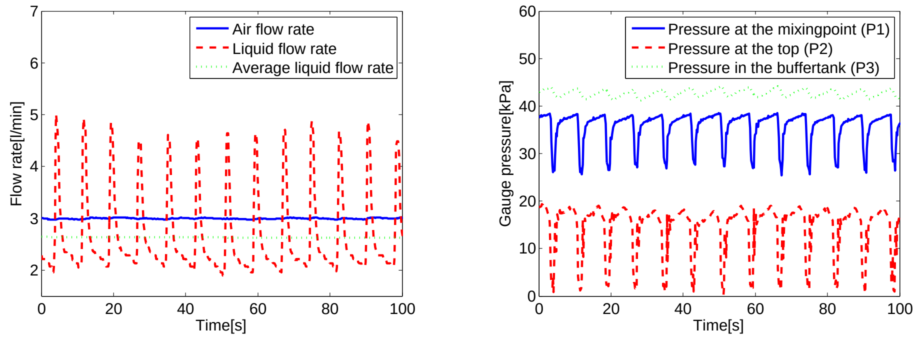
4.1 Basis condition without control

4.1.1 Inflow conditions

Conditions which slugging can occur are depended on the ratio of liquid and gas in the pipeline. Usually, a decrease in gas flow will result in more slugging, except when in the type 2 slugging regime. For this situation, decreasing the gas flow further will result in a more stable flow regime, called bubbleflow. Many factors was considered when deciding the appropriate flow rates of water and air for the series of experiments. For example, ratio of air/water, size of the pipeline, capacity of pump and air source, critical valve opening and slugging type. After carefully considering different options and some trial and error, it was decided to use 3 l/min of air and approximate 2.8 l/min of water, see Figure 4.1. These conditions were also close to the conditions used by Hyllestad[16].

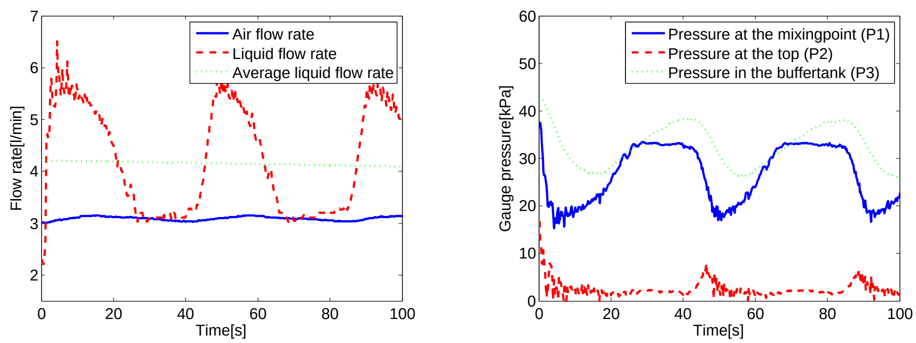
The water flow rate was very difficult to set, because of large variation in the flow rate, seen in Figure 4.1(a). Opening the choke valve fully, the flow regime changed to slugging (type I), illustrated in Figure 4.2(a).

In the following series of experiments, a constant flow rate of air and water was used. As a result, the water and air flow rates needed to be readjusted when the valve opening in open loop was changed. However, when using a controller in closed loop mode, it was considered not to be reasonable to adjust the inflow conditions.



(a) Inputs (b) Pressures

Figure 4.1: Basis condition with 10% valve opening



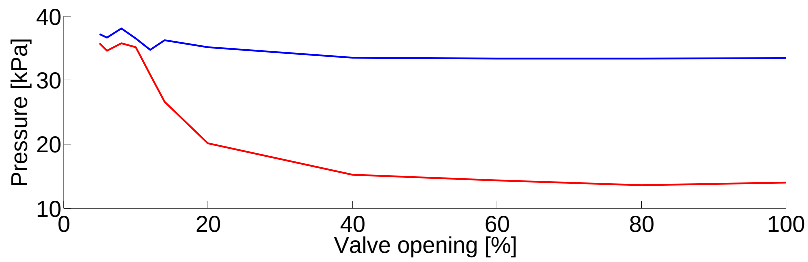
(a) Inputs (b) Pressures

Figure 4.2: Basis condition with 100% valve opening

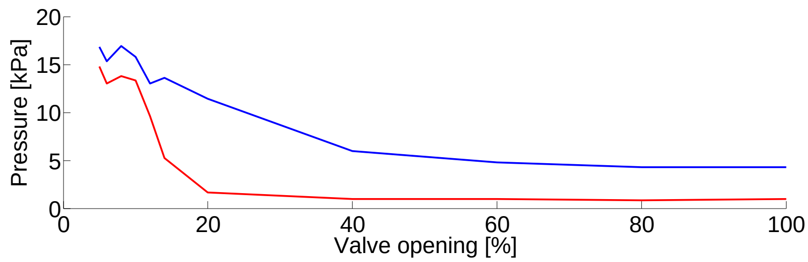
4.1.2 Bifurification diagram

The critical stability point is the maximum choke valve opening the system can have while being stable. Stable meaning where the system does not have large periodic variations in pressure. A bifurification diagram can be used to pinpoint the critical stability point. In a bifurification diagram, the critical stability point is where the maximum and minimum pressures approach a finite value.

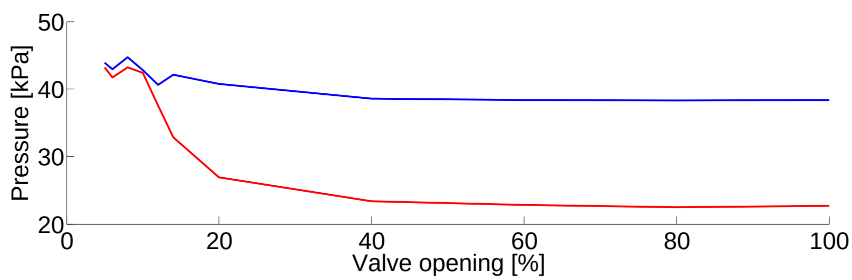
The bifurication diagrams were created by changing the choke valve opening while keeping the water and air flow rates constant. The resulting diagrams are given in Figure 4.3. In the stability region small pressure variations were present. These pressure variations were not regarded to be caused by severe slugging, but due to hydrodynamic slugging. The critical stability point was found by varying the choke valve opening, keeping the inflow conditions constant. The critical stability point was found to be at approximately 12% choke valve opening.



(a) P1 diagram.



(b) P2 diagram.



(c) P3 diagram

Figure 4.3: Bifurification diagrams for the riser system using the basis inflow conditions from section 4.1.1. Critical stability point was found to be at approximately 12% choke valve opening.

4.2 Tuning the controller

The controllers were tuned by using the tuning rules developed by Skogestad et al.[25]. Closing the loop was done using a standard PID controller. In the Skogestad tuning method[25], only a P control is required to determine the optimal tuning parameters. The LabVIEW PID module requires all three P, I, and D inputs. Eliminating the D part was achieved by setting τ_D equal to zero. The integral part of the controller was eliminated by setting τ_I equal to a large number or alternatively equal to zero because of the way the PID controller module was programmed. The controller gain (P) was changed to achieve a step response close to the recommend 0.3 overshot. Noise made interpretation of the response difficult, especially for the pressure sensors in contact with the two phase flow. To handle this, the response data was filtered using a Butterworth filter. More detailed information about this filter are given in appendix B. Using a filter, the high frequency noise effect was considerable reduced, but at an expense of larger deadtime.

