

Pressure-Flow Network Modeling

TTK 4550 Project report

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Abstract

The project is motivated by desire to investigate the reason of at times large oscillations under loading of the liquid propane to the tankers at the Kårstø processing plant. This paper describes procedure of modeling of loading equipment which is in use. The flow network is build by alternated pressure nodes and flow elements. Where pressure nodes represent junction points while flow elements are valves and pipes. Flow is given by the pressure difference between two nearby pressure nodes. At the end the simulation results is compared with measurements from the real plant.

Preface and Acknowledgements

The following report is the result of the Specialization Project TTK4550. The project has been conducted during the first semester of the 5th year of Engineering Cybernetics at Norwegian University of Science and Technology - Trondheim, Norway.

I would like to thank my supervisor, professor Sigurd Skogestad for continuously guidance and motivation. Also I would like to thank Marius Støre Govatsmark for support and very interesting and motivational trip to Kårstø.

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Chapter 1

Introduction

1.1 General information about Kårstø

Kårstø processing plant is situated at the west coast of Norway in Tysvær, south for the Haugesund. It receives natural gas from several fields at the Norwegian and North seas. Gas comes through the pipeline and get's separated into sales gas and several liquid products at the plant. Sales gas transports further to Europe through Europipe2. Liquid products like ethane, propane, isobutane, normalbutane, naphtha and stabilized condensate get stored in the storage tanks before they loaded to the tankers and shipped to different parts of the world. On average, there is more than 2 ships per day with a LPG-products sent from Kårstø.

1.2 Description of the loading equipment

The liquid is transported by two pumps from storage tank to the the measurement station and there after to the ship. The measurement unit provides overflow protection and measurement. Main flow control valve is located after it. During the loading, there is a significant variation in the loading rates. In the beginning there is low rate (<100 m³/h). Then loading rate increases stepwise to the higher rate (>3000 m³/h) where most of the transfer take place. At the end, loading rate reduced stepwise back to the low rate. Pressure at the different places of the equipment varies a lot under different loading rates. It is desired that the major pressure loss should be across the main control valve(FV-valve). In such way it will spare the inventory at the measurement station.

Proving of the flow rates is done by connecting each single loop in the measurement station to the proving loop. Which is basically a liquid tank. By recording the time it takes to fill this tank, it is possible to verify the flow rate of the loading. When the proving procedure happening there is an extra pressure drop across the test loop. To maintain a constant flow rate, the pressure must increase. This is done by decreasing the valve opening in the second open loop in the measurement station.

The sketch of the model, figure 1.1. It is a simplified model with all essential parts of the loading equipment. The liquid transported by pump from the storage tank, pass through the measurement station (FMC1-3), further through the flow control valve to the tanker. FMC 1-3 is a three parallel loops in the measurement unit. Real equipment contains five parallel loops, but only two of which can be active at the same time. That's why it is only three of them sketched in the figure. Number 1 and 2 have throughput of 1800 m³/h while FMC3 has throughput of 400 m³/h. The last one is used under start and closure procedure when the total flow rate is under 400. Maximum rate through the system is 3600 m³/h which is supplied by the two pumps in the real life.

