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PROSJEKTTITTEL:

Anti-slug control, an experimental approach

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av

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Abstract

In the offshore oil industry, multiphase flow over large distances might lead to a flow regime called slug flow. The flow pattern is characterized by large liquid volumes flowing separately from the gas. An oscillating behaviour of the pressure is then observed.

Slug flow was modelled in a lab-scale pipeline-, riser- and separator system at the Norwegian University of Science and Technology (NTNU). During this project, the apparatus was rebuilt and new pressure measurements, in addition to a venturi, were added to the system. The software used to perform the measurements and control the system was programmed using LabVIEW.

The aim of the project was to use different pressure measurements in feedback controllers to eliminate the slug flow. A cascade control structure was also implemented and tested. A strategy of using random valve openings in the control valve used to stabilize the flow was also tried out.

The feedback control structure proved successful for the measurements farthest away from the separator and the control valve. As the measurement approached the control valve, avoiding slug flow became more difficult. The cascade control structure also gave positive results. Implementing a random valve opening strategy did not counteract the slug flow behaviour.

Acknowledgements

As I am writing the final words of this project, looking back at all the experiences gained from it, I see that the achievements would not have been possible without the assistance of various people. I would therefore wish to thank the following people for their help and support during the work on this project;

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Contents

1 Introduction

1.1 Background

The fifth year project is part of the Master degree education at the Norwegian University of Science and Technology (NTNU). It is a preparation to the more rigorous master thesis that is to be performed the last semester of the studies. The project has been carried out at the Department of Chemical Engineering.

1.2 History

Many of the pipelines connecting the wells and the platforms in the North Sea carry multiphase fluids. The number of remote sub-sea wells being connected to the existing facilities due to available capacity is increasing and will continue to increase in the decades to come[1]. Therefore, investigation of multiphase flow is of growing importance to the offshore oil industry. The transport and control of multiphase flow, often referred to as flow assurance, will become more complex as different well streams are more often being mixed sub-sea. In addition, satellite wells are drilled in greater distances from the processing facilities, increasing the challenges with multiphase flow.

Multiphase pipelines and riser systems connecting satellite wells and remote installations to the processing unit give rise to flow variations disturbing the separation processes. One form of these flow variations is *slug flow*, in which the liquid flows intermittently along the pipes in a concentrated mass, called a *slug*[1]. This often occurs when liquid blocks the low point in the pipe, forming a liquid slug. The liquid flowing upstream the slug will make the slug grow, while the gas leads to a pressure increase. When the pressure is high enough to overcome the weight of the liquid slug, the liquid slug and the gas will flow through the system and thus depressurizing the pipe. The process is cyclic, as a new slug will build up and the process will repeat itself. This gives an oscillating pressure in the pipelines as well as a varying flow into the separation system at the processing facilities. Slugging can also occur inside the oil wells and in the processing facilities.

A direct result of the slugging is the large and rapid flow variation. This in turn will lead to poor separation in the inlet separator of the processing unit. In the worst case, the separator might be flooded[2]. The regularity of the process is also affected when the slugging leads to platform trips and plant shutdowns. Another problem is a capacity reduction in the separation and the compression units due to the need for larger operating margins in the units. Additional unwanted flaring[1] is another issue caused by slug flow, increasing the environmental impact of oil production.

There are several ways to avoid severe slugging. First of all, slugging is avoided on new plants by proper pipeline topology design or installing slug catchers. Increasing the separator size, or installing gas lift are solutions that can be implemented on existing systems[3]. Another option that can be implemented on existing systems, is to choke the topside valve[2]. This solution will eliminate the slug flow in the pipelines, but leads to a pressure increase in the pipes. An increased pressure leads to reduced production rate and can decrease the total recovery from a field.

All the above mentioned solutions to either avoid slug flow or its consequences are costly, either because of increased capital cost or reduced income when less oil is produced. A way to eliminate the slug flow without the mentioned drawbacks is the implementation of control systems[4]. Successfully implemented control will stabilize the system under conditions that normally lead to slug flow[4]. So far, the testing of the control systems have been implemented in rigorous simulators like OLGA, simulated in Matlab, or been based on experiments[5].

1.3 Scope of the project

This project is partially a continuation of the earlier work performed by Bårdsen[2], Søndrol[5], Dahl-Olsen[6], Storkaas[3,4,7] and Sivertsen[8]. Their work consists of both theoretical and experimental implementation of different control structures to a lab-scale experimental model of a riser and separator system. The lab-scale test rig is called the Miniloop, imitating a pipeline-, riser- and separator system. This project is based on experimental work performed on the Miniloop.

The Miniloop was rebuilt and all pipes were renewed. New instruments were also added to the system. The entire hardware needed to transfer data between the instruments and the computer, in addition to the computer itself were replaced with newer equipment. Before rebuilding the Miniloop, all the new equipment had to be acquired. A user interface program to control the Miniloop was also developed using LabVIEW.

For the experimental part, the main target was to apply new measurements to control the system, after verifying that a pressure measurement around the wellhead in a feedback controller could stabilize the system. At first, open-loop pressure measurements were performed to investigate the system behaviour. Then, the verification of the previous results was performed. In the following experiments, pressure measurements between the topside and the well were investigated to see if it is possible to avoid slugging using those measurements.

Another task in this project was to see if a venturi and its differential pressure measurement can be applied in a cascade control configuration to control the system. But first, the venturi had to be tested, to see how it responded to the system, and if it would affect the system in any kind of way. For this project, a venturi had to be custom made. The last task of the project was to see if a random valve opening could be used to control the process.

During the experimental work, water was used as a substitution for the oil and water mixture in oil pipes, while air was used instead of the gas mixture present in the pipes. The viscosity of the liquid and density of the gas used are not the same as in a real system, but still assumed to be suitable for developing slug flow and then avoid it.

Since all the work performed was experimental, the tuning of the controllers was also performed by empirical trial and errors. The controllers were tuned until the system was stabilized satisfactory. Satisfactory means that the average valve opening would result in severe slugging in open loop.

2 Theory

2.1 Slug flow

Slug flow is characterized by liquid flowing intermittently in the axial direction in a pipe, with the gas transported as bubbles in between the slugs[1]. The slug flow pattern can occur on different time- and length scales depending on the mechanism causing the slug flow. In a pipeline-riser system, the slug flow can be divided into four types[7]:

- *Hydrodynamic slugging* develops in horizontal parts of the pipeline when liquid waves grow on the gas-liquid interface and eventually close the cross-section, thus forming liquid slugs.

- *Riser slugging* occurs when liquid blocks the low-point where a down-sloping pipeline is attached to a riser. The blockage initiates the slug, which thereafter grows upward in the riser and back through the pipeline. This continues until the pressure build-up over the slug is sufficiently high to blow it out of the riser, whereupon the entire cycle is repeated.

- *Terrain slugging* involves slug development where pipelines traverse rough seafloor terrain. The slug picks up liquid accumulated in inclined sections and may become very extensive.

- *Transient slugging* is caused by increased liquid flow rates at pipeline exit to processing facilities in response to changes in operating conditions.

Riser- and terrain induced slugging are both types of gravity induced slugging, which will be the topic in this project.

2.1.1 Riser induced slugging

A low point in the pipeline topography followed by an inclining section can cause riser induced slug flow. For the slugging to occur, the pipeline pressure and flow rate, both needs to be low, as is the case for many mature fields. Upstream of the slug, a large volume needs to be available for the build-up of gas and thus building up the pressure. Slugging is a cyclic process and can be divided into four stages. Figure 2.1 visualizes the four steps[8];

1. Liquid is accumulated at a low point in the pipe.

2. The gas flow is being blocked by the liquid, so the pressure upstream the slug increases and the slug itself continues to grow.

3. When the pressure upstream the slug overcomes the hydrostatic head of the slug, the gas starts to penetrate the liquid and the liquid is being pushed through and out of the riser.

4. The pressure drops and the gas is no longer able to push the liquid through the riser. Some liquid will fall back down the riser, accumulates at the low point and reinitiates the cycle again.

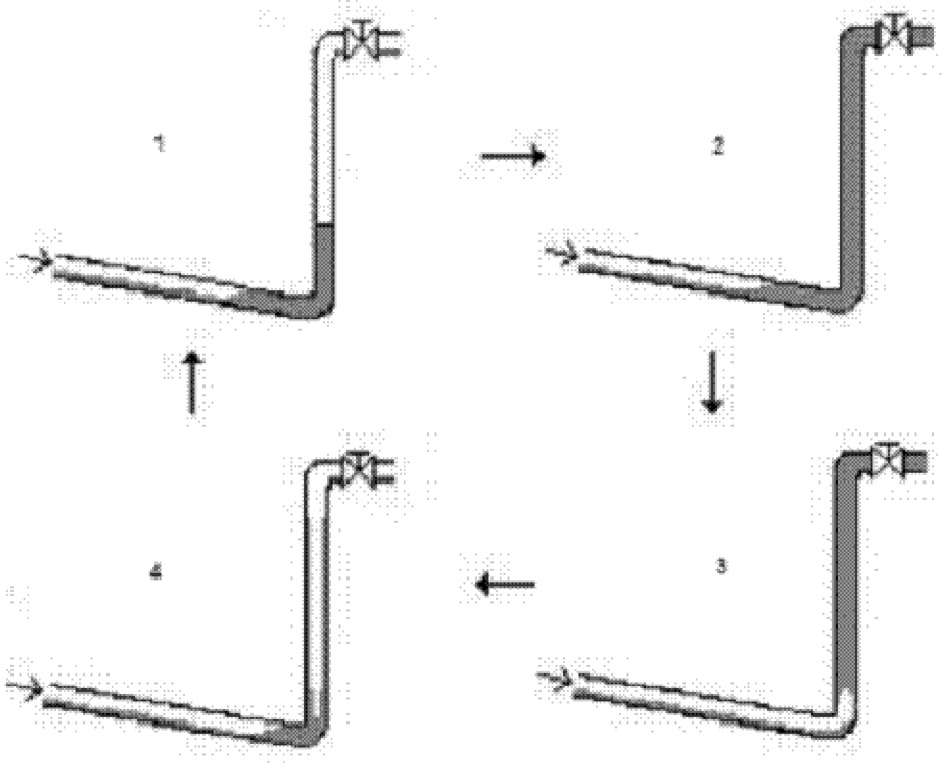

Figure 2.1[8] An illustration of the cyclic behaviour of gravity induced slug flow.

2.1.2 Avoiding slug flow by choking the topside valve

By choking the topside valve, the pressure upstream the valve will increase. As the valve opening is decreased, the pressure will increase, until the pressure reaches a value where slugs are not formed in the low points. The valve opening, z, where the slug flow is eliminated is called the critical valve opening[7], z_{crit}.

The system can be investigated by performing open-loop experiments at varying valve openings. By systematically reducing the valve opening, z_{crit} can be found. This can be valuable information when a control system is implemented on the system. If the control system leads to a higher average valve opening and a lower pressure in the pipelines than during choking the valve, the control system is beneficial.

2.2 Control system

Several different strategies can be implemented to control the system. In this project, several simple feedback configurations are applied as well as a cascade control structure. The following sections will describe the control configurations and the controllers used in the project.

2.2.1 Simple feedback controller

The generalized control configuration for feedback control is shown in figure 2.2.
In the Miniloop, the system contains disturbances, which often are referred to as process noise, in addition to measurement noise. The pressure upstream the valve depends on the valve position, so controlling the valve position by a pressure measurement, implies the implementation of a feedback controller. In the figure below, the measurement noise and the disturbances are included in the block diagram for the feedback control system.

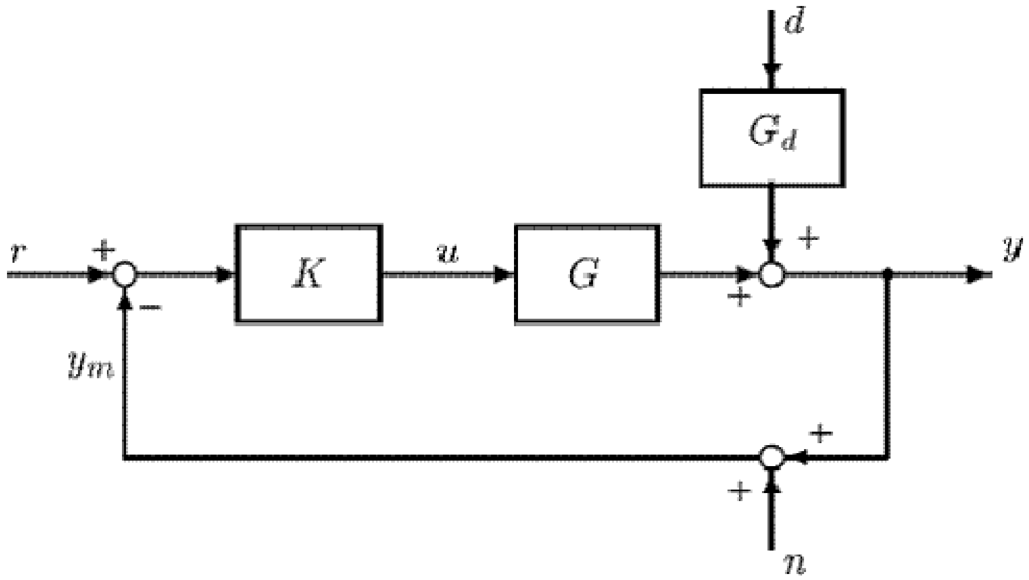

Figure 2.2 One degree-of-freedom feedback control configuration[9].

For the feedback control configuration;

K	general controller
G	the plant
G_d	disturbance model
r	reference inputs; commands, set-points
d	disturbances; process noise
n	measurement noise
y	plant outputs
y_m	measured y
u	plant inputs; manipulated variables, control signals

From the feedback control model, the output, y, is given by;

$$y = G(s)u + G_d(s)d \tag{2.1}$$

where the s denotes the Laplace-domain variable, and u is given by;

$$u = K\left(r - y_m\right) \tag{2.2}$$

2.2.2 Cascade controller

The Miniloop can also be controlled by a cascade controller, where a measurement is used to control the valve position and works as a normal feedback control loop. This control loop is called the inner loop. The inner loop's reference is given by an outer controller that keeps another measurement around a given set-point. Figure 2.3 shows a systematic representation of a cascade controller.

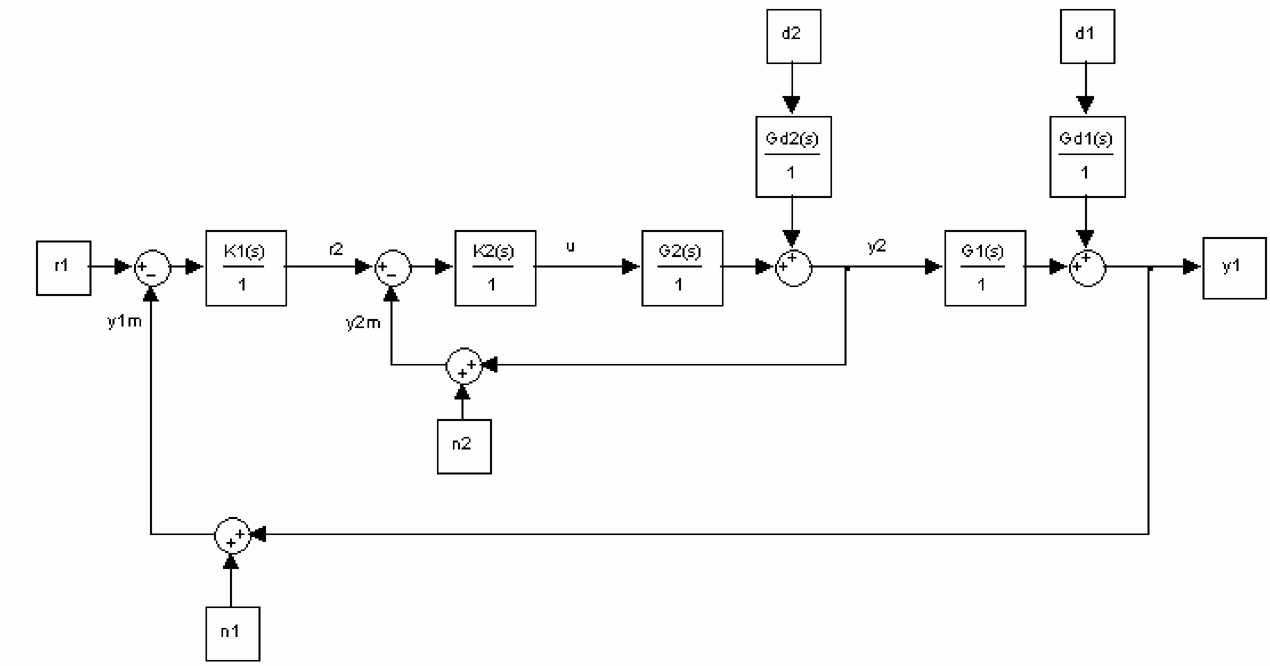

Figure 2.3 Block diagram of a cascade control system[10].