At first, the system was set using the basis inflow condition described in section 4.1.1 with the choke opening at 10 %. At this condition, it was not possible to reach the 30% overshoot requirement without saturating the choke valve. A solution to this problem was to set the basis condition at 30 % choke valve opening instead.

4.2.1 Tuning using P1 as the controlled variable

The signal from the P1 pressure sensor, located at the mixing point of water and air, contained lot of noise. The system was set at the basis condition from section 4.1.1 with 30 % choke valve opening. The P1 sensor was used as the controllable variable (CV) and the loop was closed using a P controller. Using a controller gain of -10, a system response similar to the response recommended in the tuning method was reached. The single P controller could stabilize the system at a setpoint of 23 kPa. Since only a P controller was used in this closed loop system, an offset of about 3 kPa was present. Interpretation of the signal was difficult because of the noise, but a Butterworth filter was added to make the interpretation easier. In addition, different online techniques were used in an attempt to minimize the noise. Time averaging and filters of various types was implemented in LabVIEW, but with no significant success.

In Figure 4.4 the original closed loop system response and the post processed, filtered signal is shown. A 4th order Butterworth filter with a cutoff frequency of 0.125 Hz was used to produce the filtered signal. The tuning parameters was found by analyzing the filtered response using the Skogestad method[25] and are listed in Table 4.1. It was difficult to find a suitable gain, which had an overshoot close to the recommenced 30 % overshoot. The overshoot (found in appendix C) was twice the size of the recommended overshoot. The large amount of noise made the overshoot not visible if decreasing the controller gain.

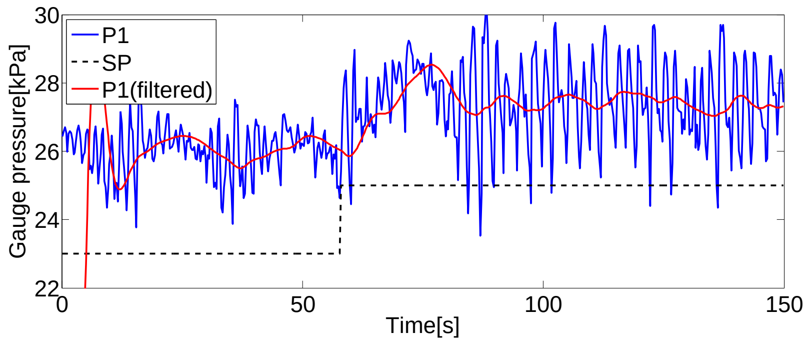


Figure 4.4: Setpoint change for a closed loop experiment with a P-controller and P1 as the CV.

4.2.2 Tuning using P3 as the controlled variable

The Signal from the pressure sensor in the air buffer tank was not affected by noise in the same manner as the other sensors. This was probably because no water was in contact with the pressure sensor. Having set the system at the basis flow condition at 30 % choke opening, the setpoint was changed from 33 kPa to 30 kPa. The P controller was tuned with a gain equal to -5. This setting resulted in an overshoot close to 30 % without saturating the choke valve. This is Illustrated in Figure 4.5. Listed in Table 4.1 are the tuning parameters found from the tuning experiment.

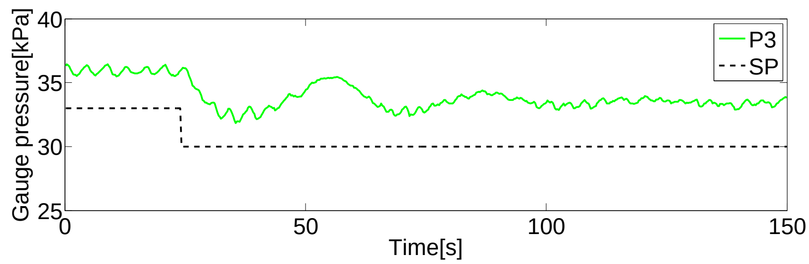


Figure 4.5: Setpoint change for a closed loop experiment with a P-controller and P3 as the CV.

4.2.3 Tuning using P4 as the controlled variable

Tuning the P controller when using P4 as the CV was done similar to the P1 case. The system was set at the same conditions as before (30 % choke valve opening). The setpoint was changed from 23 kPa to 25 kPa with a controller gain of -2.5, and the system response was recorded. Similar to the P1 case, the overshoot was difficult to observe for small controller gain because of noise. The overshoot was thus larger than the recommended 30 % overshoot. A 4th order Butterworth filter with a cutoff frequency of 0.125 Hz was used to interpret the system response. Both the system response and the filtered signal are illustrated in Figure 4.6. Table 4.1 lists the tuning parameters used in further experiments.

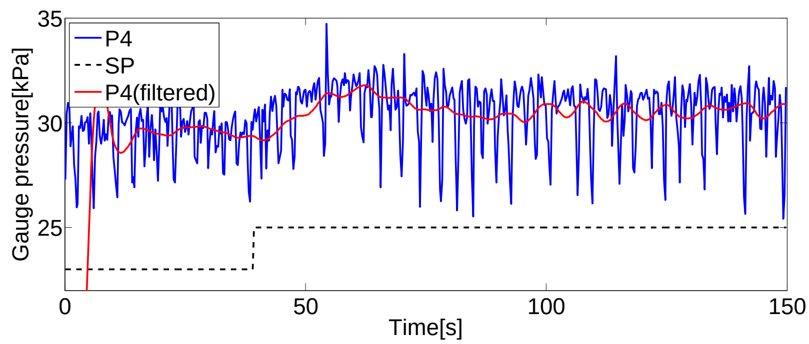


Figure 4.6: Setpoint change for a closed loop feedback experiment with a P-controller and P4 as CV. A 4th order Butterworth filter with 0.125 Hz cutoff frequency was used to remove parts of the noise from the system response.

Table 4.1: Tuning parameters.

Controllable variable	Proportional gain (Kc)	Integral action (τ_I)
P1	-4.4067	0.2627
P3	-2.9088	0.4705
P4	-1.7745	0.2460
P4-P2	-0.5457	0.2588

4.3 Closed loop response

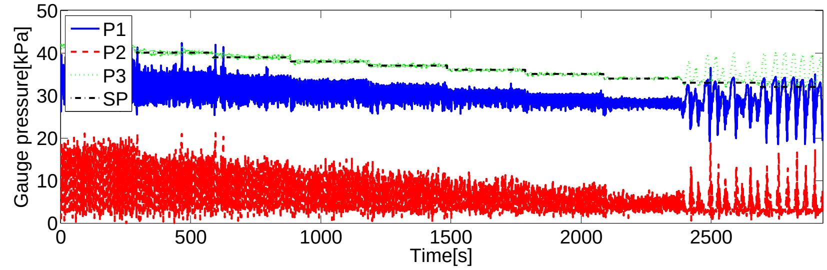
A consistent tuning rule is important when comparing different CVs. Ideally, the tuned systems should be comparable, after having used a tuning method like the closed loop SIMC method[25]. For comparing the robustness of the different CVs, the setpoint was changed after a certain period of time, and forcing the system to operate at a higher choke valve opening. After reaching steady state, the setpoint was again changed. This procedure was repeated until steady state not could be reached and the system became unstable. The average choke valve position of the last stable setpoint is an indication of the controller scheme robustness.