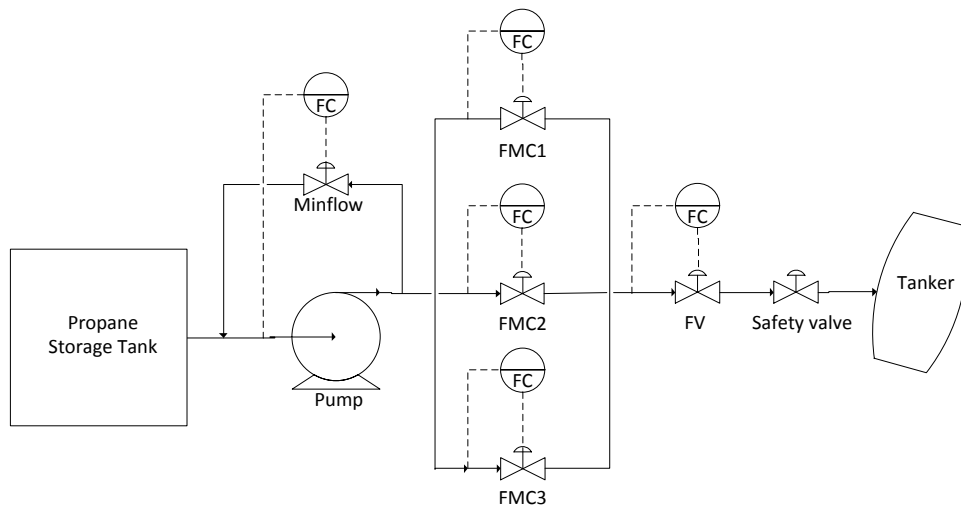


Figure 1.1: Simplified model

There is two alternative ways to control the flow rate. Alternative 1: Flow rate is controlled by the measurement station itself. The setpoint for the

throughput is set to the FMC1-3 controllers. FV-valve is adjusted manually to compensate for the large pressure drop across the measurement unit. Possible significant pressure drop is the disadvantage with such structure. Alternative 2: Flow rate is controlled by the FV-valve. FMC1-3 is fully open(60%) and provides the overflow protection for the active loops. In case of the overflow, the FV and FMC-valves can have different setpoints and counteract each other. FMC-controllers is tuned to be faster than FV to avoid the saturation of FV.

1.3 Objectives

Sometimes one can observe significant oscillations under loading which can be caused by existing control structure. The purpose of this project was to develop a model of such loading equipment. After that simulate its behavior with current control structure at the different flow rates. Further, the model can be used to investigate and suggest new control structure.

1.4 Structure of the rapport

This chapter gave insight into the principle of operation of the loading equipment at the Kårstø processing plant. Next chapter gives a description of the modeling procedure of a flow-pressure network components. The following chapter describes building of the overall model of the loading equipment. Then there is a chapter with simulation results, followed by the discussion.

Chapter 2

Pressure-flow network model

The idea was to create a palette of units which can be used in the Simulink later to building the overall model. This section intended to introduce into concepts of block building. The main idea is to divide the model into N cells. Where each of them contains a pressure node and a flow element. Similar to the start of the Rhie-Chow Interpolation Method (Rhie & Chow 1983). Pressure node is a dynamic element where pressure for the current point is calculated based on the flow into and out of the node and the mass inside the node. Flow element is a straight static where the current flow calculates based on the pressure difference between two pressure nodes. The overall model can be seen as a one dimensional grid of all cells combined together with a boundary conditions given at the both ends, figure 2.1. System by it self is very stiff and has very fast and small dynamics. Velocities and pressures in the flow network varies a long the flow direction only and it is assumed that there is no vapour generation within volume. In general the

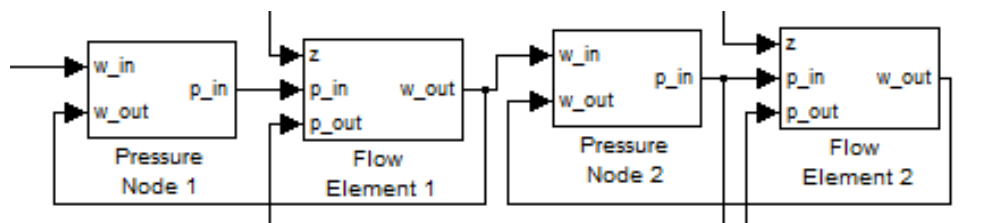


Figure 2.1: Flow-pressure network

pressure nodes can be seen as a junction points between the flow elements. The overall model must have structure of alternating pressure nodes and flow elements.