The symbols in the figure describing a cascade controller are described as follows;

G1	plant, outer loop
G2	plant, inner loop
Gd1	disturbance model, outer loop
Gd2	disturbance model, inner loop
K1	general controller, outer loop
K2	general controller, inner loop
u	manipulated variable
r1	reference input, outer loop
r2	reference input, inner loop
d1	disturbances, outer loop
d2	disturbances, inner loop
n1	measurement noise, outer loop measurement
n2	measurement noise, inner loop measurement
y1	output, outer loop
y2	output, inner loop
y1m	measured *y1*
y2m	measured *y2*

From the block diagram of a cascade controller, the output, *y1*, of the process can be found;

$$y1 = G1(s) \cdot y2 + Gd1(s) \cdot d1 \qquad \textbf{(2.3)}$$

where the *y2* is the output from the inner loop;

$$y2 = G2(s) \cdot u + Gd2(s) \cdot d2 \qquad \textbf{(2.4)}$$

The manipulated variable, *u*, is given with respect to the reference of the inner loop, *r2*;

$$u = K2 \cdot \left(r2 - y2m\right) \qquad \textbf{(2.5)}$$

and *r2* is defined by the controller of the outer loop and given with respect to *r1*;

$$r2 = K1\left(r1 - y1m\right) \qquad \textbf{(2.6)}$$

2.2.3 Control Algorithm

The controllers applied to the Miniloop are PID-controllers. PID-controllers can be configured in a variety of ways. The controller algorithm of the PID-controllers used for the Miniloop, is shown figure 2.4. In the figure, *Ti* is the integral time, *Td* is the derivative time and *Kc* is the proportional gain of the controller. The s^{-1} term is an integrator, while the *du/dt* block will differentiate its input.

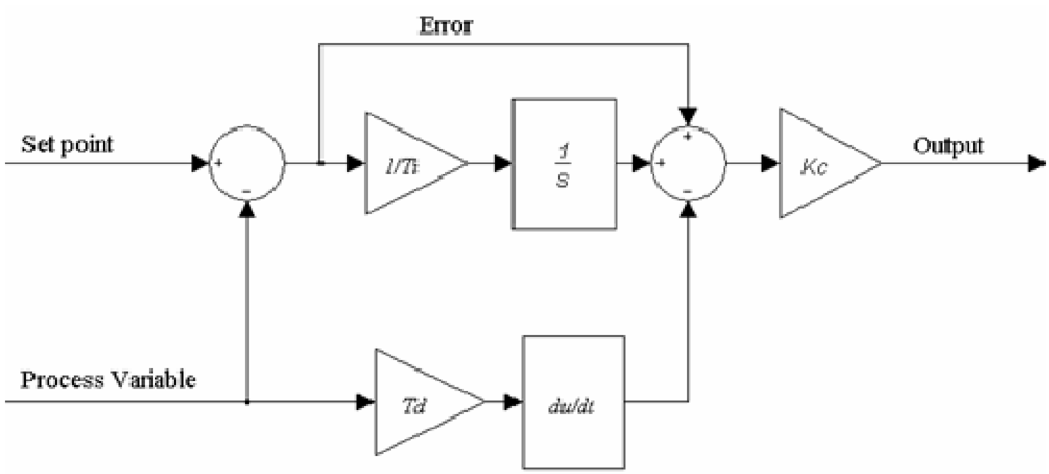

Figure 2.4 Block diagram of the PID control algorithm[11].

The mentioned PID algorithm was chosen to control the system, because the algorithm was predefined in a ready-to-use PID-block in Labview, the program chosen to control the Miniloop.

By regarding the block diagram for the PID controller, it can be shown that the controller output in the time domain, is given as;

$$u = Kc\left[(r-y) + \int \frac{r-y}{Ti}dt + \frac{d}{dt}\left(y \cdot Td\right)\right] \qquad \textbf{(2.7)}$$

where *y*, the controller input, is the measured process variable, *u*, the controller output, is the input to the process, *r* is the set point and *t* is the time-variable.

3 Experimental

3.1 Apparatus

A visual overview of the Miniloop is given in figure 3.1. As seen from the figure, air flows through the system, being mixed with circulating water that is pumped around the system by the pump PU. The two phases flow together after the mixing point, and are separated in a separator tank, ST, at the top. The water flows back to a water reservoir tank, WT, and can continue the cycle, while the air is flashed out of the tank. In order to achieve slug flow, sufficient gas volume for pressure build-up is needed. Two air buffer tanks, BT1 and BT2 are therefore placed upstream the water-air mixing point. The air flow into the system, as well as the water circulation rate can be manually adjusted by the valves V1, V2 and V3. The flow rates are continuously being measured by flow transmitters before the mixing point. Four pressure sensors, P1 through P4, are placed in the multiphase pipe in order to measure the pressure at the different pipe-locations. There is a control valve, CV, upstream the separator. A Venturi is placed before the valve, with a differential pressure sensor measuring the pressure difference between the narrow and the wide part of the Venturi.

All the instruments will send analogous signals to an electric cabinet that contains FieldPoint modules communicating with the software in the computer. The FieldPoint modules will send digital signals to the computer and the control system software, LabVIEW. The signals between the computer containing the controller, and the control valve also go via the FieldPoint modules.

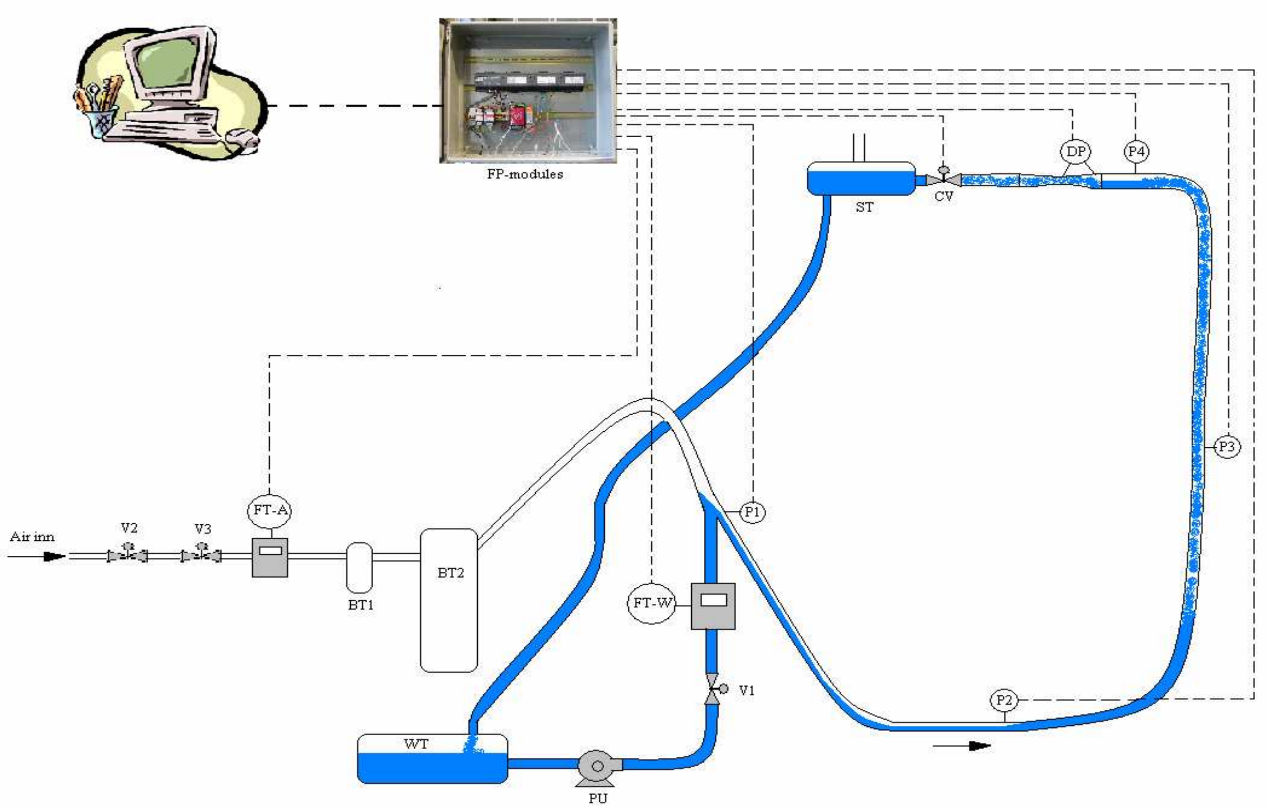

Figure 3.1 Flow sheet of the Miniloop.

The equipment in the Miniloop and the notation used in the flowsheet are tabulated in table 3.1. Below the table, a short description and a picture of the equipment is given.

Table 3.1 The equipment used in the Miniloop

Symbol	Full name
V1	Manual valve for water
V2	Manual valve for the air inlet
V3	Manual valve for the air
PU	Pump (Grundfos Solarpumpe UPS 25-120-180)
FT-W	Flow transmitter for water (Gemü 3021)
FT-A	Flow transmitter for air (ColeParmer (EW) 32707-36)
WT	Water reservoir tank
BT1	Buffer tank 1, air
BT2	Buffer tank 2, air
ST	Separator tank
P1	Pressure sensor (Motorola, MPX 1500DP), mixing point
P2	Pressure sensor (Motorola, MPX 1500DP), low point
P3	Pressure sensor (Motorola, MPX 1500DP), riser
P4	Pressure sensor (Motorola, MPX 1500DP), before valve
DP	Differential pressure sensor (Motorola, MPX 1500DP), for Venturi
CV	Control Valve (Gemü 554, 20 mm)
FP-modules	FieldPoint modules

The circulation pump used is situated between the water reservoir tank and the air-water mixing point. It can pump against a head of maximum 10 bar pressure. Figure 3.2 shows a picture of the pump.

Figure 3.2 The water circulation pump.

The flow rate meter for water is placed right upstream the air-water mixing point. It is based on a turbine flow measurement. The water flow rate is shown in L/min on its displays. The signal sent from the rate meter is a 4-20 mA analogue current signal which depends on the measured flow rate. The meter is shown in figure 3.3.

Figure 3.3 Flow rate meter, water.

The flow rate meter for air is placed between the air inlet and the buffer tanks. The principle for the measurement is thermal gas flow measurement. The air flow rate is shown in L/min on its display, with a range from 0 to 10 L/min. The meter provides an analogue 0-5 V voltage signal which varies with the air flow rate. Figure 3.4 shows the air flow meter.

Figure 3.4 Flow rate meter, air.

The water reservoir tank has a cylindrical shape and is made out of transparent plexiglass. The tank provides the capacity needed to continuously feed the pump with water. After going through the pipeline system, the water from the topside separator is returned to the reservoir tank. A picture of the water tank is shown in figure 3.5.

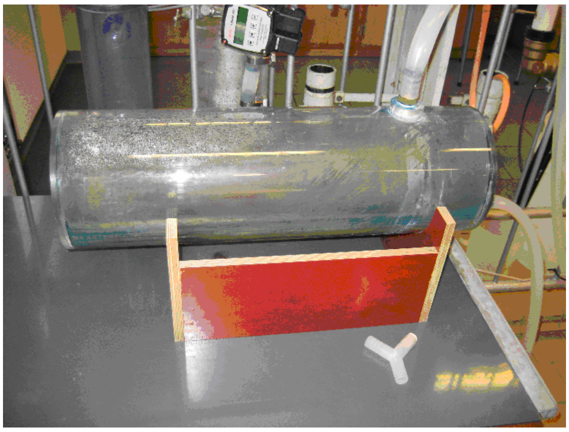

Figure 3.5 The water reservoir tank.

The buffer tanks for the air are situated between the air inlet and the air-water mixing point. Both tanks are cylindrical and provide sufficient large air volume to build up pressure during slug flow. Slug flow would not be possible without a volume where the pressure can build up. These tanks are also made out of transparent plexiglass. Different air volumes can be achieved by simply using one of the two tanks, or by filling up part of the available volume with water. Figure 3.6 shows a picture of the two tanks.

Figure 3.6 Buffer tanks for air.

The separator tank is depicted in figure 3.7. This tank is also made out of transparent plexiglass and shaped cylindrical. It has one inlet on the side and two outlets; one at the bottom and one at the top. The outlet at the top releases the air, while the bottom outlet is for the water recycle. Water is returned to the reservoir tank.

Figure 3.7 The separator tank.

The pressure sensors, like the one shown in figure 3.8 measure the pressure difference between the pipe and the atmosphere. They send analogue voltage signals in the range of 0.2-4.5 V to the FP-modules. The measured pressure range is 0-100 kPa and has a linear relationship with the signal.

Figure 3.8 A pressure sensor.

The venturi was custom made in glass. A venturi is constructed in such a way that the pressure of the flowing fluid is recovered as the fluid exits the venturi. Thus the energy loss through a venturi can be neglected. Figure 3.9 shows how the DP-cell is connected to the venturi. The differential pressure sensor is of the exact same type as the other pressure sensors, but measures the pressure difference between two points in the venturi, instead of the gauge pressure in the pipe. The signal range of 0.2-0.45 V of the sensor is linearly related to the measurement range of 0-100 kPa.

Figure 3.9 Venturi with DP-sensor.

The control valve is positioned upstream the separator at the top of the riser. It is depicted in figure 3.10. Pressurized air (4-8 bar) is needed to operate the actuator, and was supplied by the built-in pressurized air system in the laboratory. The actuator needs a 24 V power source and receives a signal between 4-20 mA from the electrical box. The signals from the FP-module are 0-10.2 V signals that need to be converted to a current signal before it is sent to the control valve. The relationship between the sent signals and the valve opening is linear.

Figure 3.10 Control valve.

The pipes used in the Miniloop are transparent silicon-rubber pipes with an internal diameter of 20 mm. A piece of the pipe is shown in figure 3.11.

Figure 3.11 Piping.

3.2 Data processing

In order to analyze the measurement data from the instruments on the Miniloop, the data needs to be recorded and stored. This is achieved by connecting all the instruments to a terminal base, which the FieldPoint modules are attached to, in the water proof electrical cabinet. Figure 3.12 shows the electrical cabinet containing the FP-modules. The dark grey FP-modules are placed at the top of the cabinet. The leftmost module is the connection between the other FieldPoint modules and the computer. Second from the left, is an Analogue Output (AO) module connected to the control valve, while the two modules to the right are Analogue Input (AI) modules. All the measurement instruments are connected to the AI module. Each AI and AO module has got eight channels, and can thus be connected to eight instruments. Appendix A gives an overview of the different channels with the corresponding instruments and signals.

Figure 3.12 The water proof cabinet with the FieldPoint modules in it.

The computer that receives the data needs a FieldPoint driver, so that the data can be read and transferred to the appropriate software. The software used was LabVIEW 8.2, and the FP-driver needed to be compatible with the software and the FP-hardware. A driver compatible with both is National Instrument’s *Measurement & Automation Explorer, version 4.1,* which was chosen for this purpose.

To be able to control the system with the predefined PID-controllers, an extra PID control toolset had to be installed with the software. It was available as an add-on in the LabVIEW version used in the project.

LabVIEW is a graphical drag and drop programming language and is a powerful tool for measurement analysis and data acquisition. Its programming language is called G and is based on C+. The program is divided into two main parts, the front panel and the block diagram, each in a separate window. The front panel is the user interface including knobs, buttons, indicators and graphs, thus resembling a control room screen. The block diagram window contains the code represented by interconnected blocks.

The front panel programmed to control the Miniloop is given in figure 3.13.