4.3.1 Subsea anti-slug control schemes

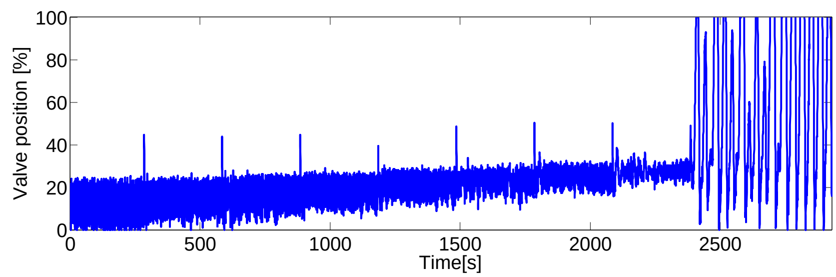
4.3.1.1 Pressure in the buffertank (P3)

A measurement of the buffertank pressure is not obtainable in a real riser system. A real riser system consists of a very long pipeline connecting the wellhead to the riser. The idea behind the buffertank is to emulate the gas volume in this long pipeline section, thus making the experiment more compact and space efficient. Nevertheless, the buffertank pressure proved to be a good measurement without too much noise. Tuning the system was done according to the tuning procedure described in section 4.2.

Using a PI controller and P3 as the CV, the system became unstable at a choke valve opening of approximate 27 %, as seen in Figure 4.7. Even though the system became unstable, the system did not directly go into the severe slugging state. Instead the system had high frequency pressure variations, similar to type II slugging.



(a) Pressure response.



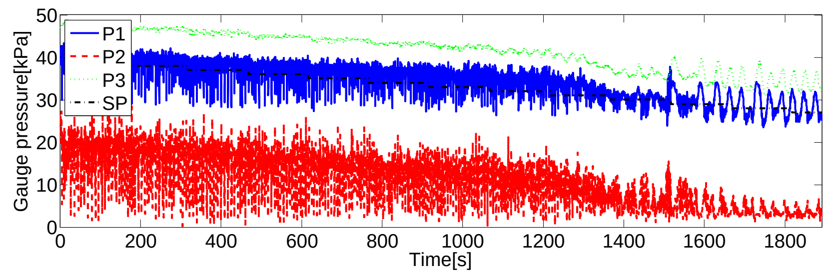
(b) Valve action

Figure 4.7: Decreasing the setpoint resulted in a unstable system at valve openings close to 27 %. A PI controller with tuningparameters given in Table 4.1 was used.

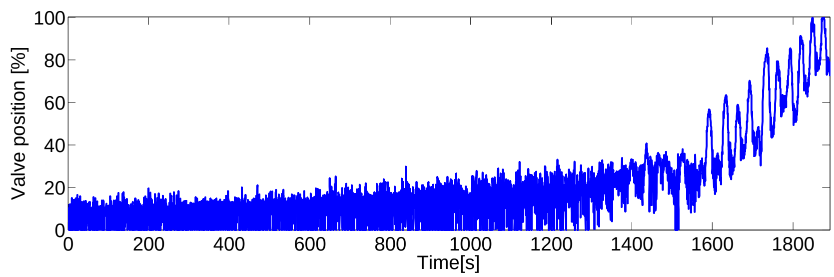
4.3.1.2 Pressure at the mixingpoint (P1)

Measuring the pressure at the mixing point was a larger challenge than measuring the pressure in the buffertank due to the amount of noise present in the signal. The noise, probably due to water flow near the pressure sensor, hid the system response when doing a step in the setpoint. This made obtaining tuning parameters difficult. The tuning parameters listed in Table 4.1 were used in the following experiments for testing the system robustness.

To compare the robustness with the P3 case, the same setpoint experiment was performed. This experiment resulted in a choke valve opening of 25 % before the system became unstable. This is illustrated in Figure 4.8, and could indicate that this control scheme is less robust than the P3 case.



(a) Pressure response.



(b) Valve action

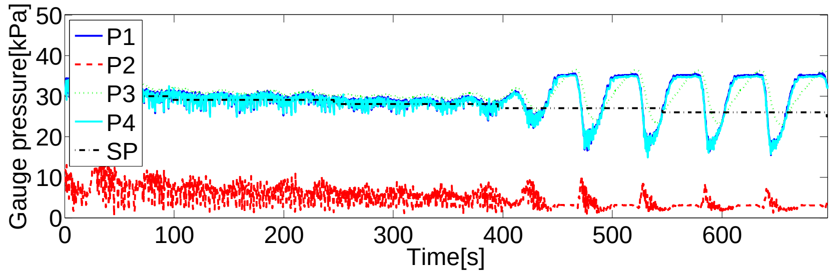
Figure 4.8: Decreasing the setpoint resulted in an unstable system at valve openings close to 25 %. A PI controller with the tuning parameters listed in Table 4.1 was used to close the loop.

4.3.1.3 Pressure at low point (P4)

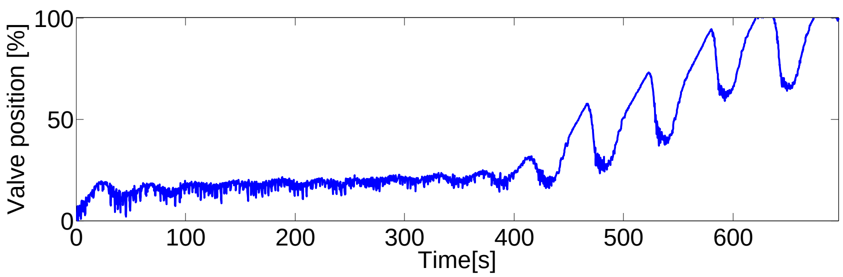
Near the end of the experimental period, an additional pressure sensor was installed at the riser low point.

Tuning the PI controller was done using the same procedure as the other controllers above, using the closed loop method by Skogestad et al.[25].

When gradually decreasing the setpoint, thus increasing the choke valve opening, the system became unstable at approximately 19 % valve opening. This significantly lower than both other measurements further upstream. The result from the setpoint decrease experiment is illustrated in Figure 4.9.



(a) Pressure response.



(b) Valve action

Figure 4.9: Using P4 as the CV, the system became unstable at 19 % choke valve opening.

4.3.1.4 Pressure drop over the riser (P4-P2)

If neglecting the friction, the pressure drop over the riser is proportional to the mass of liquid in the riser according to the DiMeglio model[8]. DiMeglio et al.[8] suggested this pressure drop to be a good CV candidate[8]. It was observed that using a P controller could make the system stable. However, introducing integral action made the system unstable. Starting with a stable system, the controller was able to keep the system stable, but doing a small setpoint change caused large instabilities, as illustrated in Figure 4.10.