2.1 Basis elements: Pressure node

Pressure node is a dynamic element. Model of it is based on principle of compressibility of fluid. As when the pressure increases the mass inside the valve or a pipe should increase too. Relationship is given through a compressibility coefficient ϵ and shown in 2.1. Equation with two unknown p and m . Mass is found by the integration of the difference between the flow into and out of the valve. Then pressure p at the current node can be found. There is necessary to choose a reference flow to decide m_0 and p_0 . The reference mass (m_0) depends on the assumed volume of the valve. Pressure (p_0) is decided by reading of the pressure measurements from the true equipment at the constant flow rate of 3500 m³/h.

$$\frac{m - m_0}{m_0} = \epsilon \frac{p - p_0}{p_0} \quad (2.1)$$

where:

- m = liquid mass
- m_0 = liquid mass at the chosen reference flow
- ϵ = relation coefficient of compressibility of liquid
- p = current pressure
- p_0 = pressure at the chosen reference flow

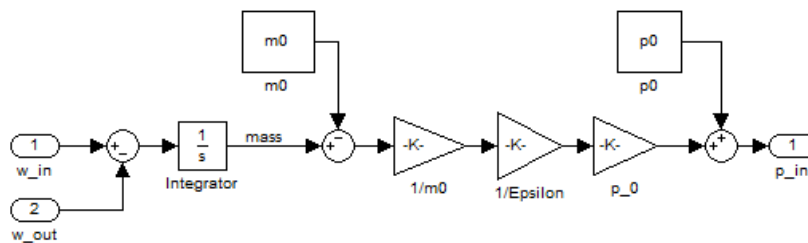


Figure 2.2: Pressure Node in Simulink

2.2 Basis elements: Flow element

Flow element is a pure static and represents valves and pipes in the system. The flow through the valve is given by

$$q = C_v f(z) \sqrt{\frac{\Delta p}{\rho}} \quad (2.2)$$

where:

- C_v = flow coefficient. The performance of the valves can be compared by their C_v coefficients.
- $f(z)$ = valve characteristics
- Δp = differential pressure across the valve
- ρ = density

Flow element is created in Simulink as a MatLab function with this parameters as inputs. p_{in} is a pressure at the inlet and comes from previous pressure node. Next node defines pressure at the outlet p_{out} of the valve.

2.2.1 Valve characteristics

There are three types of valve characteristics, figure 2.3.

- Linear - flow rate is proportional to the valve lift. $f(z) = z$
- Equal percentage (logarithmic characteristics) - valve lift increase the throughput with a constant percentage of the previous flow. $f(z) = R^{z-1}$
Rangeability R is defined as a ratio of the maximum to minimum controllable flowrate and generally given by the valve producer.
- Fast opening - valve type which gives large change in the throughput by small valve lift from the closed position. Often used for the on/off operations. $f(z) = z^{1/\alpha}$

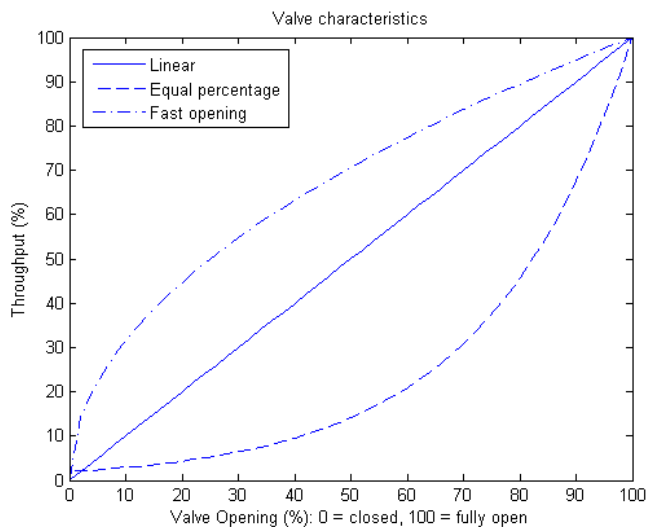


Figure 2.3: Valve Characteristics

2.3 Pump

The pump block has defined pressure-flow curve, with a fixed speed. Model used in this project is very simple. The curve was approximated by a Matlab function *polyfit()* and implemented in Simulink. Matlab code for the pump can be found in appendix D.2. Pressure p_{in} is given by a boundary condition while p_{out} comes from the following pressure node. Pump block takes the difference in pressure and return appropriate flow value from characteristics. Pump characteristics was extended to handle lower flow rates, appendix C.1.