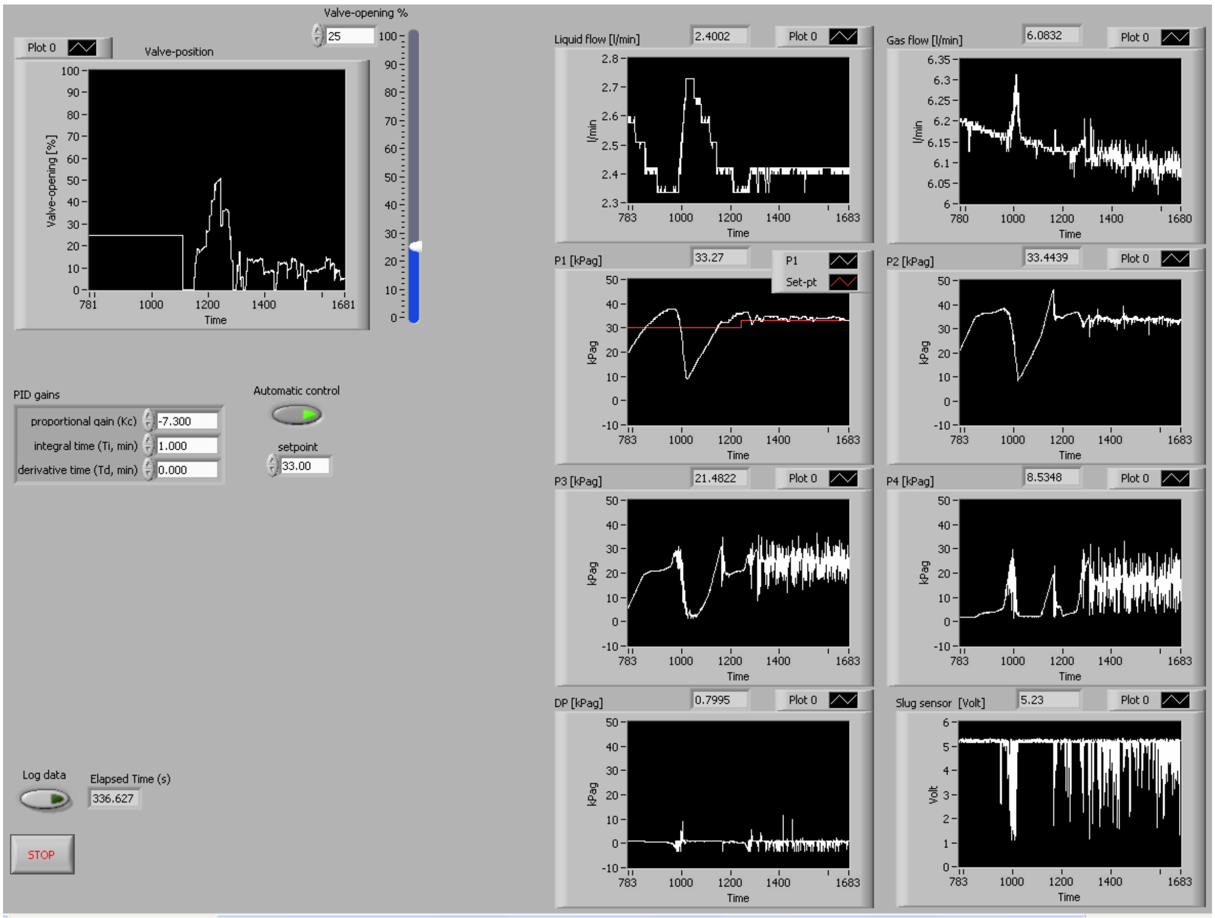

Figure 3.13 The front panel of the LabVIEW program made to control the Miniloop.

3.3 Running the Miniloop

There are several guidelines needed to follow when running the Miniloop, in order to not damage the equipment. A step-by-step start-up and shut-down procedure with some additional important remarks are given in appendix B.

3.4 Experiments performed

Earlier work performed by Sivertsen[12] shows that severe slug flow is obtained with a water flow rate of 4.9 to 5.6 L/min and a flow rate of 5.5 to 5.9 L/min for the air. All performed experiments in this project, were based on obtaining slug flow and then either taking open-loop or closed-loop measurements. During slug flow, the water flow rate varied between 4.9 and 5.8 L/min, while the gas flow rate varied between 5.6 and 5.8 L/min with a 25 % valve opening, before the system was controlled. The variations were caused by the pressure oscillations in the system, which affects the flow through the pump and the valves.

Some of the experiments on the Miniloop were performed before the venturi was installed, while others were performed afterwards. After the venturi was installed, two of the previous experiments were repeated to see if the venturi would have any effect on the system.

For the open-loop experiments, the pressure sensor P3 was placed 3.5 metres from the air-water mixing point, and only 0.5 metres downstream P2. The P3 measurements were quite similar to the P2 measurements. Therefore, P3 was moved to a position around the mid-point between P2 and P4, 5 metres away from the mixing point, when an attempt to eliminate the slug flow with only measuring P3 was carried out. Table 3.2 gives an overview of the performed experiments. Each experiment is described in more details in the following sections. The results from the experiments are given in chapter 4.

Table 3.2 An overview of the performed experiments

Experiment	**Performed before?**
Open-loop measurement of:	
-P1	Yes[5]
-P2	No
-P3	No
-P4	Yes[5]
Simple feedback control by measuring:	
-P1	Yes[5]
-P2	No
-P3	No
Testing the venturi:	
-Pure air flow	No
-Pure water flow	No
-Feedback control by measuring P1	No
Cascade control by measuring:	
-$\sqrt{DP}$ in the inner loop and P1 in the outer loop	No
Random valve opening	No

3.4.1 Open-loop experiments

The pressure in the system oscillates during slug flow. The maximum and minimum pressures for all pressure sensors where recorded for different valve openings. These data were used to create four bifurcation diagrams, one for each pressure sensor, showing how the pressure in the system varies with different valve openings. The volumetric flow rates of air and water were held constant during these experiments.

3.4.2 Simple feedback control with pressure measurements

Three sets of experiments with a simple feedback control structure were performed. The three different measurements used for the experiments were P1, P2 and P3 respectively. The experiments using P1 and P2 were carried out before the venturi was installed, while using P3 as the process measurement was performed afterwards.

First, a PI controller was tuned to tame the slug flow with a single pressure measurement. The tuning was performed by trial and error, until the controller managed to stabilize the system. The control structure is shown in figure 3.14.

After tuning the controller, the system was tested by measuring how the process output, i.e. the pressure, reacted when the controller was turned on. Another test was performed to see how the controller stabilizes the process during step changes. Finally, the robustness of the controller was tested by varying the flow rates. If the controller still stabilized the system, the controller would be robust and acceptable.

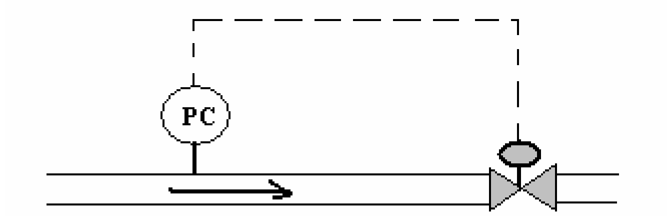

Figure 3.14 The control structure of the simple feedback control system.

Using P1 to control the system has been tested with positive results before[2]. A verification of the positive results was desired. It was however unclear if the P2 or P3 measurement for control purpose would be successful.

3.4.3 Testing the venturi

The purpose of installing a venturi on the Miniloop is that the mass flow through the venturi can be indirectly measured and used as a measurement for control purpose. The mass flow of a two phase flow through an orifice is shown to be directly proportional to the square root of the pressure difference over the orifice[13];

$$w \propto \sqrt{DP} \tag{3.1}$$

In the above equation, w is the mass flow rate and DP is the differential pressure over an orifice, or in this case the two parts of the venturi.

After the venturi was installed, open-loop measurements of the differential pressure between the narrow and wide parts of the venturi were performed. The measurements were performed for pure gas and pure liquid flow respectively to see if the venturi will give a pressure difference for both phases.

A venturi is shaped in a way that it will recover the pressure in the flowing fluid, and thus not lead to any pressure increase upstream itself. To determine if the venturi had any effect on the rest of the system, two of the experiments where P1 was measured and used to control the system were repeated. An experiment checking if the controller could stabilize the pressure as well as an experiment with set-point changes was performed.

3.4.4 Cascade control to eliminate slug flow

A cascade control structure with the square-root of DP in the inner loop and P1 in the outer loop was tested. The controller was tested by checking the stability during set-point changes, as well as testing the robustness when disturbances like changes in the flow rates were introduced.

3.4.5 Random valve opening

An idea for controlling the system is to not use a traditional controller, but to generate random signals to the valve and have random valve openings. The random valve position might eliminate the slugging and stabilize the flow. The random valve position was set within a boundary of high and low values;

$$z_{\min} \leq z \leq z_{\max} \tag{3.2}$$

where z_{min} and z_{max} are the minimum and maximum boundaries respectively, for the valve position, z. The low boundary was set to zero, while the maximum value had an initial value of 50 % and was slowly reduced in order to see what values would stabilize the system.

3 Results and discussion

4.1 Open-loop measurements

The open-loop measurements at varying valve openings were all conducted with constant flow rates and resulted in a series of data showing the oscillatory pressure behaviour. The maximum and minimum pressure values from each pressure sensor were used to draw the bifurcation plots given in figures 4.1 to 4.4.

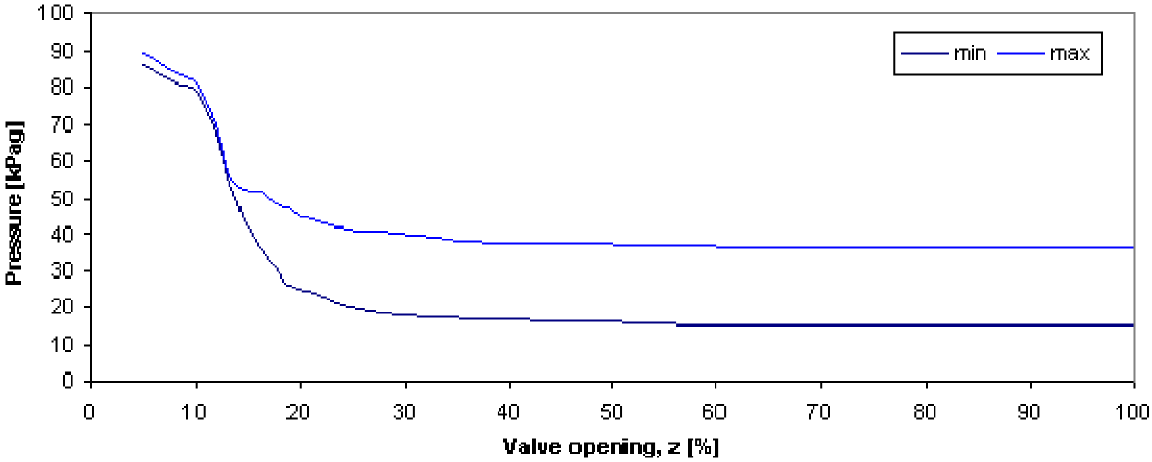

Figure 4.1 Bifurcation plot showing how P1 varies with different valve openings.

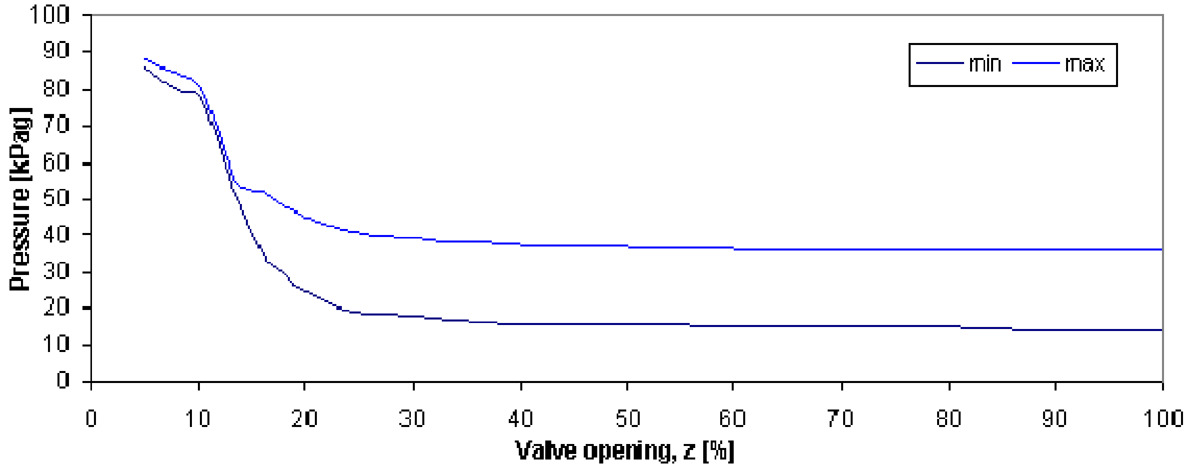

Figure 4.2 Bifurcation plot showing how P2 varies with different valve openings.

As seen from the bifurcation diagrams, the pressure throughout the entire pipe will vary between a minimum and a maximum value for all valve openings above 13 percent. Choking the valve to an opening of 13 percent or below will lead to a non-oscillating behaviour of the pressure, which means that the slug flow is eliminated. Thus z_{crit} is 13 % for the system with the given conditions.

Another trend worth noticing is that from around z = 20 % and downwards, the minimum pressure starts increasing drastically as the valve opening is reduced. The same trend is noticed for the maximum pressure as the critical valve opening is reached. At a 10 percent valve opening, the pressure is more than twice as high as during maximum valve opening, for all four measurement points in the pipe.

The open-loop measurements therefore show that choking the valve will reduce and even eliminate slug flow. The drawback is that the pressure in the pipe- and riser-system increases. For a pipe going into an oil well, the increased pressure means a reduction in the production rate, and eventually in the overall oil recovery from the well.

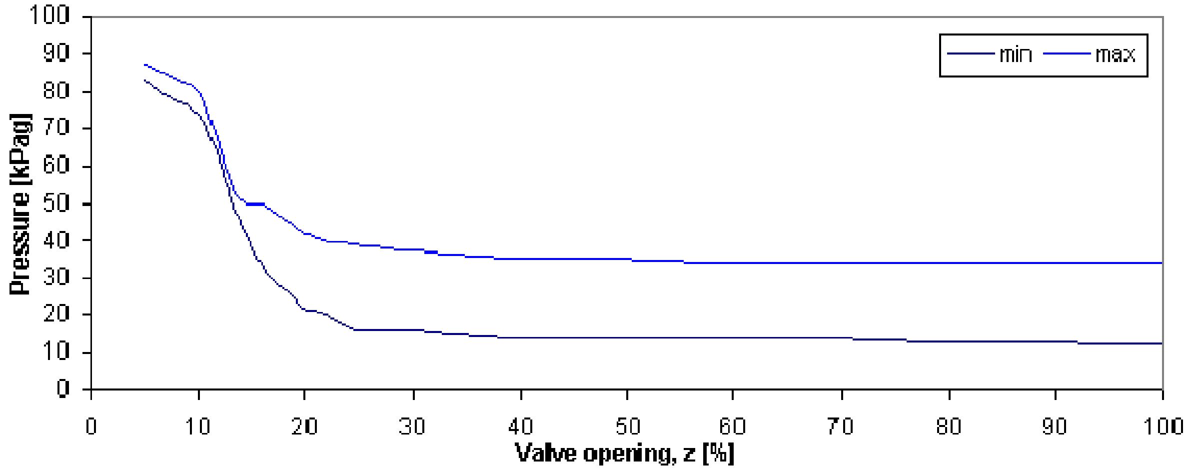

Figure 4.3 Bifurcation plot showing how P3 varies with different valve openings.

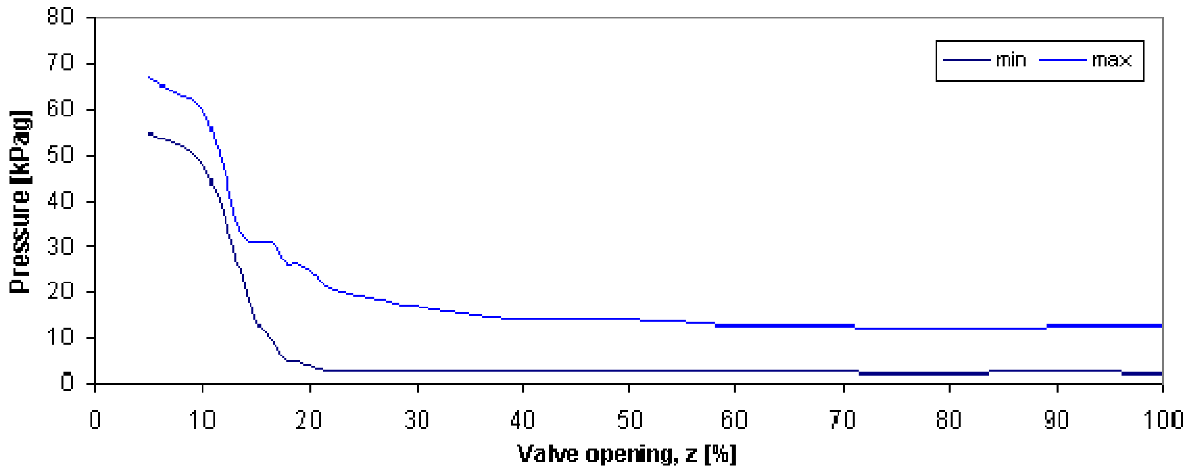

Figure 4.4 Bifurcation plot showing how P4 varies with different valve openings.

4.2 Simple feedback control with pressure measurements

4.2.1 Tuning the controllers

The controllers were tuned by trial and error. For the controllers using P1 and P2 respectively as the process measurement, the pair of the proportional parameter and the integral time of the controllers that could stabilize the system were found. Their values are given in table 4.1.

Table 4.1 An overview of the controller settings and the given pressure set points.

Measurement	*Kc* [kPa^{-1}]	*Ti* [min]	Set-point [kPag]
P1	-7.10	1.3	30
P2	-11.3	0.65	30

For the controller measuring P3, many different controller settings were tested, without any positive result. This could mean that P3 is too close to the top side where a single measurement can not be used to stabilize the system[14]. Another possibility is that it is difficult, though possible to control the system by measuring P3, even though this was not proved in this project.

After tuning the controllers, the stability and robustness tests were performed. The two following sections present the results from the experiments. The first section describes the system when P1 is used as the measurement, while the next section is dedicated to the experiments with P2 measurements.