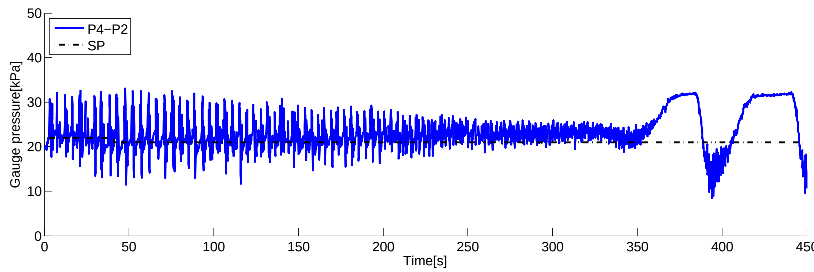


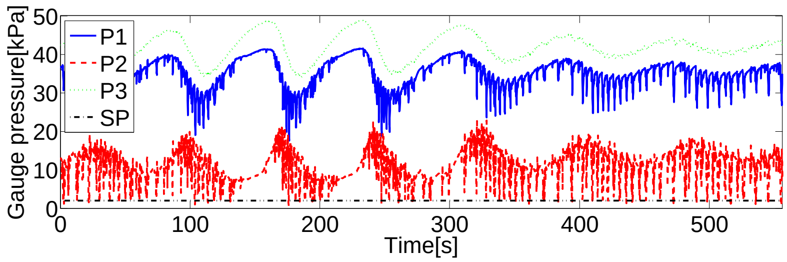
Figure 4.10: System was stable at first, but a small setpoint change at after 40 seconds caused the system to become unstable.

4.3.2 Topside anti-slug control schemes

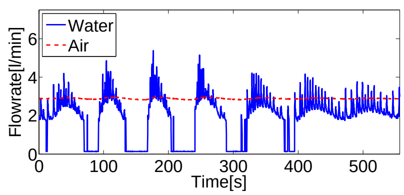
4.3.2.1 Topside pressure (P2)

Previous controllability analysis by Hoel Helgesen[14] and Sivertsen[23] have shown that stabilizing a riser system using topside pressure measurements only are difficult. An attempt to verify these claims was done using experiments. As expected, the riser system could not be made stable using a P controller and P2 as the CV. Figure 4.11 shows the system response from the latter experiment. Before closing the loop, the system was stable at 10 % valve opening, but closing the loop made the pressure oscillate resulting in an unstable system. After turning off the controller again, the system became more stable. It seems like the controller makes the system less stable with a P controller, than without.

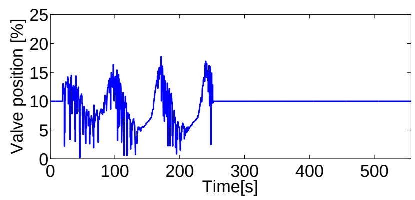
Strangely, reversing the sign of the controller resulted in more stable system than the negative feedback equivalent in Figure4.11. Figure 4.12 showed that the positive feedback system was stable until a choke valve opening of 18 %. When decreasing the setpoint , thus the choke valve opening to about 16 %, the system again approached a stable state again. In Figure 4.13 it is proved that the controller did stabilize the system in a region which was naturally unstable. For both cases the signal given to the controller was time averaged over 30 samples. The global sample rate was set to 100 samples each second, which results in a sample rate of 3.333 samples each second to the controller. The same time averaging method was also used with the negative feedback, but the result here was similar as without time averaging.



(a) Pressure response.

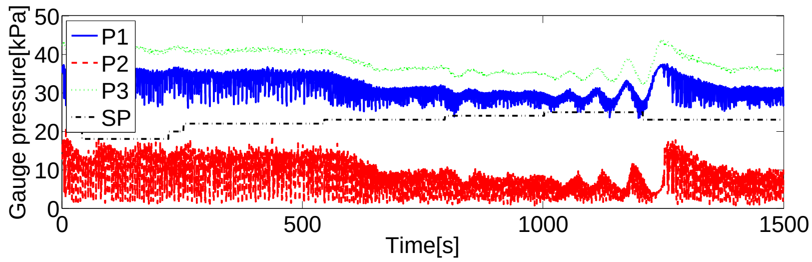


(b) Water and air inlet flow rates.

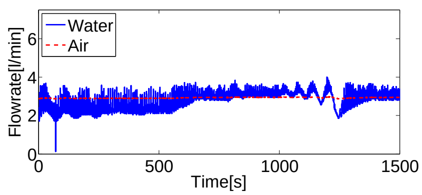


(c) Valve action.

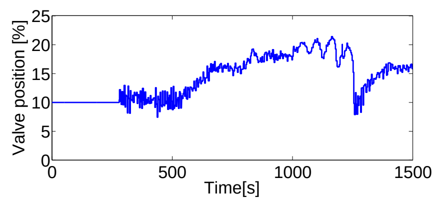
Figure 4.11: Using only the top pressure measurement it proved impossible to stabilize the system. A P controller with a gain of -1 was used. First the system was brought to a stable state before the controller was initiated. Only a small change in setpoint was enough to make the system unstable.



(a) Pressure response.

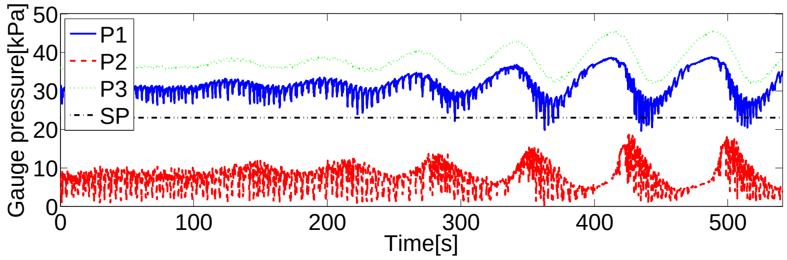


(b) Water and air inlet flow rates.

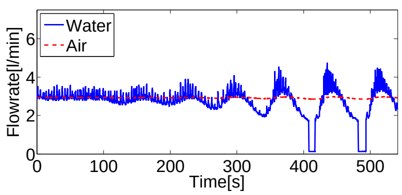


(c) Valve action.

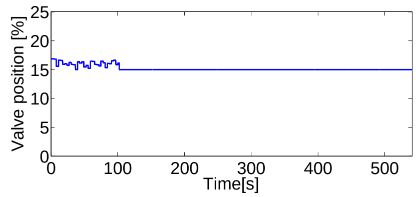
Figure 4.12: The system could be stabilized using topside pressure as the CV when reversing the sign of the controller gain.



(a) Pressure response.



(b) Water and air inlet flow rates.



(c) Valve action.

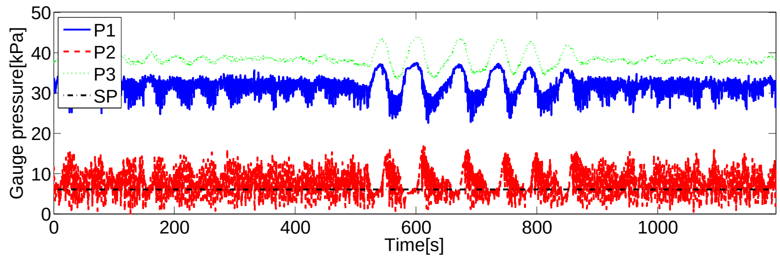
Figure 4.13: Using the positive feedback P controller and P2 as the CV, the system was initially stable at 15 % valve opening. Turing off the controller made the systems unstable. This is indicating that the controller is able to extend the non-slugging region.