2.4 Valve opening dynamics

It takes time to open any valve. That brings the delay in control and important dynamics in the system. Firstly it was considered to use a actuator model as suggested by (Hangos & Cameron 2001) on page 77. It is generally based on force balance of all forces applied to the actuator. Resulted model will be a second order differential equation. Since the most of the modeling and implementation take place in Simulink there is possible to model opening dynamics in a different way. The derivative of valve lift z is opening speed. By setting the boundary on the opening speed and then integrate it back, it is possible to model the same effect, figure 2.4. First saturation block set the boundary on the opening speed $-\frac{1}{\tau} \leq \dot{z} \leq \frac{1}{\tau}$ where τ is opening time constant. Second saturation block represent the physical limit between 0 and

1, respectively for the closed and fully open valve. Constant τ is set to 10 in the simulations.

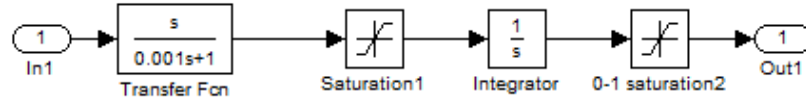


Figure 2.4: Opening dynamics

2.5 Controller

PID controller is widely used feedback controller. It is used in industry to control flow rates, temperatures, pressures, etc. It uses the error between setpoint and measurement as an input. The output is decided by the three terms, P, I and D. Proportional, integral and derivative. P-term produce output proportional to the error. I-term remove the steady state error. D-term is used to suppress fast changes in the deviation. Mostly, the D-term is not used in practice since it is quite sensitive to the measurement noise. Transfer function for the PI-controller: $u = K_c \left(\frac{T_i s + 1}{T_i s} \right) e$. Simulink block can be found in the appendix B.1

2.6 Selector

Selector receives measurement of the current flow and decides which loop/-valve in the measurement station should be fully open (60%). If flow rate is under 400 m³/h - third loop is open. If flow rate larger than 400 and less then 1800 the first loop is open. When flow rate larger 1800, first and second loops are open. There is added the valve opening dynamics as described in section 2.4 to selector controllers. Simulink block, can be found in appendix B.2

2.7 Summary

The structure of the model has been described in this chapter and single elements was created.

Following rules for the modeling must obey:

Pressure modules can be connected only to flow modules. Flow modules can be connected only to pressure modules. Two valves cannot be connected directly but must have a pressure node between them.

Despite of the introduced dynamics in the pressure nodes, the system is very stiff and has very fast response. Simulation of such sharp systems must use proper algorithms like ode15s in Matlab instead of the ode45.

Chapter 3

Application to Kårstø network

The implementation was done through the whole project period by building the small parts and testing the system on the way. Overall system, figure 3.1 was build from the blocks presented in previous chapter. Start and end of the pressure-flow network is defined by the boundary conditions. On figure it is storage tank and tanker with pressure values in Pa. Figure, can also be found in appendix A.1. Specific equipment parameters such a pipe lengths, diameter, C_v constants stored in the main.m file.

Model structure follow the principle of alternating pressure and flow modules. It starts with a pressure boundary condition. Then there is a pump, which is a flow element. Followed by the pressure node and so on, until the last flow element and the pressure boundary condition on the other side is reached. Connection wires between blocks can represent flows, measurements and control signals.