4.2.2 Controlling the system with P1 as the measured process output

After the controller was tuned, its ability to keep the system stable over time was tested. The process was run in open-loop for ten minutes before the controller was turned on. The closed-loop performance was recorded for 30 minutes. The charts in figure 4.5 show the results.

By viewing the results, it is obvious that the slugging is eliminated as the pressure oscillations are eliminated, and the pressure stabilizes around the set-point. The pressure varies between 22 and 40 kPag in open-loop before it stabilizes when the controller is turned on. The actuator works over a wide range before finally working around an opening of 20 to 30 percent after about two minutes of control. It is worth noticing that the valve openings are well above z_{crit} of 13 percent, which means that the system is stabilized in a domain where slug flow usually dominates. This is also seen from the pressure set-point, as the system stabilizes around a pressure of 30 kPag, which is below the pressure in a choked system.

The last chart in the figure is given to show that the flow rates also oscillate during slug flow. Both the air and water flow rates stabilize when the Miniloop is being controlled. The reason for the large variations in the water flow rate is that the pump was working with a constant speed. As the pressure in the system increases, the pump will circulate less water than when the pressure is lower. Thus the flow rate oscillation for the water is in anti-phase with the pressure oscillations. The oscillation of the gas flow rate is less significant, because the air is supplied from a central, more powerful compressed air system.

In the 21st minute, a sudden change in the pressure is noticed. One explanation is that the pressure slowly starts oscillating without the controller being good enough to handle it. Another matter that was observed several times, is that when the computer's processor is loaded, the communication between the computer, and the instruments and the control valve is broken. Signals between the different components are not sent for up to three seconds when this happens. The control valve shuts when the communication is broken, and the result will be a sudden increase in the pressure. Also, some other kind of non-measured disturbance might have affected the system, and thus changing the pressure.

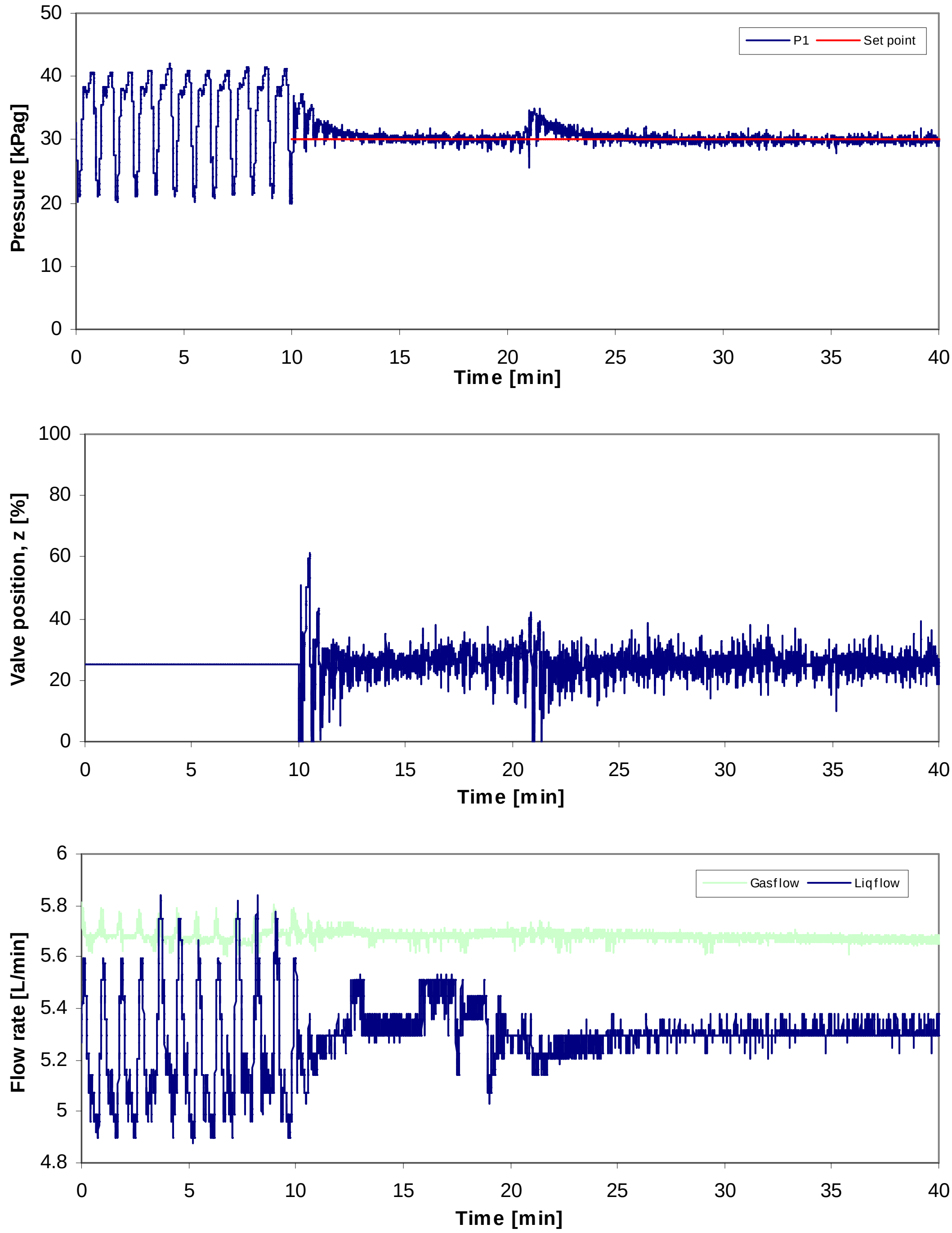

Figure 4.5 Applying feedback control by measuring the pressure P1, eliminated slug flow.

The controller was also tested if it handles set-point changes. The results for a 10 percent set-point increase from 30 kPag to 33 kPag are shown in figure 4.6. As seen from the plots, the controller handles the transition from open loop to the 30 kPag set-point well. Also increasing the set-point to 33 kPag is handled well. The remarkable phenomenon is that returning the set-point to 30 kPag results in trouble for the controller. The pressure starts oscillating, though with a smaller amplitude than during the open-loop slugging. This can be interpreted as light slugging. The pressure might have been stabilized if the controller would be kept on for a longer period, but this was not tested.

Further on, it seems like the actuator works in a broader range during the high set-point, although the pressure seems more stabilized. Increasing the pressure set-point point seems to have decreased the average valve-opening, which is reasonable, since a pressure increase implies more resistance against the flow. When the pressure was reset to 30 kPag, the valve-opening started varying more as the pressure started oscillating.

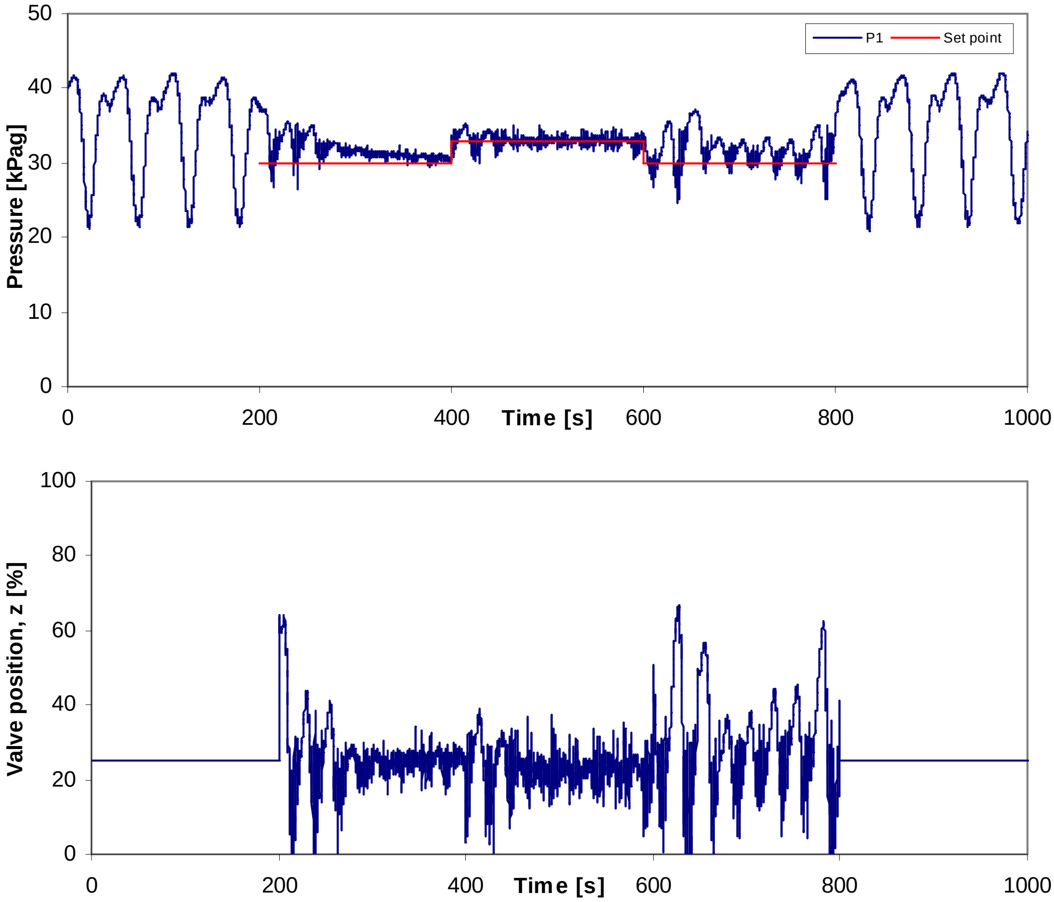

Figure 4.6 The response of the system towards set-point changes for P1.

For eliminating the slug flow, the controller performs acceptable. Regarding the set-point changes; the performance is acceptable for an increase in the pressure set-point, however the response to the set-point decrease is not acceptable. As seen from the above figure, the pressure starts oscillating when the controller is turned off, as expected.

The robustness of the controller was tested by varying the flow rates into the system. Figures 4.7 and 4.8 show the results from these experiments. The controller was turned on after 15 minutes of recording the open-loop behaviour. The first figure shows the results from almost an hour of operating time, while the second figure gives the succeeding operating hour.

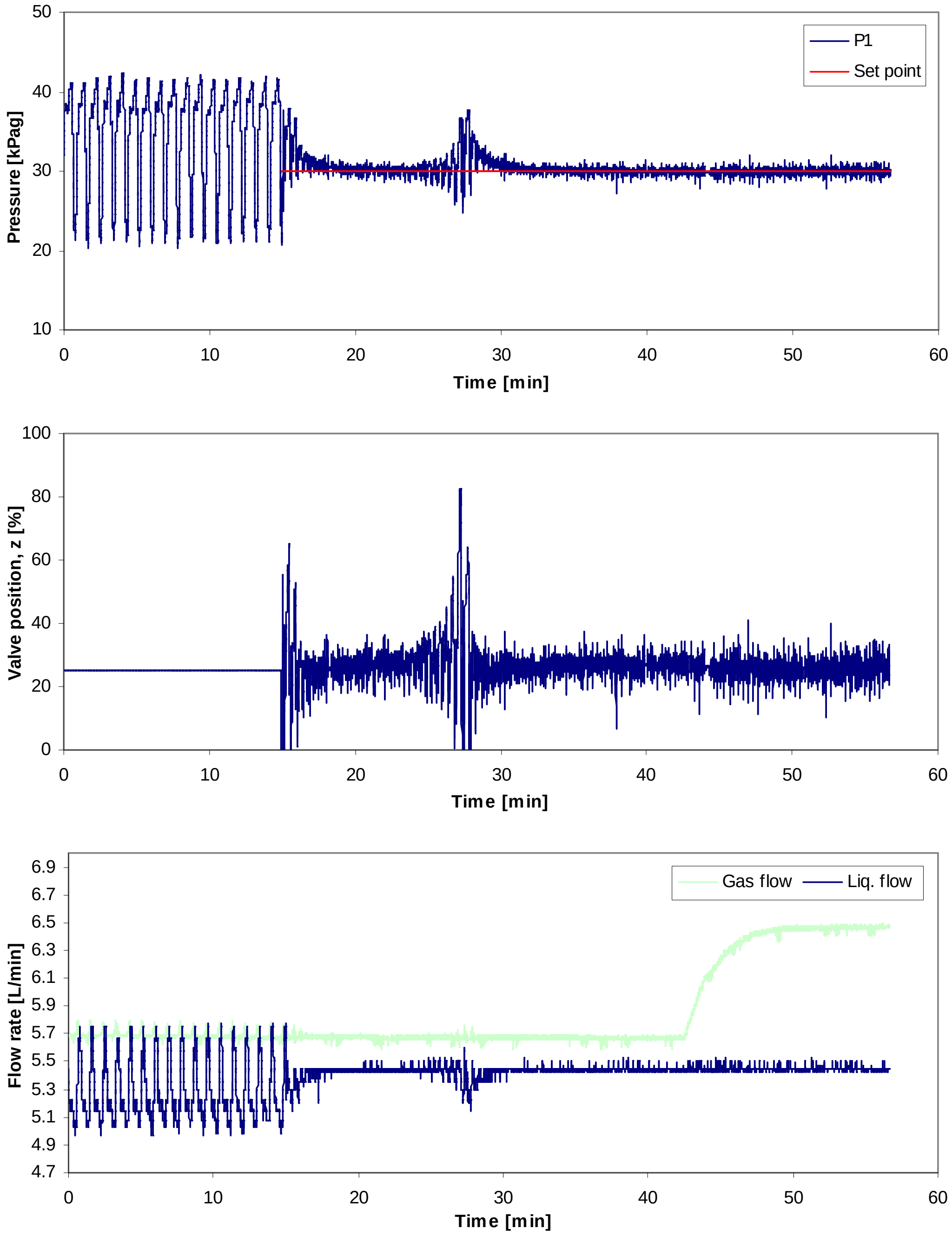

Figure 4.7 Results from the controller test with varying flow rates (part I).

In the 25th minute, the pressure starts drifting, and the valve works to counteract the drifting. The controller does not stabilize the pressure before the amplitude of the pressure oscillation reaches 8 kPag.

Increased air flow rate after 42 minutes was an external disturbance, which was not made deliberately. This actually helps in a positive way against slug flow, because more gas is available to lift the liquid up the riser, as in applying gas lift.

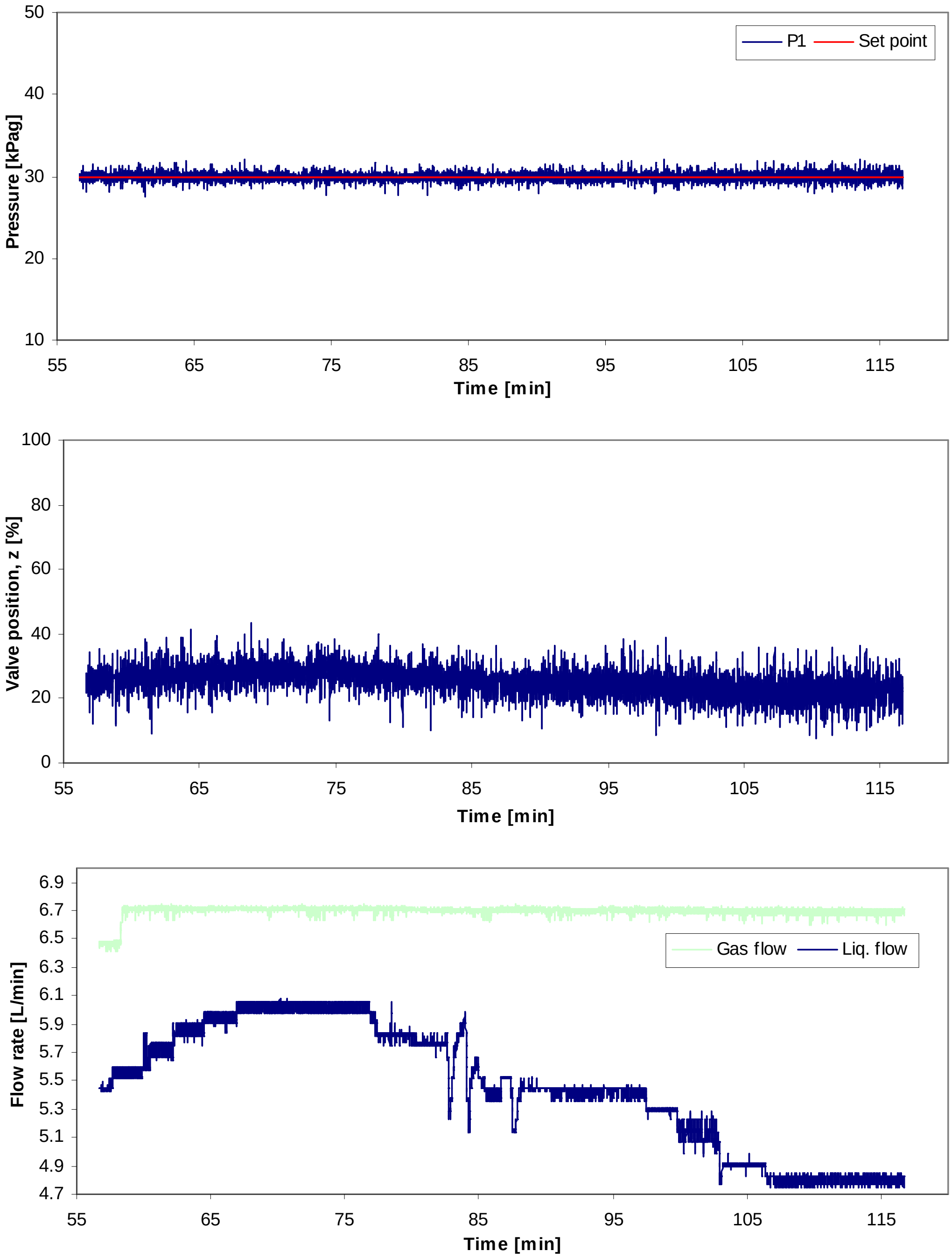

Figure 4.8 Results from the controller test with varying flow rates (part II).