4.3.2.2 Density control

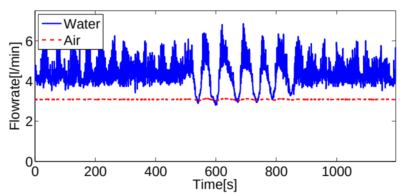
Slug sensors have been used in previous experiments by Bårdsen[3], Sønderol[33] and Sivertsen[23]. At first, experiment was run without coloring matter in the water resulting in no distinct difference in the signal regardless if water or air was passing the slug sensor. After adding a coloring matter, the optical signal was completely absorbed by the water when a slug was passing. Signals from the slug sensor could almost be considered as a binary signal, since the signal was either 5 volt or 1 volt.

Sivertsen[23] found promising results using a slug sensor, both in cascade configurations and as single measurement. However, from experiments it became clear that using the slug sensor signal for control was more difficult than using the continuous pressure signals. Reaching a setpoint was difficult, because of the alternating signal. When adding a PI controller, the integral term made the choke valve drift away because the designated setpoint not could be reached. A P controller was easier to implement, and Figure 4.14 shows that the system could be stabilized using a slug sensor measurement.

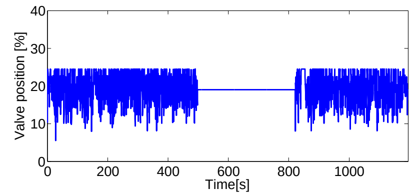
Measurements from the slug sensor are closely related to the instant density in the point of measurement. With proper scaling and simple algebra, an estimation of the fluid density can be found. This density would be useful in the calculation of the mass flow rate.



(a) Pressure response.



(b) Water and air inlet flow rates.



(c) Valve action.

Figure 4.14: Stabilizing the riser system using the slug sensor signal as the CV was possible with a P controller. The system was set to have 3 l/min gas flow and 2.8 l/min water flow at 10 % choke valve opening. The system was unstable at 19 % valve opening without control, but became stable in closed loop with a P controller at the same average choke valve opening.

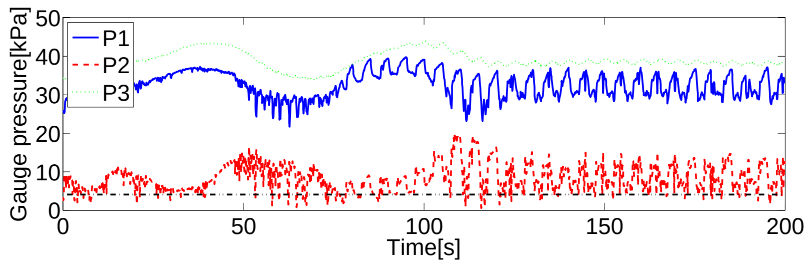
4.3.2.3 Control using an estimate of the topside flow rate

According to theory behind a venturi tube, the flow rate can be estimated by using two pressure measurements, one at the narrow part and one at the wide part of the tube. A venturi tube with 10 mm radius at the narrow part was installed at the top of the riser, as illustrated in Figure 3.2. A DP-cell, specially designed for measuring small pressure differences, was installed and connected to the venturi tube.

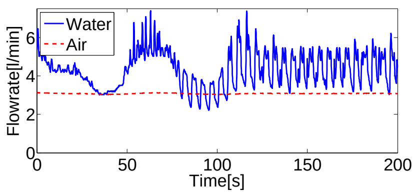
This measurement was supposed to be a vital part in many different control structures. Using equation A.4 from appendix A the volumetric flow rate can be estimated from the pressure difference measurement. It should be noted that this estimation is only valid for incompressible fluids, which is not completely true since for this experiment since gas is present. However, the estimation could still be useful and effective for control. The mass flow rate can also be estimated if the fluid density is known. As previously explained, the density could be estimated using measurements from the slug sensor. These estimators could be used separately or in the inner loop of a cascade structure. After different trials with very high flow rates with pure air, pure water and mixtures of both, it became apparent that the DP-cell with working range 0-6 kPa was not sensitive enough to register any pressure difference created by the venturi tube. Some pressure readings were seen when the venturi tube was installed upstream the choke valve, but further investigation reviled that pressure oscillations from the riser somehow manifested in the DP-cell. Moving the DP-cell to the downstream side of the choke valve confirmed this. There are three solutions for this problem. The obvious one would be to get a more sensitive DP-cell, but already the used DP-cell is in the lowest range available. Increasing the flow rate to induce more pressure drop in the venturi tube can be another possible solution. This would not be a good solution since the flow pattern will only have the slugging characteristics in a limited flow range for the given dimensions. The final solution is to reduce the diameter of the narrow part of the venturi tube. This will probably be the simplest solution, but during the timeframe for this thesis no other venturi tubes were available

4.3.3 Stabilizing the system using square wave signal

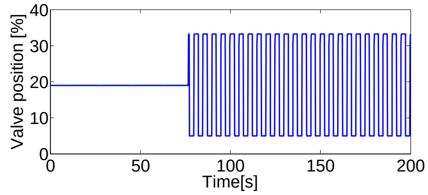
During the experiments when using the slug sensor, it was observed that the valve was responding in a regular pattern. This pattern was simulated using a square wave signal. The idea was that this signal could stabilize the system without the need for measurements. The valve was given a square wave signal using frequencies in similar range as the valve response from the previous experiment with the slug sensor. Giving the valve an oscillating behavior had a positive effect for some frequencies. In Figure 4.15 the system has been given a square wave input at frequency of 0.2 Hz, which is close to the input from the slug sensor experiment. The system showed a significant change when the input signal was initiated, and could be considered stable since no large pressure variations were present. When decreasing the frequency (Figure 4.16), the system became more stable than in open loop, but less stable than the 0.2 Hz case. Increasing the frequency to 0.6 Hz (Figure 4.17) did not show much effect in the system stability. From these results indicates that there is an optimal frequency for the given system. The point of initiation could influence the previous result. However, starting the square wave signal at various places in the slugging cycle always resulted in a stable system.



(a) Pressure response.

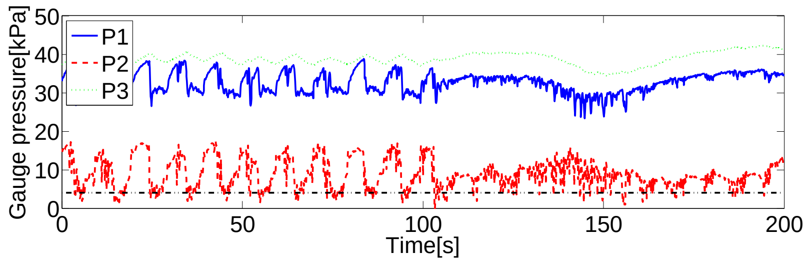


(b) Water and air inlet flow rates.

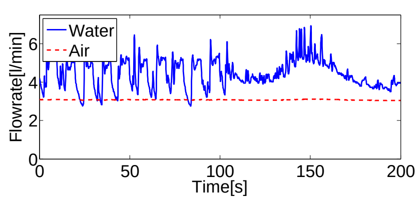


(c) Valve action.

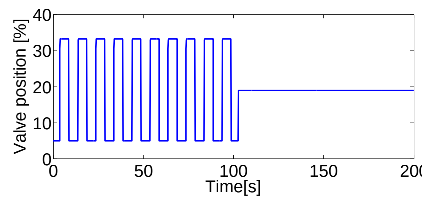
Figure 4.15: Using a squarewave signal (0.2 Hz) as an input signal to the choke valve had a positive effect on the system stability.