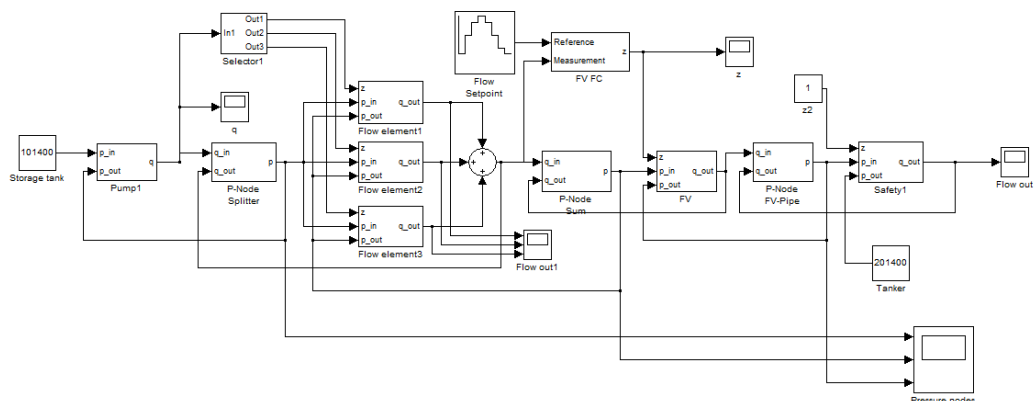


Figure 3.1: Overall model

The equation to calculate flow rates was changed to 3.1. It is an equation that suits the definition of the flow coefficient C_v used at the real equipment, such that the given C_v 's can be used directly.

$$q = \frac{C_v}{11.7} \sqrt{\frac{\Delta p}{SG}} \quad (3.1)$$

where:

- Δp - differential pressure across the valve [kPa]
- SG - specific gravity ($\rho_{propan}/\rho_{H_2O}$)

There are spend a lot of time to connect the model and try out different blocks to receive values close to measurements from real equipment. The choice of the m_0 and p_0 inside the pressure nodes is challenging to observe. The p_0 was read from the measurements of the real equipment while m_0 was found by calculating the volume of the valve together with some nearby pipe element. The choice of this constants was made separately which maybe not quite correct, probably. Since there is a relation between mass and pressure inside the pipelines which depends on the assumed length. It was not managed to implement the minflow valve which has strong influence on the system at low and medium flow rates. Also anti-wind up is not implementer in the controllers. Model implemented with only one pump which has max flow rate of the 1750 m³/h while the real equipment contains two such pumps in parallel. Thats why the C_v constant for the main control valve is divided by 2. This is also the reason that only two of three loops in the measurement station is in use under simulations.

Chapter 4

Results

The model was simulated with a stepwise increase in the flow rates. Pressures at the different pressure nodes was acquired and is summarized in the table 4.1. Table 4.2 contain pressure measurements from the real equipment. Splitter pressure node is located between the pump and measurement station(FMC). Sum node is located between FMC and main control valve (FV). End node situated after the FV-valve. Values in tables are given in bar.

Flowrate	Splitter node	Sum node	End node
Low	15	14	2
Medium	13	8	2,5
High	10	3,5	2,8

Table 4.1: Simulated

Flowrate	Splitter node	Sum node	End node
Low	12,8	12,5	1,5
Medium	10,5	9	3,6
High	9	6,5	6,2

Table 4.2: Measurements real equipment

As it can be seen from the tables, the pressure values and pressure drops are higher in the simulated model. Not implemented minflow valve is probably the reason for that at the low rates. The same can be partly applied for the medium flow rates. At the same time it is obvious to see that high pressure drop take place after the main control valve in the real equipment.

It was tried to implement into model by decreasing the flow coefficient of the safety valve. And by introducing the pressure drop due to the friction in pipes. That together gave an increase to about 3.5 bars at the outlet which is still too low value.

Following elements is created:

Flow modules: valve, pump which calculates flow, by given inlet and outlet pressure.

Pressure node. Calculates pressure, by given input and output flow rates.

Following rules must be obeyed: Only pressure modules can be connected to flow modules. Only flow modules can be connected to pressure modules. Two valves cannot be connected directly. They must have a pressure node between them.

Chapter 5

Discussion

It took time to get started with the project and get first results. The literature search on my own in the beginning gave a lot of reading materials without any good specific and comparable examples to the problem. With a better understanding of the working principles in the late phase of the project there was discovered several scientific articles with related material to the topic of pipeline modeling. Among others the review article about gas pipeline modeling techniques. Although the search for the relate literature was done from the early beginning. Such article could help a lot in the start phase. Further work is considered to be an implementation of the minflow valve, analyses and implementation of the control structure, use of the existing components to model building. I would try to read more about this topic on holiday. Now with a better understanding of the working principles I would considered to implement the code in the s-function in Matlab.