After approximately one hour, the liquid flow was ramped up (by small steps) from 5.4 to 6.0 L/min before being gradually stepped back down. Finally, the water flow rate was ramped down to 4.8 L/min. As seen from both the pressure measurement and the valve position, the controller handles these planned disturbances quite well. The pressure is kept around its set-point, and the valve position does not vary much more than it does without the disturbances.

As the liquid flow rate increases and then decreases, the average valve opening seem to increase slightly and then decrease in line with the flow rate variations. The actuator operates in a wider range at low liquid flows, than at the high flow rates. The last trend might indicate that challenges with slugging are more serious as the liquid flow rate decreases.

4.2.3 Controlling the system with P2 as the measured process output

By using the tuning parameters given in table 4.1 for the controller, the slug flow was eliminated and the pressure and the flow were stabilized. The stability of the controller was tested by seeing how the controller could stabilize the process around the set-point. Results from the test are shown in the charts of figure 4.9. In open-loop, the pressure oscillates between 20 and 40 kPag, but stabilizes when the controller starts moving the actuator. The average valve opening in the system seems higher than the critical value, and the average pressure seems lower, than the pressure when the valve is choked to eliminate the slug flow.

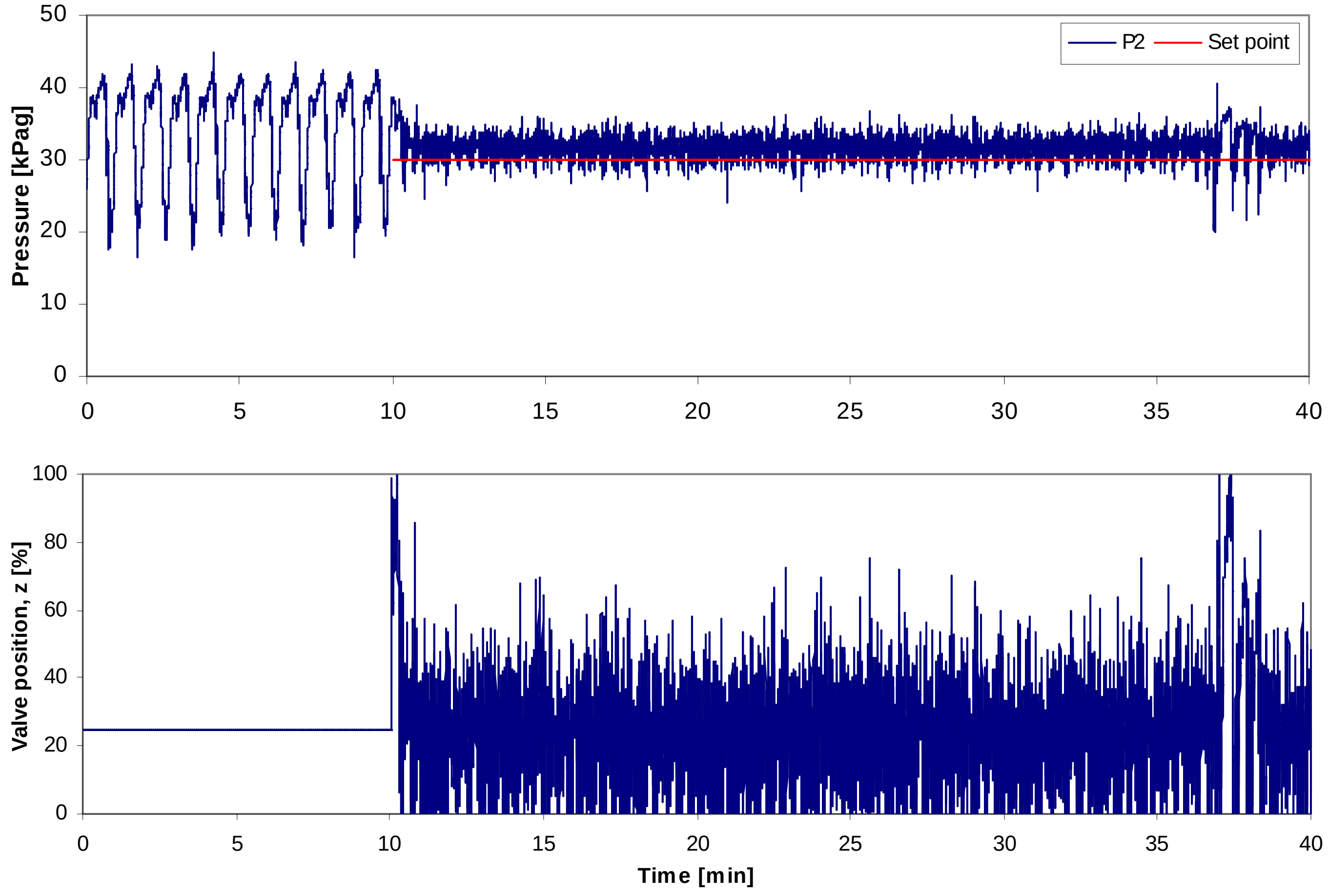

Figure 4.9 Eliminating slug flow by applying feedback control by measuring P2.

From the figure above, it is clear that the controller does eliminate the slug flow and stabilizes the pressure. However, it seems like the average stabilized pressure is slightly above the set-point of 30 kPag. Another remark is that the actuator activity is quite large, and it is saturated from the low boundary many times. The valve is opened up to around 50 percent, although the opening does peak above that many times.

The incidence after 37 minutes does not seem like a slow pressure drift, but rather like a sudden change in the process. This incidence might be explained by a failure in the communication as described earlier for the same experiment with P1 as the measured variable.

This experiment shows that moving the pressure measurement from P1 to P2 does complicate the control to some extent. It is unclear however if some other parameters for the controller would have given a smoother behaviour of the system, and less deviation between the response of the two controller configurations.

The system's response towards set-point changes was tested. The results from the experiment are given in figure 4.10. The pressure is quickly stabilized after the controller is switched on after 200 seconds of recording the open-loop behaviour of the system.

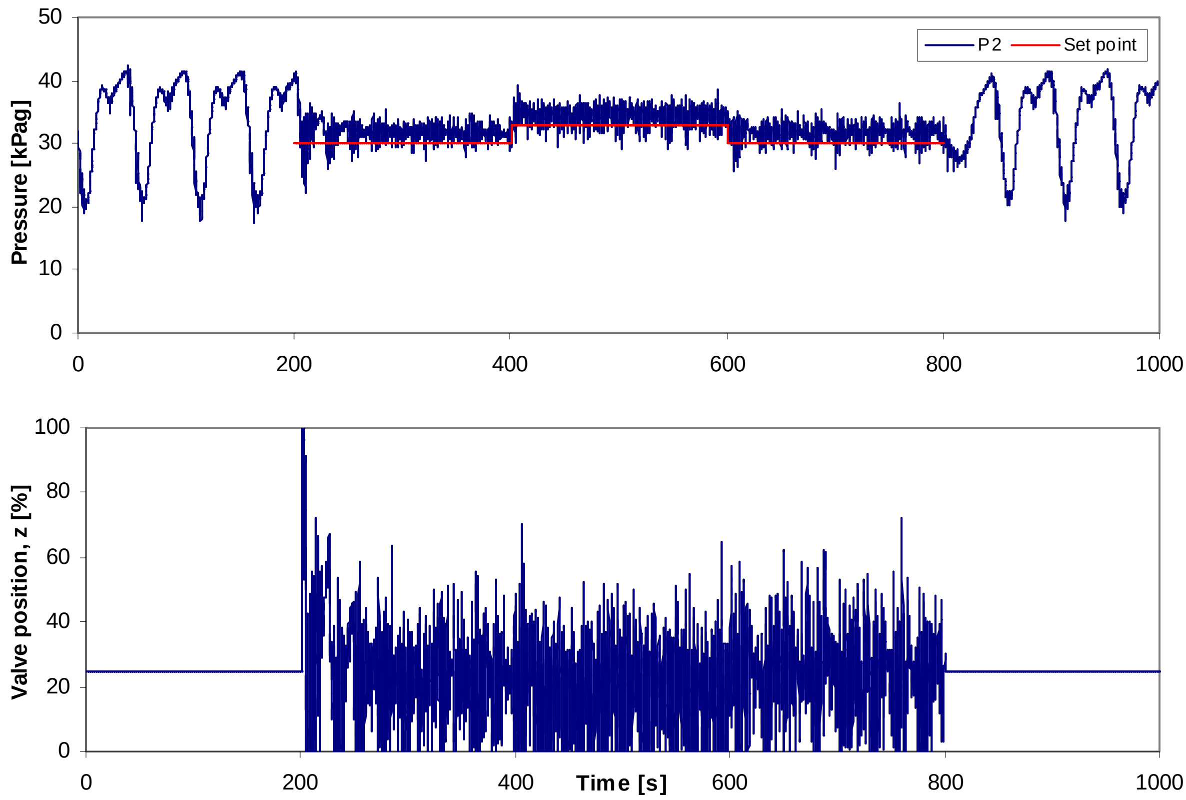

Figure 4.10 The response of the system towards set-point changes for P2.

A 10 percent increase in the set-point from 30 to 33 kPag is handled well by the system, as for the set-point reduction, back to 30 kPag. For both set-points, it seems nevertheless like the average measured pressure is slightly above the set-point. Also, it seems like the system pressure has small oscillations for both set-points, although these oscillations can not be compared to the slugging oscillations

The valve opening values for the 30 kPag set-point seem to be mainly in the range of 10 to 40 percent, although it sometimes peaks both over and below that range. For the set-point of 33 kPag, the valve opening varies mainly between 0 and 40 percent, with some peaks exceeding that range. The valve is saturated more often in the low boundary for the higher set-point. A higher set-point for the pressure does imply that the system needs to be choked more to keep a higher pressure.

After 800 seconds of operation, the controller was turned off. Immediately after that, the slugging behaviour reappeared and the pressure started oscillating again. The valve was set to a constant value of 25 percent opening after the controller was shut off.

Following the set-point changes, the experiment with varying flow rates was performed to evaluate the robustness of the controller. Figures 4.11 and 4.12 show the results. The first of the two figures shows the first hour of operation, while the other shows the second operating hour. After 15 minutes of open-loop data-recording, the controller was switched on.

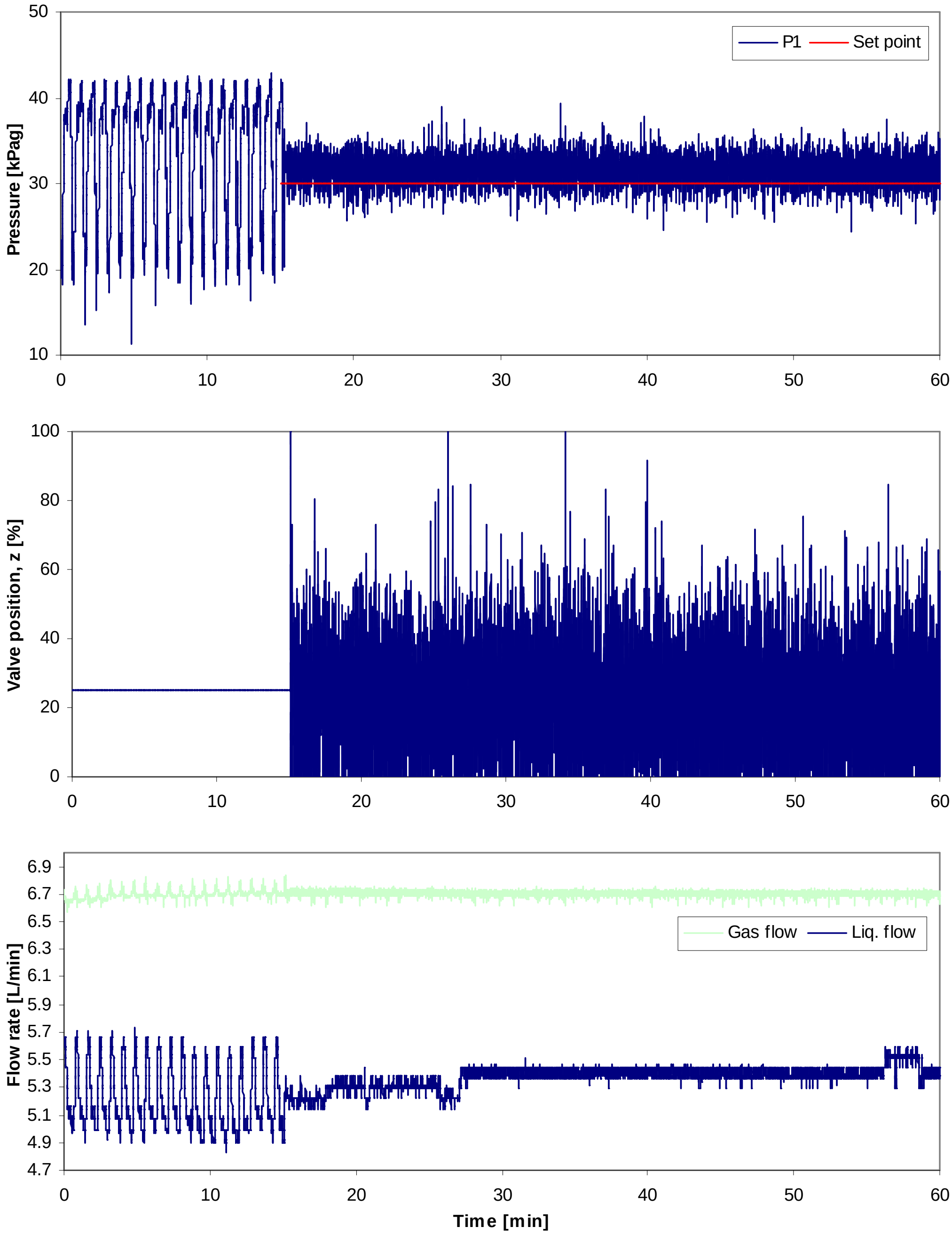

Figure 4.11 Results from the controller test with varying flow rates (part I).

From the charts, it is shown that the pressure does stabilize when the controller is turned on and the slugging is eliminated. What can also be noticed is that the pressure seems to have an offset to the set-point. The average pressure seems to be around 2 kPa higher than the given set-point of 30 kPag, as for the other experiments where P2 is the process measurement. This confirms the fact that the controller could have been tuned better.

The actuator operates in a wide range, from 0 percent to around 50 percent opening, with peaks that reach up to even 100 percent opening. The 0 percent openings does not seem to be occasional peaks, but quite common for the valve opening, which means that saturation at the low boundary takes place.

No changes to the flow rates were carried out, before 60 minutes of operation. The variations in the flow rate before that is due to uncontrolled disturbances.