(a) Pressure response.

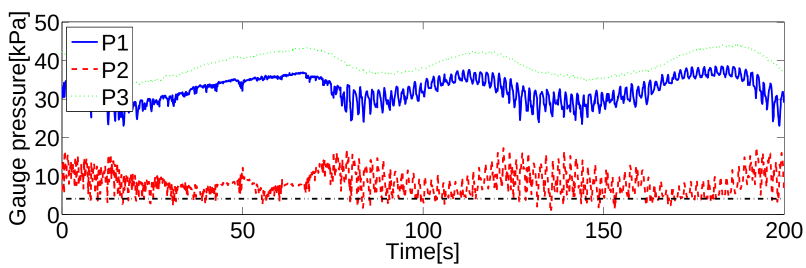


(b) Water and air inlet flow rates.

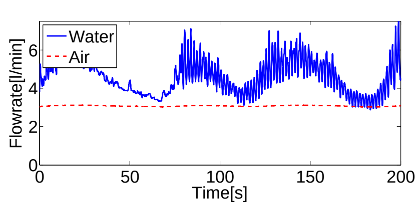


(c) Valve action.

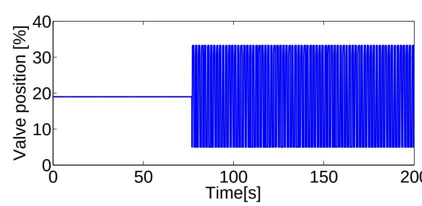
Figure 4.16: Decreasing the frequency to 0.1 Hz made the system less stable than the 0.2 Hz case.



(a) Pressure response.



(b) Water and air inlet flow rates.



(c) Valve action.

Figure 4.17: Increasing the frequency to 0.6 Hz did not make the system more stable. From this result it is likely that there exists an optimal frequency where the system is most stable.

Chapter 5

Discussion

5.1 Tuning

A large part of this thesis has been to find comparable tuning parameters. As mentioned before, without using a systematic tuning method the different control schemes would not be comparable. It would not be possible to know how good the tuning parameters for a specific controller would be compared to other controllers if a trail an error method was used for tuning. In former experiments[23][22][9][16][33][3] no such systematic method was used, and the results could be shifted due to poor tuning. Most of the results in this thesis are obtained using a systematic method. However, due to the large amount of noise present in the signal from some of the sensors also these results could also be biased. Many online methods were used in an attempt to limit the present noise. Increasing the sample rate combined with time averaging and/or filtering using a filter module from the PID LabVIEW package are examples of methods implemented in the LabVIEW program. Appendix C shows a comparison of the tuning parameters with different controller gains and noise-limiting methods. It is evident that there is a large deviation between the different tuning experiments. This is probably caused by noise and the large overshoot in some of the experiments. A large overshoot makes the tuning method weaker as opposed to when the overshoot is within the method specification. One of the trends present in the Table is an increasing overshoot in relation to increased gain. Another trend is that the integral action (lower τ_I) increases more when doing a negative setpoint change as opposed to a positive setpoint change. The latter can be explained by that the system responds almost twice as fast when doing a negative perturbation as opposed to a positive perturbation in the setpoint. Physically this makes sense, because doing a negative step in setpoint will reduce the pressure by opening the choke valve. Releasing pressure will always be faster than building pressure.

5.2 Problems faced during the thesis

In the beginning of the experimental period, tuning of the PI controller for the different cases was performed. Unfortunately, this tuning was not done correctly. During the tuning, the choke valve became saturated resulting in non-comparable and sub-optimal tuning parameters. This accident was not discovered until late in the thesis and a large amount of the experiments needed to be redone. During the re-tuning of the controllers, it became clear that reaching 30 % overshoot without valve saturation was impossible when the system conditions were set at 10 % choke valve opening. A system response close to 30 % overshoot was obtained using a system basis at 30 % instead. It was assumed that this would not influence the results in a large extent as long as this was done consistently for all controller schemes.

5.3 Comparing the results

Riser systems controlled by PI controllers are very sensitive to disturbances and changes in inflow condition. For this reason the setpoint decrease experiments are effective when comparing the robustness of different closed loop systems. A decrease in setpoint will decrease the pressure inside the system and result in higher inflows. A robust controller will be able to handle a wide range of conditions and will handle a larger setpoint decrease better than a less robust controller. Thus the most robust controller scheme was the one which could stabilize the system at the largest choke valve opening.

For the single measurement experiments, the robustness decreases when measuring further upstream the low point of the riser. Topside measurements were found difficult to use as a controllable variable. This has also been verified by other analysis and experiments[14][23][22]. It can be argued that controlling further upstream would give better control, because the controller would have more time available to counteract the system. As the analysis[14] predicted, the system could not be controlled using topside pressure measurements. Surprisingly the system could be controlled using reversed controller gain (P-controller). This was accidentally discovered when inserting the gain for the negative feedback experiment. One possible explanation could be that the controller gets more sensitive to the high frequency part of the signal as suggested by Skogestad[26] when reversing the controller gain for a system containing right half plane zeroes. Further research is needed to confirm if this effect could be helpful for controlling riser systems. In general when dealing with slugging problems, it is desirable to have controllers which are more sensitive to low frequency signals and less sensitive to high frequency signals.

Table 5.1 illustrates the increasing degree of robustness using CV's further upstream the low point of the riser. If robustness is the only factor considered, the recommended CV is thus the one located nearest to the well. Other factors like increased noise level because of large distances, difficult installation and sensor maintenance makes measurements close to the choke valve favorable. Closed loop systems using topside measurements as CV's could not be tuned in a systematic way. Comparing these systems, tuned using trial and error, with the other closed loop systems given in Table 4.1 would not give any information about the system robustness. The large uncertainty in tuning parameters would make the two systems not comparable.

Table 5.1: Choke valve opening which the system could not maintain stability.

Anti-slug control schemes	Choke valve opening [%]
Open loop	12
P1	25
P3	26
P4	19
P2 (reversed gain)	18

5.4 Further work

This thesis has mostly looked into control schemes with single pressure measurements. Some attempts were made to obtain stable topside measurements, but this was for the most part not successful. A natural extension of this thesis would be find more controller schemes which could be tuned using the closed loop SIMC method and compared with the results in this thesis. Listed underneath are some potential controller schemes:

- Reduce the venturi size to increase the pressure drop. The mass flow rate and volumetric flow rate can possibly be used in a single feedback loop.
- Use the mass flow rate or the volumetric flow rate in the inner loop in a cascade configuration.
- Process the slug sensor signal such that it can be used as a CV.
- Investigate if the tuning rules can be applied to a controller scheme using the P2 signal with reversed gain as the CV.
- Do more experiments which uses the pressure drop (P4-P2) over the riser as the CV. Find the performance and possible setpoint drift when using a P controller only. Compare with the single measurements PI controller.

In addition more effort should be done in reducing the hydrodynamic slugging present when choking the system. More work should be put into developing filters and time averaging methods for minimizing measurement noise. Other experimental setups will become available in the near future. Some of these results should also be repeated and verified in larger scales.

Chapter 6

Conclusion

6.1 Subsea measurements

The best single loop control strategy proved to be the use of the pressure measurement in the air buffer tank (P3) as CV. Using this anti-slug control strategy, the stability region could be increased from 12 % to 27 % choke valve opening. This will result in an increased oil production rate. Increased wear on choke valve, costly maintenance and installation of subsea pressure sensors are the main drawbacks with this control strategy. The general trend illustrated in Table 5.1 was that the robustness increased upstream for the single feedback loop cases.

6.2 Topside measurements

To use topside measurements as the CV are favorable as opposed to the bottom measurements due to practical reasons and noise level. I this thesis it was found problematic to stabilize the system using topside pressure measurements. Reversing the controller gain could surprisingly stabilize the system with a performance close to controllers using subsea pressure measurements as the CV. Other single topside measurements like density measurements and flow rate estimation were tested, but could not be compared with the other single measurements since the attempt to implement the tuning method by Skogestad[25] failed.

6.3 Other control strategies

The pressure drop over the riser was suggested by DiMeglio[8] to be an estimator of the liquid mass in the riser. DiMeglio[8]claimed that this pressure drop is a good CV. As opposed to this claim, results from experiments performed in this thesis showed that the closed loop system could not be stabilized using the pressure drop over the riser as the CV when integral action was present. Inspired by the valve action from the density control experiments, a square wave input signal was tested. The square wave signal did make the system more stable, but the degree of stability was depended on the frequency of the signal. Illustrated in the Figure 4.15, an optimal frequency close to 0.2 Hz was found for this particular setup.

Abbreviations

CV - Choke valve

DP-cell - Differential pressure cell

HSE - Health Safety and Environment

IMC - Internal Model Control

NTNU - Norwegian University of Science and Technology

P - Proportional

PI - Proportional-integral

PID - Proportional-integral-derivative

RHP - Right half plane

SIMC - Skogestad Internal Model Control

Bibliography

[1] ABB, (April 2002), *Delivering the complex integrated solutions that characterize the future*, http://www02.abb.com/global/seitp/seitp161.nsf/0/13fe0ef224b55668c12571570050a940/$file/Synergy4-IndustrialIT.pdf, [downloaded 20.07.2011].

[2] ABB, (14.12.2004), *Transient/slugging*, https://www.abb.com/cawp/seitp161/2cfdabece457886841256f500041089e.aspx, [downloaded 12.12.2010].

[3] Baardsen, I. (2003), *Slug regulering i tofase strømning, Eksperimentell verifikasjon*, Master Thesis at Department of Chemical Engineering NTNU, Trondheim, 90.

[4] Bai, Y. (2001), *Pipelines and Risers*, Elsevier, Nederlands, 498.

[5] Butterworth, S. (1930), *On the Theory of Filter Amplifiers*, Wireless Engineer, vol. 7, 536-541.

[6] Courbot, A. (1996) *Prevention of Severe Slugging in the Dunbar 16' Multiphase Pipeline*, 28th Annual Offshore Technology Conference May 6-9, Houston, Texas.

[7] Di Meglio, F., Kaasa, G.O, Petit, N. (2009), *A first principle model for multiphase slugging flow in vertical risers.*, Joint 48th IEEE Conference on Decision and Control and 28th Chinese Control Conference, 8244 - 8251.

[8] Di Meglio, F., Kaasa, G.O., Petit, N., Alstad, V. (2010), *Model-based control of slugging flow an experimental case study*, 2010 American Control Conference, Baltimore USA, 2995-3002.

[9] Fahadi, J. (2007), *Anti-slug control, an experimental approach*, Project at Department of Chemical Engineering NTNU, Trondheim, 50.

[10] Geankoplis, C.J. (2003), *Transport Processes and Separation Process Principles*, 4th ed., Prendtice hall, 1026.

[11] Guo, B., Song, S., Chacko, J., Ghalambor, A. (2005), *Offshore Pipelines*, Elsevier, United States of America, 281.

[12] Havre, K. Stornes, K.O, Stray, H.(2000), *Taming slug flow in pipelines*, ABB review 4, 55-63.

[13] Hedne, P.,Linga, H. (1990), *Suppression of terrain slugging with automatic and manual riser choking*, Advances in Gas-Liquid Flows, 453-469

[14] Hoel Helgesen, A. (2010), *Anti-slug control of two-phase flow in risers with: Controllability analysis using alternative measurements*, Project at Department of Chemical Engineering NTNU, Trondheim, 74.

[15] Jahanshahi, E., Skogestad, S. (2010), *Simplified Dynamical Models for Control of Severe Slugging in Multiphase Risers*, Preprint submitted to 18th IFAC World Congress.

[16] Ringereide Hyllestad, E.L. (2010), *Stabilization of two-phase flow in risers from reservoirs (anti-slug control)*, Master Thesis at Department of Chemical Engineering NTNU, Trondheim, 85.

[17] Rivera, D.E., Morari, M., Skogestad, S. (1986). *Internal model control. 4. PID controller design.*, Ind. Eng. Chem. Res. 25(1), 252-265.

[18] Schmidt, Z., Brill, J., Begges, H. (1979), *Choking can eliminate severe pipeline sluging* Oil and Gas Journal, 230-238.

[19] Schmidt, Z., Brill, J.P., Beggs, H. D. (1980), *Experimental Study of Severe Slugging in a Two-Phase-Flow Pipeline - Riser Pipe System*, SPE Journal, Volume 20(5),407-414.

[20] Shamsuzzoha, M., Skogestad, S. (2010), *The setpoint overshoot method: A simple and fast method for closed-loop PID tuning*, Journal of Process Control, Vol. 20, 1220-1234.

[21] Sivertsen, H. (2008), *Stabilization of desired flow regimes*, Department of Chemical Engineering NTNU, Trondheim, 165.

[22] Sivertsen, H., Alstad, V., SPE, Skogestad, S. (2009), *Medium-Scale Experiments on Stabilizing Riser-Slug Flow*, SPE Projects, Facilities and Construction, Vol 4(number 4), 156-170.

[23] Sivertsen, H., Storkaas, E., Skogestad, S. (2009), *Small-scale experiments on stabilizing riser slug flow*, Chemical Engineering Research and Design, 88, 213-228.

[24] Skofteland, G., Godhavn, J. M. (2003), *Suppression of slugs in multiphase flow lines by active use of topside choke - Field experience and experimental result*, 11th BHR Group Multiphase Production International Conference, San Remo, Italy, 527-542.

[25] Skogestad, S., Grimholt, C. (2011), *The SIMC method for smooth PID controller tuning*, Chapter for planned PID book, Springer, 29

[26] Skogestad, S., Postlethwaite, I. (2005), *Multivariable Feedback control*, 2nd ed., JohnWiley & Sons, 595.

[27] Skogestad, S. (2003), *Simple analytic rules for model reduction and PID controller design*, Journal of Process Control, Vol. 13, 291-309.

[28] Store norske leksikon, *Flerfasestrømning*, `http://www.snl.no/flerfasestr\OT1\omning`, [downloaded 09.06.2011].

[29] Storkaas, E.(2005), *Stabilizing control and controllability: Control solutions to avoid slug flow in pipeline riser systems*, Department of Chemical Engineering NTNU,Trondheim, 148.