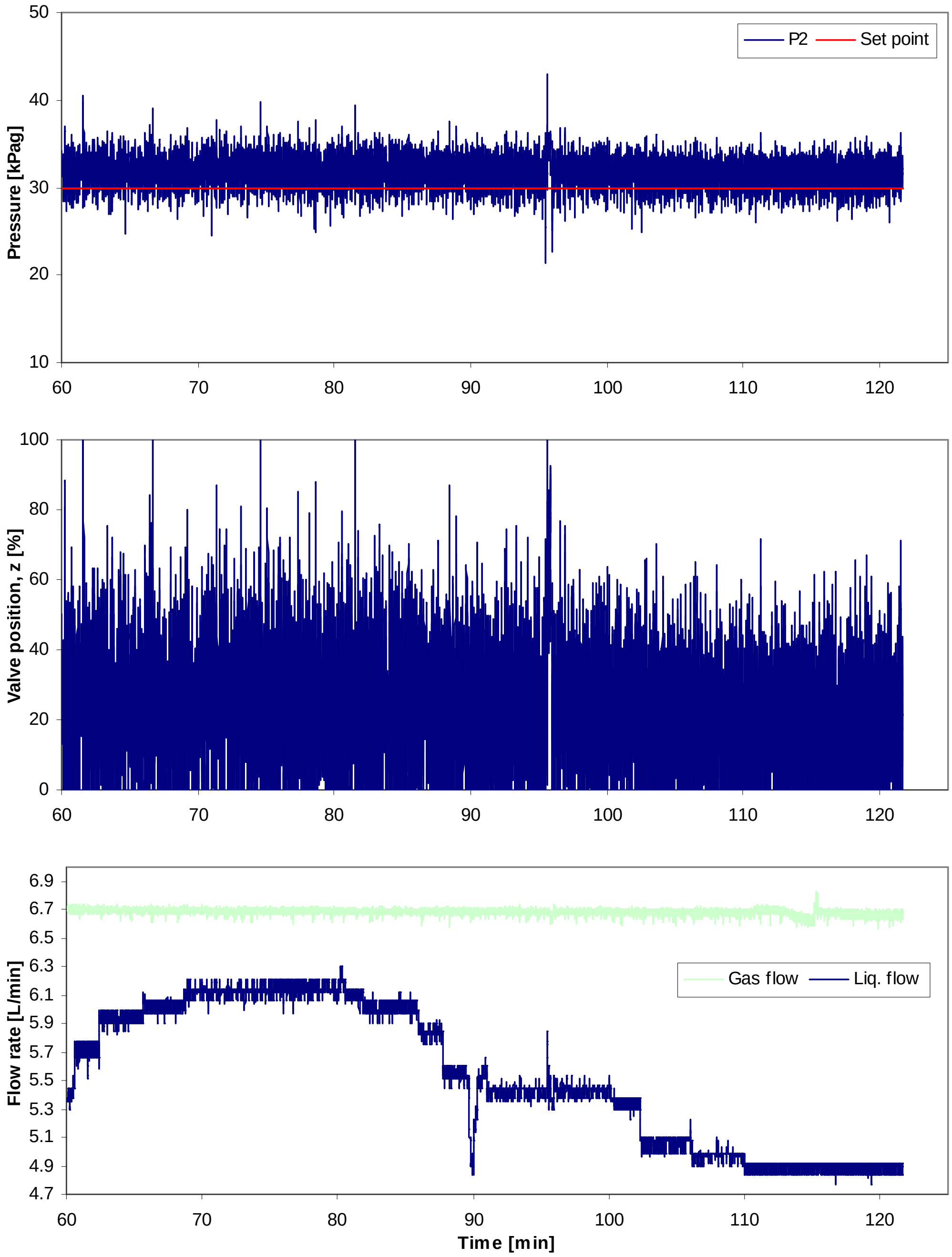

Figure 4.12 Results from the controller test with varying flow rates (part II).

After 60 minutes, the water flow rate was ramped up doing small steps, from 5.3 L/min to 6.1 L/min, and kept at the high flow rate for 10 minutes. Later the water flow rate was ramped down to around 5.4 L/min, kept there for 10 minutes and then gradually stepped down to 4.9 L/min.

The pressure is kept around the set-point the entire time, showing that the controller is in fact robust. For the different water flow rates, the actuator continues to work in a broad range. When the water flow rate is ramped up, the valve seems to open up more, and the upper peaks of the valve position are higher. At the low flow rates below 5 L/min, the average valve opening seems to be lower, while the upper peaks are clearly lower, compared to the valve openings at higher flow rates.

In the 96th minute, the pressure suddenly increases, and so does the valve opening as a reaction to that. Since the pressure increase does not seem like a slow drift away from the set-point, there are two possible explanations to that. There might be a sudden external disturbance that affected the system to response like that. The other possibility is that the signals between the computer and the Miniloop were lost for a short moment, resulting in shutting of the control valve. When the signals were sent again, a higher pressure is registered and thus a signal for an increased valve opening is sent to the control valve.

4.2.4 Controlling the system with P3 as the measured process output

Numerous attempts to tune a feedback controller by trial and error, with P3 as the measured process variable, did not result in elimination of the slug flow. This does not necessarily mean that it is impossible to control the system with a single pressure measurement in the P3 position. There might be pairs of tuning parameters that can stabilize the flow in the system, even though they were not found during these tests.

Open-loop measurements of P3 are given in figure 4.13. The measurements are taken during a constant 25 percent valve opening and shows that during the pressure build-up, there are two pressure maxima, one local, the other being both local and global. This double-maximum behaviour, as well as the noisy nature of the measurements during the pressure let-down, might be the reasons for the control difficulties.

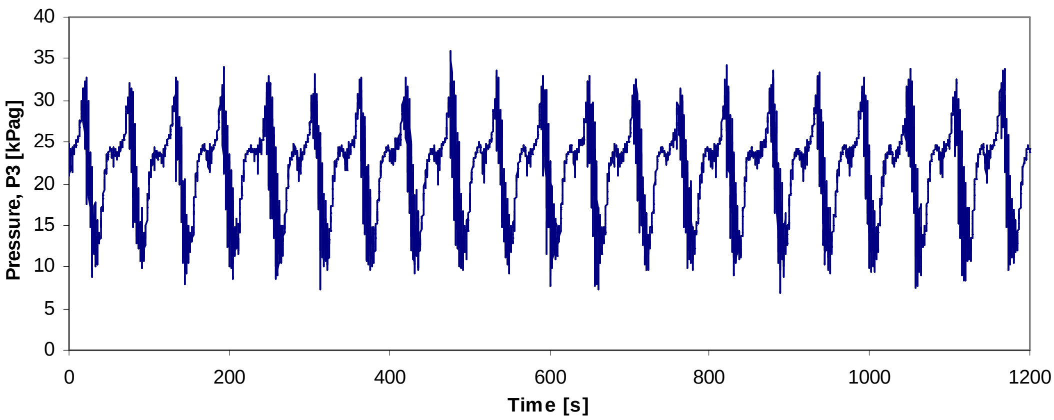

Figure 4.13 Open-loop measurements of the pressure P3 with 25 percent valve opening.

An idea for this control configuration is to introduce a filter to the measurement. Perhaps a less noisy measurement would be suitable to control the system.

4.3 Testing the venturi

The following two sections will present the results from the experiments using the venturi as a flow rate indicator. Following the two sections is a part dedicated to the results from the experiments using P1 as the measurement for a feedback controller with the presence of the venturi.

4.3.1 Pure air flow through the venturi

An experiment was performed where only air was flowing through the system and through the venturi. The pressure difference between the narrow and the wide part of the venturi was measured as the air flow was varied. The results are given in figures 4.14 and 4.15.

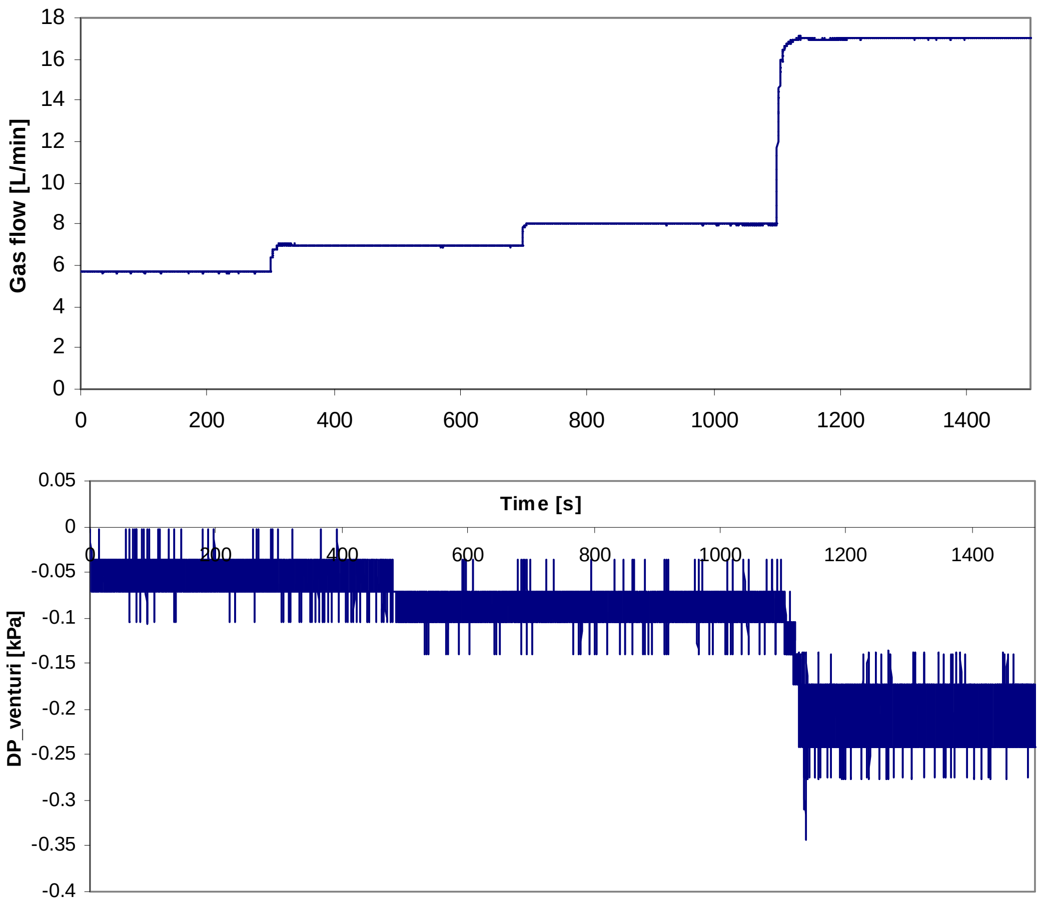

Figure 4.14 Time varying gas flow and the effect on the pressure difference in the venturi.

As seen from the above figure, the pressure difference in the venture does increase as the gas flow rate increases. This means that the pressure difference, and more specifically its square root, can be used as an indication of the gas flow rate in the system. On the other hand, the measured pressure differences are quite small for the given gas flow rates. The figure below shows a better representation of the relation between the pressure difference and the air inflow rate to the system.

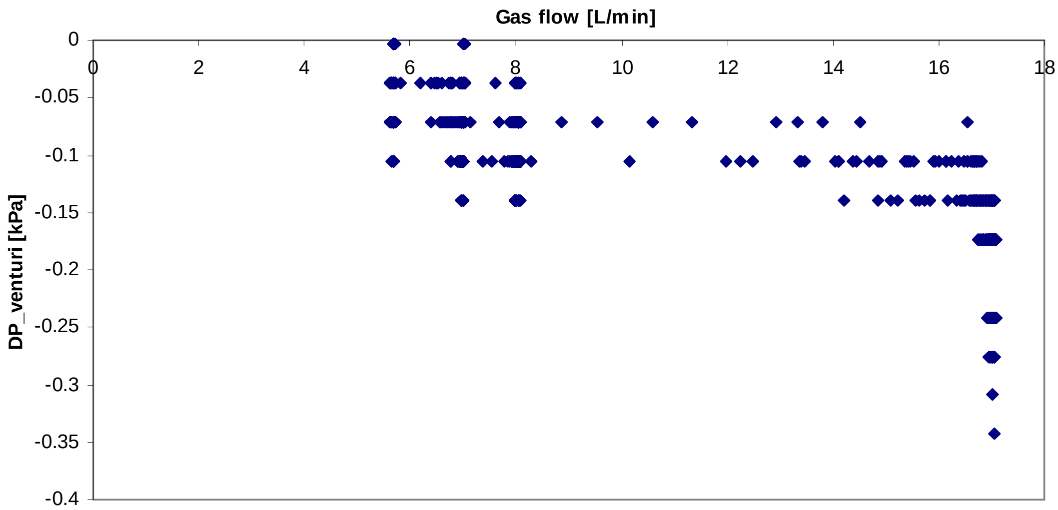

Figure 4.15 The pressure difference in the venturi as a function of the gas flow.

Having proved that the venturi is able to distinguish between different flow-rates for the air, a similar experiment was performed for a single-phase water flow.

4.3.2 Pure water flow through the venturi

The exact same experiment as the one for the air flow was performed with only water circulating in the Miniloop. Figure 4.16 shows the dependence of the pressure difference in the venturi to the flow rate of water in the system.

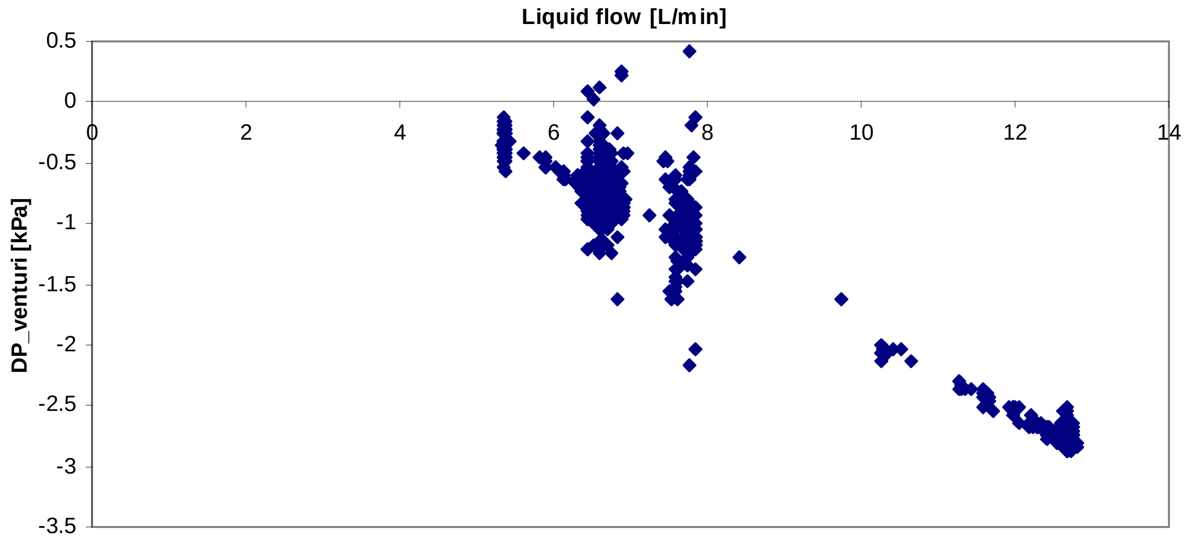

Figure 4.16 The pressure difference in the venturi as a function of the water flow.

It is obvious that the pressure difference increases as the water flow rate to the system increases. The pressure difference is much larger for a given volumetric flow rate of the liquid, compared to the gas. For the gas, a volumetric flow rate of 10 L/min causes an absolute pressure difference of approximately 0.1 kPa. The same volumetric flow rate for the liquid results in a pressure difference of around 1.9 kPa in the venturi. This difference is due to the density difference between the air and the water. The higher the density, the higher the mass flow rate for a given volumetric flow rate, and thus a higher pressure difference in the venturi will occur.

4.3.3 The effect of the presence of the venturi on the system

Before the venturi was installed, the system was stabilized by a simple feedback controller using P1 as the only measurement. The tuning of the controller and the results were given in section 4.2. The exact same control configuration with the same controller settings and set-point for the pressure was used for the stability- and set-point change tests with the venturi present in the system. Figure 4.17 shows the results from the stability test of the controller.

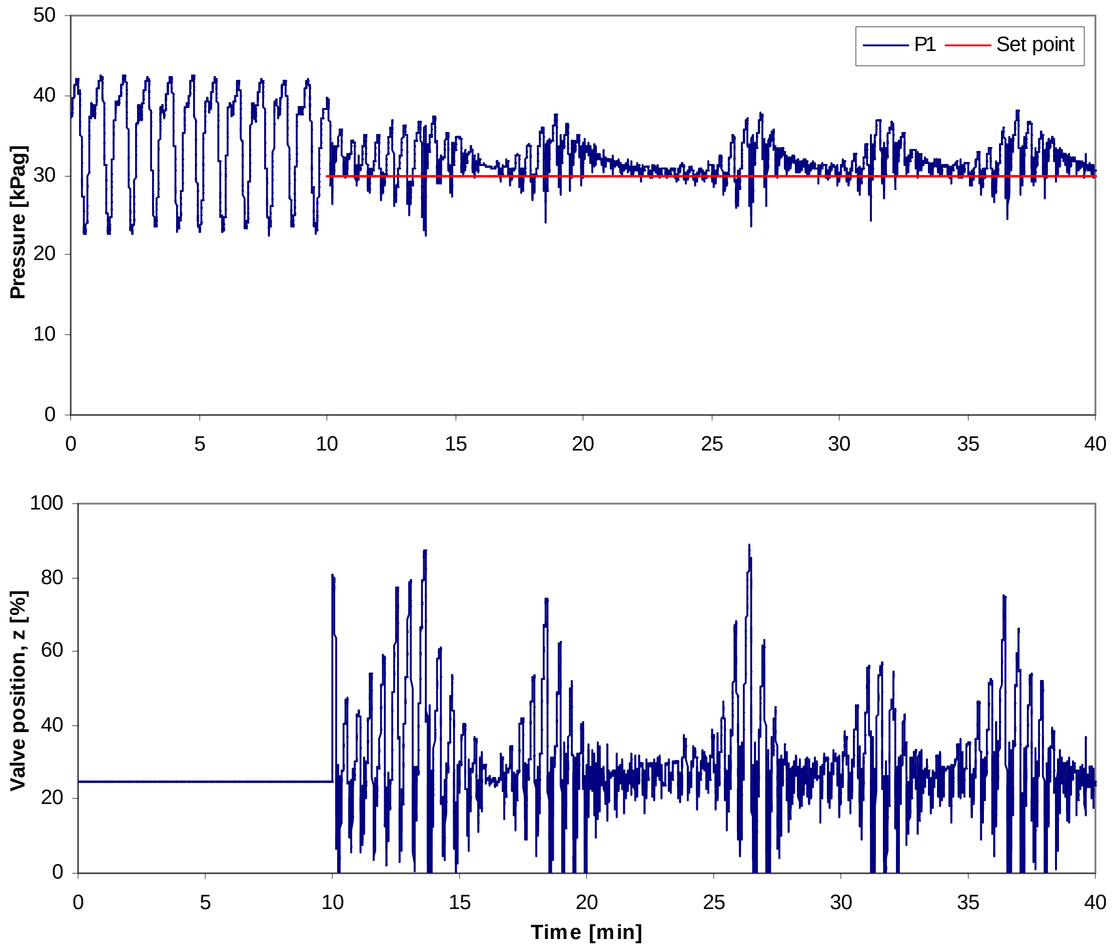

Figure 4.17 Simple feedback control by measuring P1 with the presence of the venturi.