[30] Storkaas, E., Skogestad, S., Godhavn., J. M. (2003), *A low-dimensional dynamic model of severe slugging for control design and analysis*, 11th BHR Group Multiphase Production International Conference, San Remo, Italy, 117-133.

[31] Storkaas, E., Skogestad, S. (2007), *Controllability analysis of two-phase pipeline-riser systems at riser slugging conditions*, Control Engineering Practice, Vol. 15, No. 5, 567-581.

[32] Svendsen, K. (2002), *Comparison of models for 'severe slugging'*, Project at Department of Chemical Engineering NTNU, Trondheim, 26.

[33] Søndrol, M (2005), *Anti-slug control. Experimental testing and verification*, Master Thesis at Department of Chemical Engineering NTNU, Trondheim, 112.

[34] Taitel, Y. (1986), *Stability of severe slugging*, Int. J. Multiphase Flow 12(2), 203-217.

[35] Trudvang, C.F. (2003), *Modellbasert stabiliserende regulering av gravitasjonsindusert slugging i pipeline-riser systemer*, Master Thesis at Department of Chemical Engineering NTNU, Trondheim, 57.

[36] Winder, S. (2002), *Analog and digital filter design (Second edition).*, 2nd ed., Elsevier Science, 450.

Appendix A

Venturi tube

The venturi effect is a reduction of pressure resulting by increased fluid velocity induced by a constricted pipe section. Velocity of a fluid must increase when passing a constriction to satisfy the principle of continuity. Pressure on the other hand, must decrease to satisfy the mechanical energy balance.[10] These are the basic principles used in a venturi tube (figure A.1) for measuring flow rates.

The equation for the venturi tube can be derived by assuming horizontal pipe, turbulent and frictionless flow. The mechanical energy balance between the wide point (1) and narrow point (2) (figure A.1) can be written according to equation A.1 for incompressible fluids.

$$\frac{v_1^2}{2} + \frac{P_1}{\rho} = \frac{v_2^2}{2} + \frac{P_2}{\rho} \tag{A.1}$$

Where v is the velocity, ρ is the density and P is the pressure at positions 1 and 2 shown in figure A.1.

Rearranging equation A.1 and combining with the continuity equation for constant density (A.3), the velocity at the orifice can be written:

$$v_2 = \frac{\sqrt{2(P_1 - P_2)}}{\sqrt{\rho(1 - (\frac{D_2}{D_1})^4)}} \tag{A.2}$$

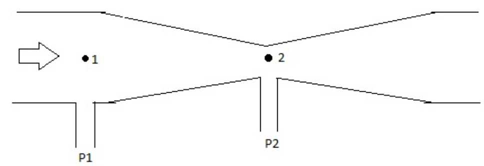


Figure A.1: Venturi flow meter.

$$v_1 \frac{\pi D_1^2}{4} = v_2 \frac{\pi D_2^2}{4} \tag{A.3}$$

Where D is the diameter at positions 1 and 2 shown in figure 3.16.

The volumetric flow rate is calculated by multiplying with the cross-sectional area at the orifice:

$$Q = v_2 \frac{\pi D_2^2}{4} = \frac{\pi D_2^2 \sqrt{2(P_1 - P_2)}}{4\sqrt{\rho(1 - (\frac{D_2}{D_1})^4)}} \tag{A.4}$$

Appendix B

Butterworth filter

A filter is used to remove a certain frequency range from a signal, usually high frequency (lowpass filter). Other common types are highpass, bandpass and bandstop filters. The Butterworth filter is a very commonly used filter, which is designed to have a flat frequency response gain, as seen in figure B.1. The filter was designed by the British engineer Stephen Butterworth, and was first described in the paper 'On the Theory of Filter Amplifiers' [5]. Butterworth showed that a lowpass filter could be designed by using the equation B.1 [36]. The resulting frequency response (gain) is shown in figure B.1. Increasing the filter order will result in larger decreasing slope, thus a faster decreasing gain. However, increasing the filter order will also increase the filter delay.

$$H(\omega) = \frac{1}{\sqrt{1 + w^{2n}}} \tag{B.1}$$

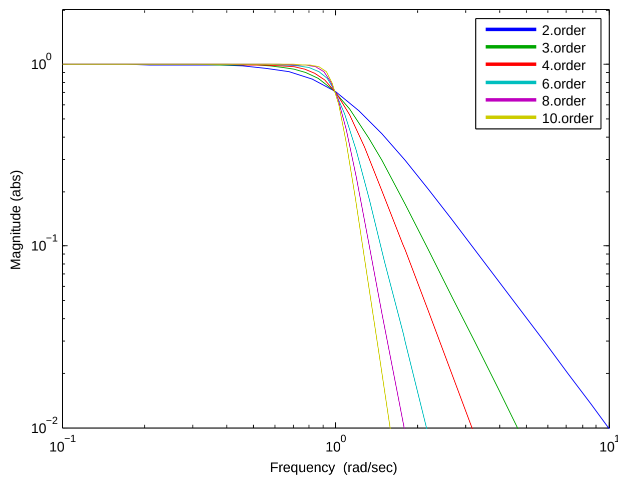


Figure B.1: Butterworth filter frequency response for different orders.

Appendix C

Tuning data

This appendix list the tuning data for the different tuning experiments in the figures below. Different methods were used to the process the data for removing noise. 'Regular' means no processing method was used, 'Avg' means the continuous average valve calculated over a given amount of time, 'Time avg' means the discrete average of a given time, and 'filter' means that the PID filter package in LabVIEW was used. Kc0 is the initial gain used in the tuning experiment, Kc is the calculated proportional gain, and τ_I is the integral tuning parameter.

Table C.1: Tuning parameters from tuning experiments using P1 as CV.

Experiment description	Kc0	Kc	τ_I	Perturbation	Overshoot
Regular	5	2.2138	0.1335	+	0.75
Regular	10	4.4067	0.2627	+	0.6667
Regular	10	4.4067	0.17	-	0.667

Table C.2: Tuning parameters from tuning experiments using P3 as CV.

Experiment description	Kc0	Kc	τ_I	Perturbation	Overshoot
Regular	5	2.9088	0.4705	-	0.3462
Regular	10	4.4979	0.3188	+	0.7917
Regular	10	5.1196	0.1837	-	0.4468

Table C.3: Tuning parameters from tuning experiments using P4 as CV.

Experiment description	Kc0	Kc	τ_I	Perturbation	Overshoot
Regular	2.5	1.7745	0.246	+	1.1818
Regular	2.5	1.3625	0.1286	-	1
Regular	5	4.1039	0.2354	+	1.2727
Regular	5	3.1833	0.1093	-	0.8
Time avg	5	5.9075	0.2965	+	1.5
Time avg	5	2.3042	0.0919	-	0.8333
Time avg 2sek	5	2.2584	0.1358	+	0.8
Time avg 2sek	5	8.7006	0.2906	-	1.76

Table C.4: Tuning parameters from tuning experiments using P4-P2 as CV.

Experiment description	Kc0	Kc	τ_I	Perturbation	Overshoot
Avg+filter	1	0.7247	0.7187	+	0.2
Avg	1	0.548	0.4115	+	0.3906
Avg	1	0.5457	0.2588	-	0.3939
Avg	2	0.8798	0.3154	+	0.7143
Avg	2	1.21	0.4293	-	0.3182