As seen from the figure, the severe slugging is damped, but the pressure is not stabilized. In fact, the pressure continues to oscillate, but with a smaller amplitude than during the severe slugging. Also, the amplitude seems to vary periodically on a larger time-scale than the pressure oscillations.

Since the pressure is not stabilized, the valve opening varies in a broad range in line with the pressure variations. The actuator does reach the 0 percent opening, but never saturates for the maximum boundary.

This experiment shows clearly that the presence of the venturi does affect the system. The constriction in the venturi gives more resistance against the flow through the system, causing slightly higher pressure upstream itself. Comparing figure 4.17 to figure 4.5, the open-loop P1 measurement before and after the venturi was installed can be read. Without the venturi, the pressure varied between 20 and 40 kPag, while with the venturi, the pressure was increased to the range of 23 to 42 kPag. This again means that the pressure set-point of 30 kPag might have been too low. Performing an experiment with an increase of the set-point could verify the above explanation.

A test making an increase in the set-point from 30 to 33 kPag was performed. The results are shown in figure 4.18. During the experiment, the controller was switched on after 200 seconds of open-loop measurements. After additional 200 seconds, the set-point change took place, but was reset after another 200 seconds.

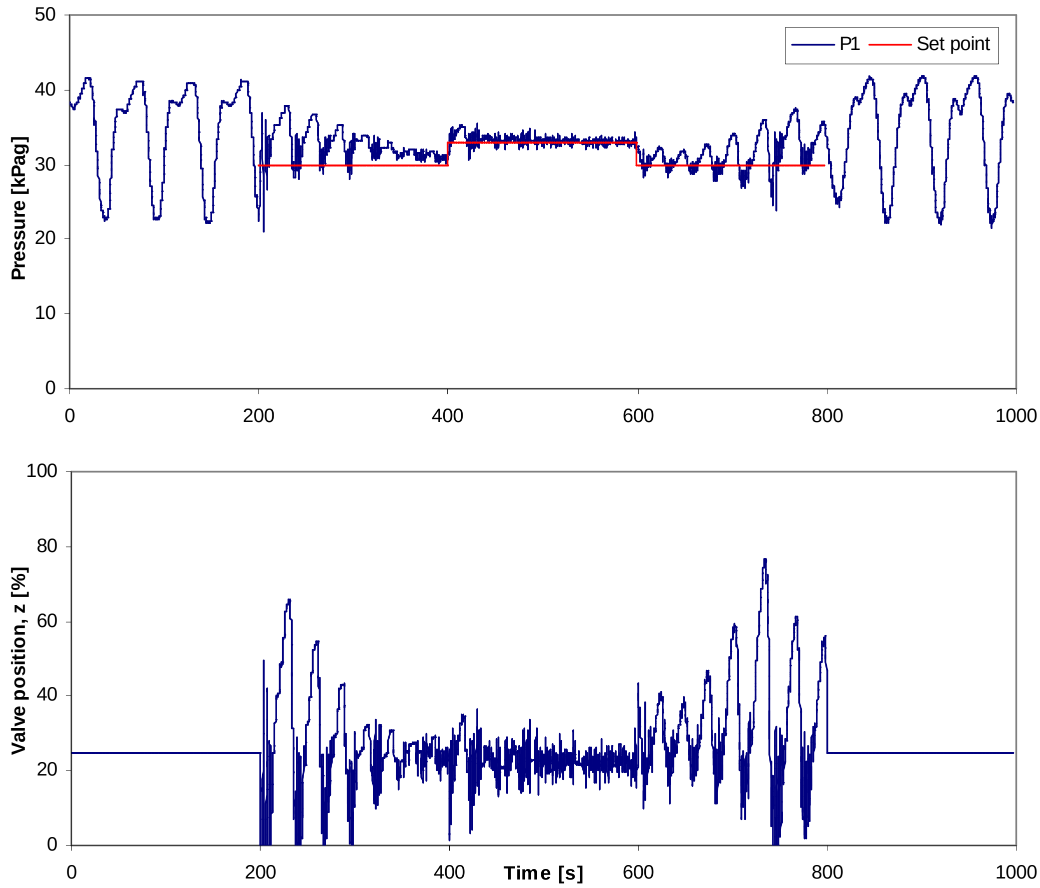

Figure 4.18 The response of the system towards set-point changes with the venturi present.

As seen from the above figure, the pressure is not properly stabilized, even though the slugging is reduced, when the pressure set-point is 30 kPag. When the set-point is increased to 33 kPag, the pressure is stabilized and the actuator starts operating in a more narrow range. The pressure starts oscillating again when the set-point is reduced to 30 kPag.

The last two experiments show that the effect of the venturi on the process is a slight increase of the pressure. A 2 to 3 kPa pressure increase made it difficult to keep P1 at 30 kPag with the same controller settings, and a higher set-point is required.

4.4 Cascade control to eliminate slug flow

A cascade control structure with a measurement of the differential pressure of the venturi, DP, and its square root used to control the valve in the inner loop was implemented. The inner loop is designed as a simple feedback control system, and its controller is called the slave controller. The slave controller received its set-point from the controller in the outer loop, which is called the master controller. The measured variable which was given a set-point in the outer loop was P1. Both the controllers were tuned by trial and error. Table 4.2 presents the found controller settings. A stable system was not achieved by only using the inner loop controller, and the outer loop was needed to stabilize the system.

Table 4.2 Controller settings for the cascade control system

Controller	Measurement	Set-point [kPag]	*Kc*	*Ti* [min]
Slave	DP	-	28 kPa^{-1}	1.0
Master	P1	33	-6	0.3

P1’s set-point was chosen to be 33 kPag instead of 30 kPag, because of the presence of the venturi which lead to a slightly increase of the pressure.

The first experiment performed with the cascade control system was a stability test where the system was run in open-loop for 10 minutes before the controller was switched on. Data with the controller turned on was recorded for 30 minutes. The results are given in figure 4.19. The plots show that the slug flow is eliminated by the cascade controller. P1 is stabilized close to the set-point, but with a small offset. It seems like the average pressure in the system stabilizes around 35 kPag instead of 33 kPag. The tuning could therefore probably be improved. Also, the pressure does vary from around 33 to 36 kPag, with peaks outside of this range, during control. The standard deviation from the average pressure should also be minimized.

In order to keep a stable system, the actuator operates in the range of 0 to around 50 percent opening, which is a quite broad range. The actuator thus saturates at the low boundary, which is also undesirable. Better tuning could perhaps reduce the actuator’s operating range and even prevent saturation at the low boundary.

In the middle chart in the figure below, DP is given, as well as its varying set-point. The large and fast variation of the set-point indicates that the outer loop might have a too fast response. On the other hand, a too slow response keeping DP’s set-point almost constant for short time-periods would probably not stabilize the system, because the inner loop alone did not manage to do so. A better trade-off could perhaps be found here.

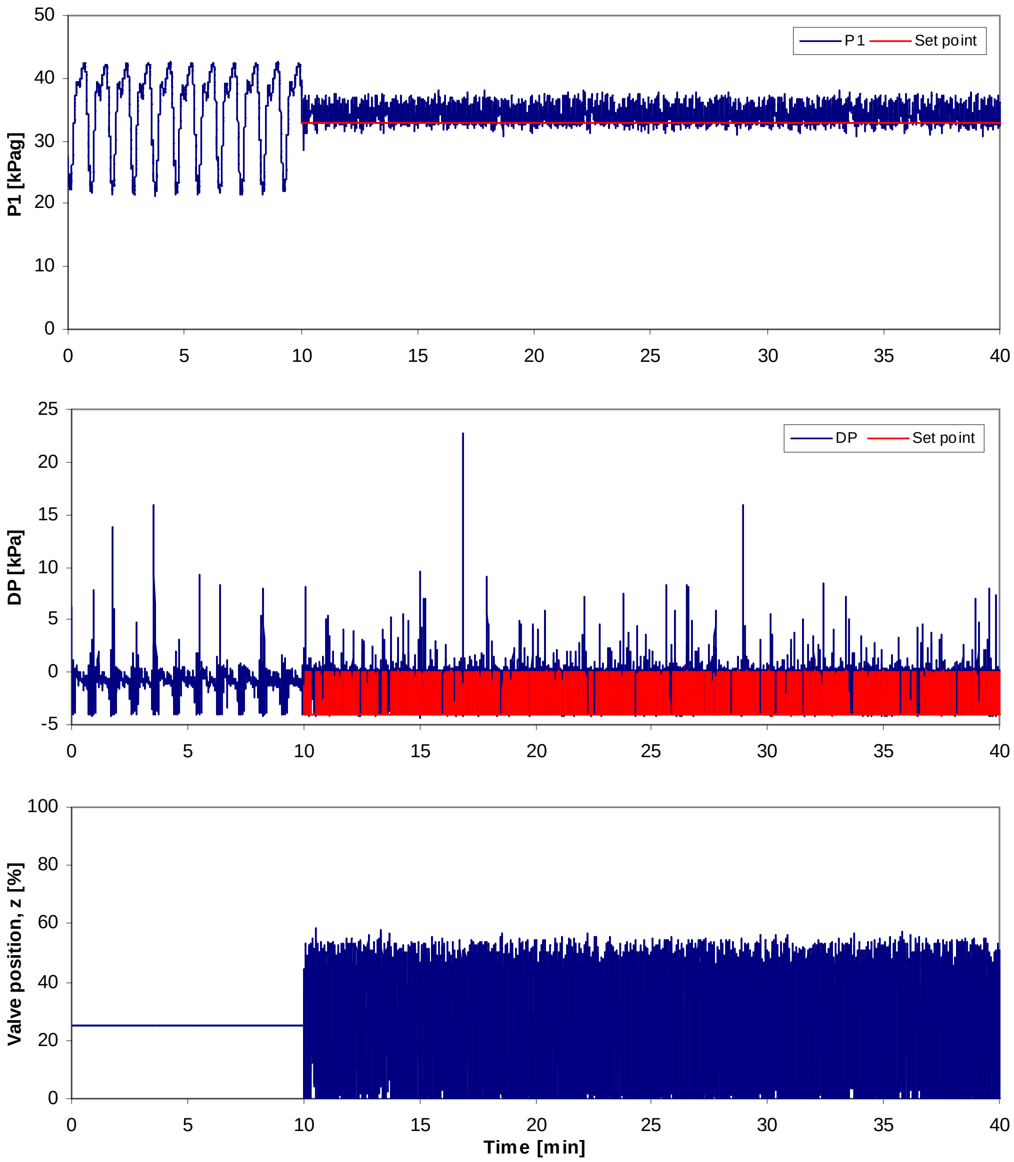

Figure 4.19 Applying cascade control to eliminate the slug flow.

Knowing that the controllers managed to stabilize the system, set-point changes were introduced to the system to see if the controllers could handle that. In the next experiment, set-point changes to both 30 and 36 kPag respectively were examined. Figure 4.20 shows the results. The slug flow is eliminated and the pressure is stabilized for all three pressure set-points. For all the set-points, the true pressure seems to have an offset of around +1.5 kPa to the set-point.

For all the set-points, the valve opening varies between 0 and 50 percent opening. It is worth noticing however that the low boundary is saturated less often for the 30 kPag set-point. The explanation is that the lower pressure in the system results in a higher average valve opening.

Regarding the varying set-point for DP, it seems to vary less for the lowest set-point for P1, and most for the highest set-point for P1.

Yet another remark is that the cascade controller stabilizes the pressure for a set-point of 30 kPag for P1. The simple feedback controller did not succeed in doing so when the venturi was present (section 4.3.3). The cascade controller seems to have broadened the operating range for the P1's set-point compared to the simple feedback controller, but on the other hand introduces more to the valve.

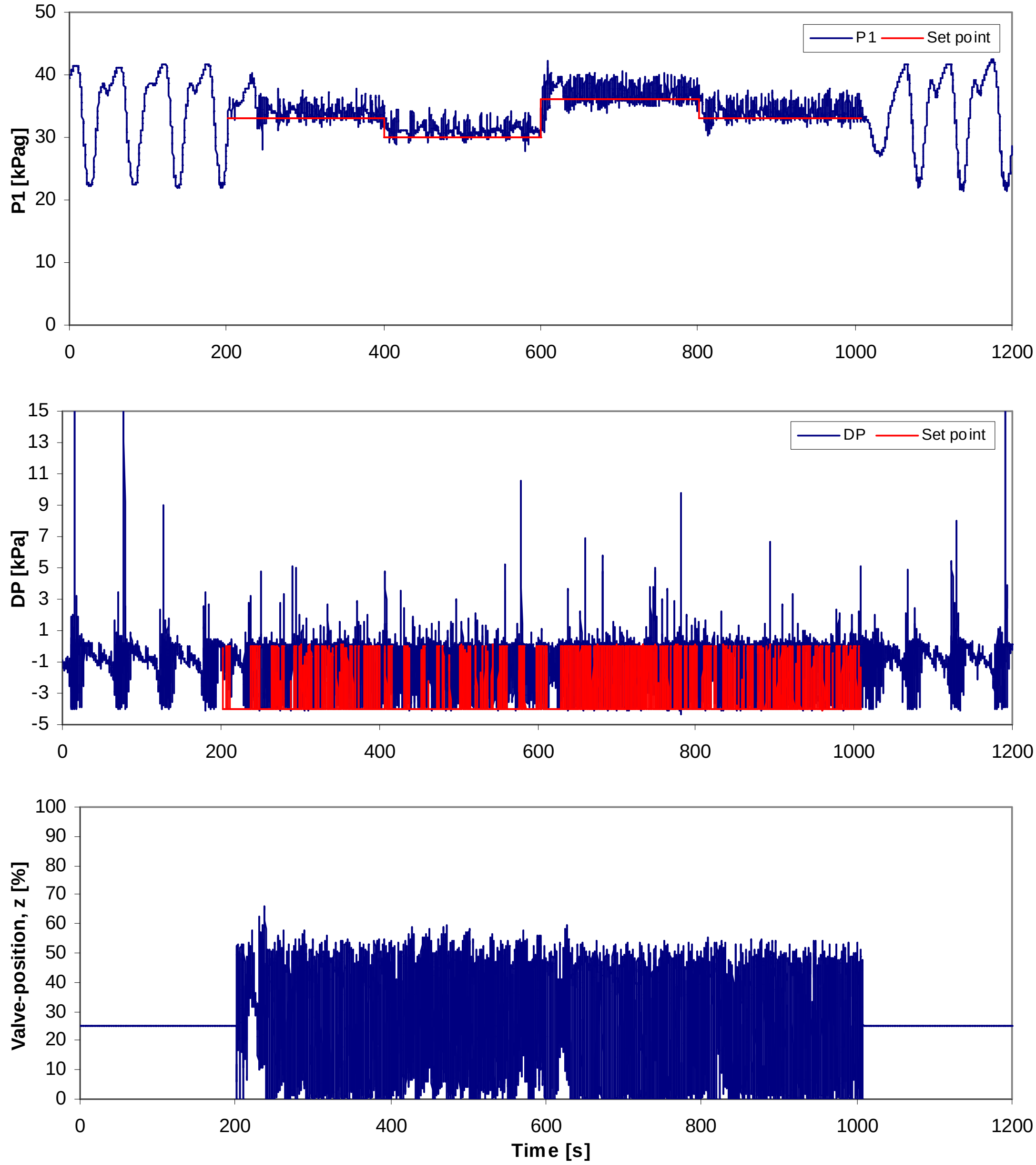

Figure 4.20 The response of the system towards set-point changes for P1.

Finally, the flow rates to the system were varied to evaluate the robustness of the control system. The inflow rate of the air was reduced from 5.7 to 4.7 L/min, before it was reset, while the water flow rate was both decreased and increased from the nominal value of 5.3 L/min. The lowest value was 4.6 L/min and the highest was 6.3 L/min for the water inflow rate. The results are shown in the four charts of figure 4.21.

For all the flow rate variations, no slugging occurs when the controller is on. The pressure P1 stays mainly in the range of 33 to 36 kPag and thus with an offset to the set-point. For the high water flow rates above 6 L/min, the average valve opening seems to increase slightly and saturates less at the low boundary. The controller is therefore robust towards variations in the inflow rates of both water and air. On the other hand, the valve operates in very broad range, and its usage should be reduced.

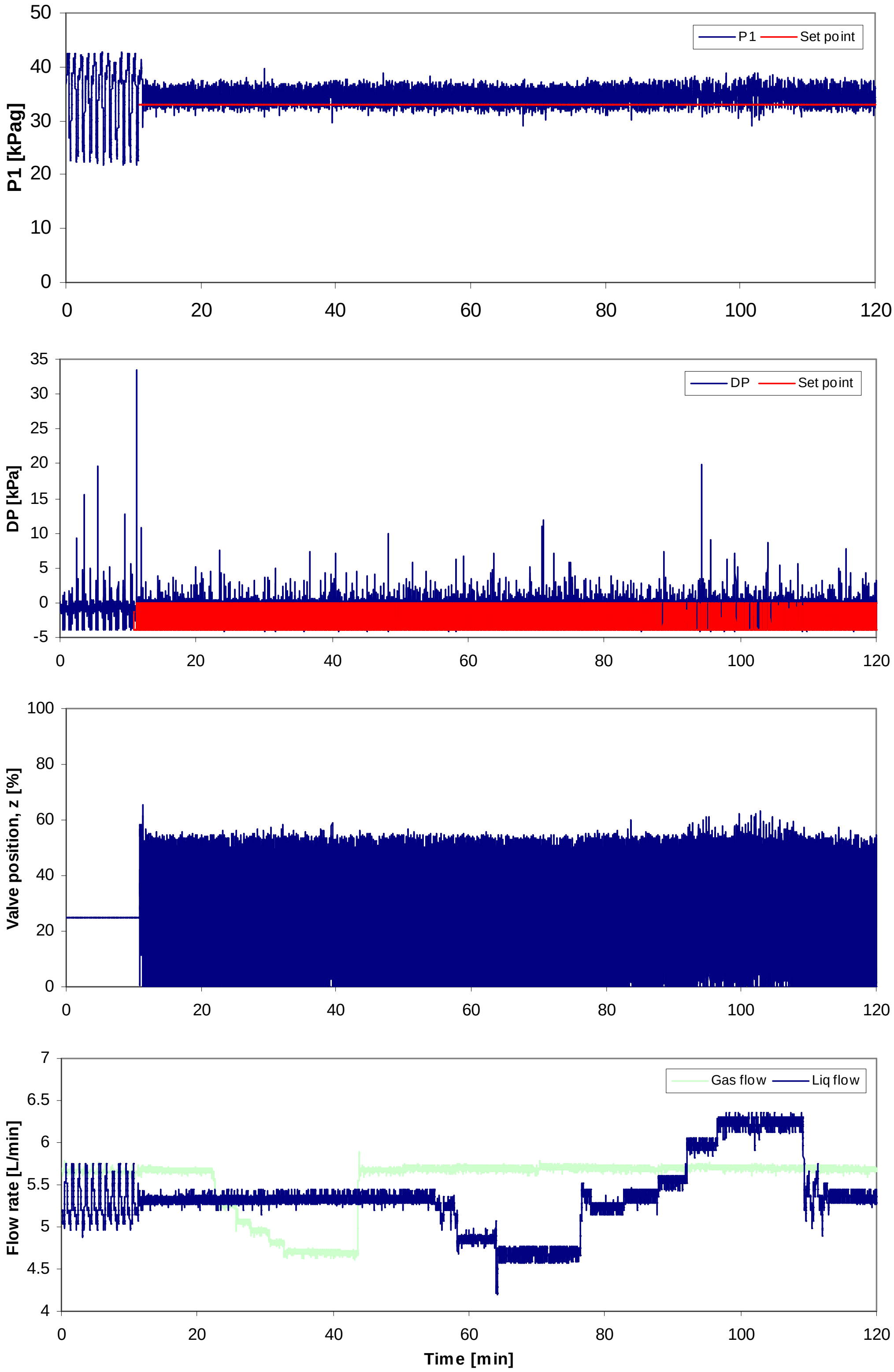

Figure 4.21 Testing the cascade control system by varying the inflow rates.

4.5 Random valve opening

By taking a short look at how the actuator in the previous experiments works, it might seem to be quite random. Therefore, an idea was to try to eliminate the slug flow by sending random signals to the valve. This idea was tested by implementing a random signal generator in the LabVIEW program, instead of a PID controller.

The system was run with a constant valve opening of 25 percent for five minutes, before the random control was implemented. After that, every quarter of a second, a new value for the valve opening was generated. The values were in the range of 0 to a maximum valve opening percent. For five minutes, the maximum value was given as 50 percent, then decreasing by 2 percent every five minutes. In other words, the maximum valve opening would be 50 percent, 48 percent, 46 percent, etc in 5 minutes for each value. This sequence was continued until the maximum valve opening reached a value of 24 percent. The results from this experiment are given in figure 4.22.

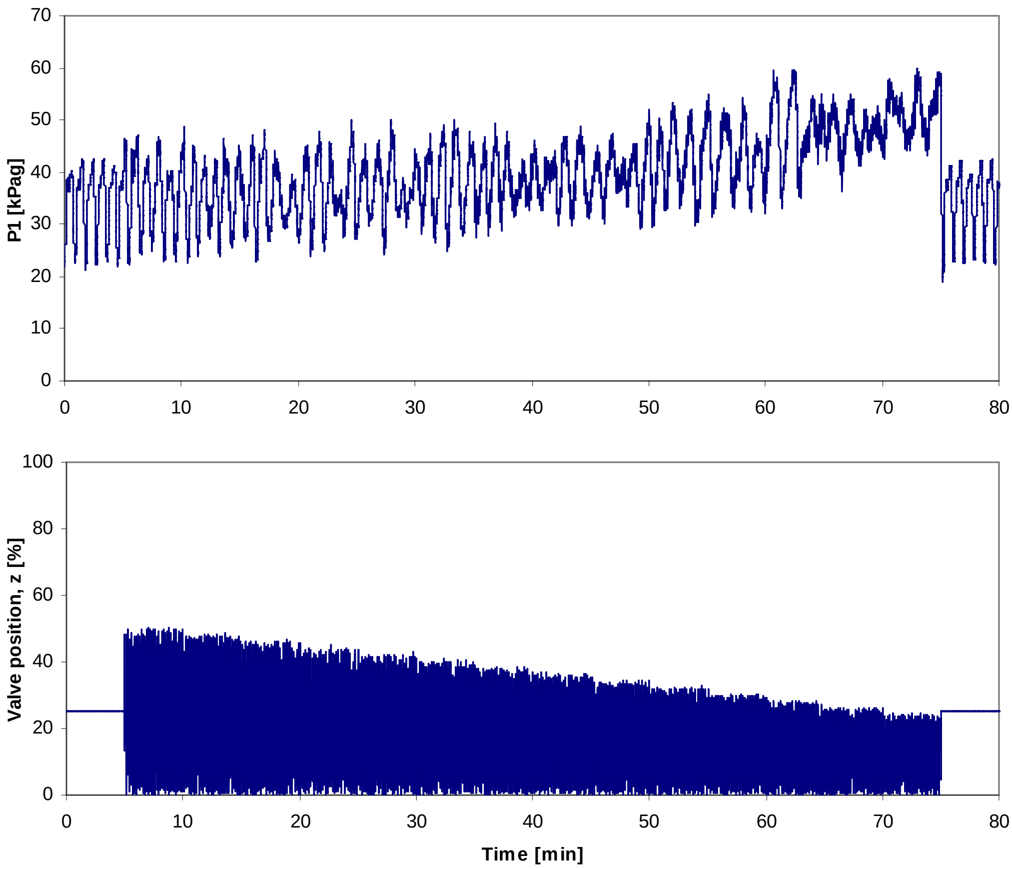

Figure 4.22 The P1 measurement and the valve opening for a random valve control.

As seen from the results, the strategy of having random valve openings failed to stabilize the pressure. The pressure increased as the valve opening was reduced as expected, but none of the valve opening ranges eliminated the slug flow. An explanation of the failure might be that some valve openings counteract the slug flow at that given moment, while the next value for the opening might contribute to increase the slugging behaviour. Overall, the slug flow is not eliminated.

Varying the time between each signal will change the time-scale of the valve movements, and perhaps give other results. Another solution might be to operate with a different valve opening range, for example between 20 and 30 percent, and perhaps obtain some other results.

4 Future work

This project has been looking into some strategies to eliminate slug flow by applying a control system. Further investigation of the slug flow phenomenon as well as strategies to eliminate this flow pattern is still needed. Some ideas for future work on the Miniloop are given below.

- New open-loop measurements where the inflow rates are not kept constant should be performed. As the valve is choked and the pressure is increasing, the inflow to the system will decrease. It would be interesting to see how the flow rates are affected by the pressure increase.

- A new attempt to control the system by measuring P3 should be carried out, in order to find out if it really is possible to control the system from that position.

- Going downstream the riser, there is a specific location between P1 and P4, where a single pressure measurement, no longer will be able stabilize the system. A series of feedback control experiments using pressure measurements at different locations on the riser should be carried out in order to find the critical location.

- The experiment with the cascade control structure, using the square root of DP of the venturi in the inner loop can be performed in a slightly different way. Instead of using P1 as the measurement for the outer loop, P2, P3 and P4 respectively can be utilized. Again, it would be interesting to see how far up the riser the pressure measurement can be, before the control strategy turns unsuccessful. Perhaps a topside pressure measurement in the outer loop could stabilize the system. In the case of using only topside measurements to control the system, an implementation of the control structure in real life is more feasible.

- Trying to eliminate the slug flow by using a random valve opening strategy was not successful. It is however worth a try to see if a different time interval between the random signals could give other results. Also, varying the range for the random signals might result in a different response in the process.

- In the Miniloop, the mixing point for the air and water is at the same height as half way up the riser. The geometry of the system could be changed to resemble a real pipeline-riser system better. The results from experiments might be different and perhaps more reliable compared to real system then.

- Open-loop experiments with varying air and water inflow ratios can be carried out, in order to find out which ratios lead to slugging. There might be only certain ratios that cause severe slugging. Such experiments can give valuable information about how for example gas lift can be applied to eliminate slugging.

- The experiments giving good results, should be implemented on a larger, pilot-scale test apparatus. In this way, it is possible to find out how the scale-up of the results from the Miniloop works out on a larger scale.

5 Conclusions

The open-loop measurements showed that the critical valve opening where slug flow is eliminated is 13 percent. At higher valve openings, slug flow will occur, but can be eliminated by anti-slug control.

Applying feedback control using pressure measurements to eliminate slug flow was successful. P1, the pressure measurement farthest off the control valve gave the best results, and as the measurement approaches the control valve, the results get poorer. P2 as a process measurement for the controller stabilized the system, but with the valve operating over a wider range than for P1. In this project, the controller using P3 as the process measurement, failed to stabilize the system.

The testing of the venturi showed that the differential pressure, DP, in the venturi varied with the flow rate of the air and water respectively. The venturi could therefore be used for control purposes to give an indication of the mass flow rate through the system. Some additional friction is introduced to the system by the venturi, as it increased the pressure in the system with around 2 to 3 kPa.

Implementing a cascade controller using the square root of DP in the inner loop and P1 in the outer loop made it possible to eliminate the slug flow. The valve usage was higher for the cascade controller than for the feedback controller with the P1 measurement, but lower than for feedback control with P2 being measured. On the other hand, the cascade controller handled a wider range of set-points for P1, compared to the feedback controller.

An attempt to tame the slug flow by having random valve openings failed. The pressure was not stabilized and the slug flow was therefore still dominating.

References

1. Havre, K., Stornes, K., and Stray, H., *Taming slug flow in pipelines*, ABB review **4**, 2000, 55-63.

2. Bårdsen, I., *Slug regulering i tofase strømning, Eksperimentell verifikasjon*, NTNU, 2003.

3. Storkaas, E., Skogestad, S., *Controllability analysis of two-phase pipeline-riser systems at riser slugging conditions*, Control Engineering Practice **15**, 2007, 567-581.

4. Storkaas, E., Skogestad, S., *Stabilization of severe slugging based on a low-dimensional nonlinear model*, NTNU, 2003.

5. Søndrol, M., *Anti-slug regulering. Eksperimentell uttesting og verifikasjon*, NTNU, 2005.

6. Dahl-Olsen, H., *Eksperimentell anti-slug regulering basert på topside-målinger*, NTNU, 2006.

7. Storkaas, E., *Stabilizing control and controllability: Control solutions to avoid slug flow in pipeline-riser systems*, NTNU, 2005.

8. Sivertsen, H., Skogestad, S., *Anti-slug control experiments on a small-scale two-phase loop*, European Symposium on Computer Aided Process Engineering **15**, 2005.

9. Skogestad, S., Postlethwaite, I., *Multivariable Feedback control, 2nd ed.*, John Wiley & Sons, 2005.

10. Seborg, D. E., Edgar, T. F.; Mellichamp, D. A., *Process Dynamics and Control, Second Edition*, John Wiley & Sons, 2004.

11. *Introduction to LabVIEW™ and Computer-Based Measurements Hands-On Seminar, January 2007 Edition*, National Instruments, 2007.

12. Sivertsen, H., Skogestad, S., *Experimental results using only topside measurements from a small-scale two-fluid lab loop* (article in progress), NTNU, 2007.

13. Fjalestad, K., Mjaavatten, A., Aaheim, R., Schüller, R., *Simple equation for two-phase flow rate prediction through chokes*, Norsk Hydro Research Centre, 2007.

14. Olsen, H., *Anti-Slug Control and Topside Measurements for Pipeline-Riser Systems*, NTNU, 2006.

Appendix A Signal data

Table A.1 Overview of the signals from each instrument.

Analog Input/Output	**Channel**	**Signal range**	**Instrument**	**Measurement Rrange**
AO-210 @1	0	0-10.2 V ~ 4-20 mAps	Control Valve (CV)	0 – 100 %
AI-100 @2	0	0 - 5 V	Gas flow Meter	0 -10 l/min
AI-100 @2	1	4 - 20 mAps	Liquid flow Meter	
AI-100 @2	2	0.2 – 4.5 V	Pressure sensor mixing point, P1	0 -100 kPag
AI-100 @2	3	0.2 – 4.5 V	Pressure sensor 2-3 m after mix, P2	0 -100 kPag
AI-100 @2	4	0.2 – 4.5 V	Pressure sensor 5 m after mix, P3	0 -100 kPag
AI-100 @2	5	0.2 – 4.5 V	Pressure before control valve, P4	0 -100 kPag
AI-100 @2	6	0.2 – 4.5 V	Pressure diff. venturi, DP	0 -100 kPag
AI-100 @2	7	1 – 5 V	Slug sensor (S2) top side	-

Appendix B User guide for the Miniloop

The following start-up and shut-down procedures should be utilized as a guidance to use the Miniloop in a correct manner.

Start-up

1. Turn on the computer and open the LabVIEW program used to control the Miniloop.
2. Ensure that the valves V1 and V3 are completely closed.
3. Connect the power to the FieldPoint modules by using the fuse switch inside the electrical locker.
4. Turn the LabView program into run mode.
5. Open up the control valve using the running program.
6. Connect the power to the pump.
7. Turn valve V2 and V3 in order to reach the desired air flow.
8. Turn the valve V1 until the desired water flow is achieved.

Shut down

1. Shut off the water circulation, using valve V1.
2. Turn off the air supply, using valve V2 and V3.
3. Turn off the pump by disconnecting its power supply.
4. Stop the running LabVIEW program.
5. Turn off the FieldPoint modules with the fuse switch in the electrical locker.
6. Close LabVIEW and shut down the computer.

Some important remarks

- If the water circulation valve is opened before the air supply, backflow of water into buffer tank 2 will occur. To prevent this, the air supply must always be turned on first and shut down after the water supply.
- The pump will be damaged if it is supplied with air. There should therefore be no air in the pipe between the reservoir tank and the pump when the pump is turned on. During operation, the water level in the water tank should be higher than the outlet to the pump to prevent air from reaching the pump.
- Every time the FieldPoint modules are turned off, the control valve will automatically close. If the control valve is not opened before air and/or water starts flowing in the Miniloop, pressure will build up in the system, harming the equipment, resulting in leakage. Therefore it is very important to always open the control valve before turning on the air and water supply.

Appendix C Data sheets for the instruments

This section contains the data sheets for the instruments used in the Miniloop.
A brief description of the instruments is given in chapter 3.1.