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Appendix A

Overall model in Simulink

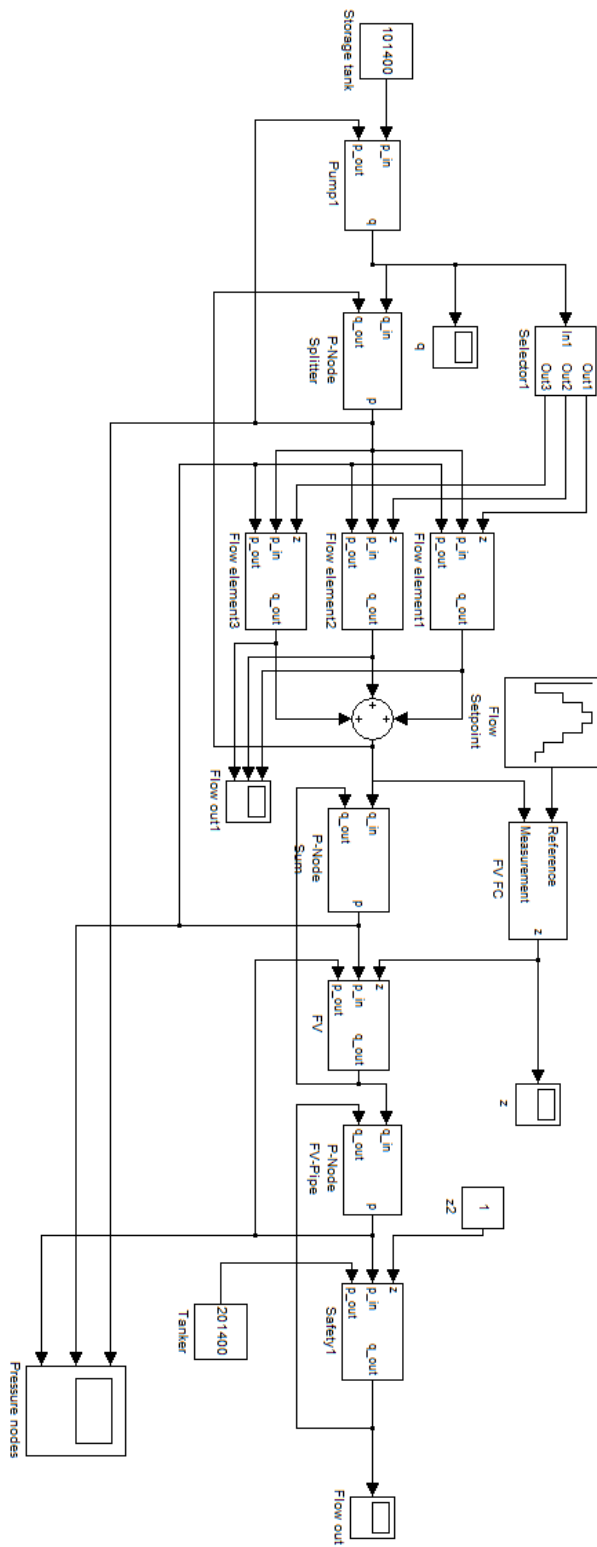


Figure A.1: Overall model

Appendix B

Simulink blocks

B.1 PI controller

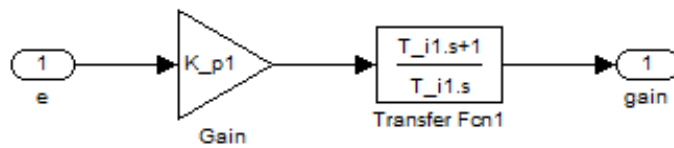


Figure B.1: PI controller

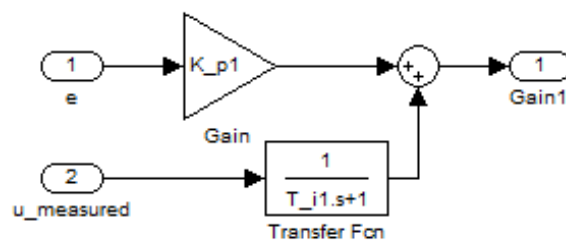


Figure B.2: PI controller w/ anti-windup

B.2 Selector

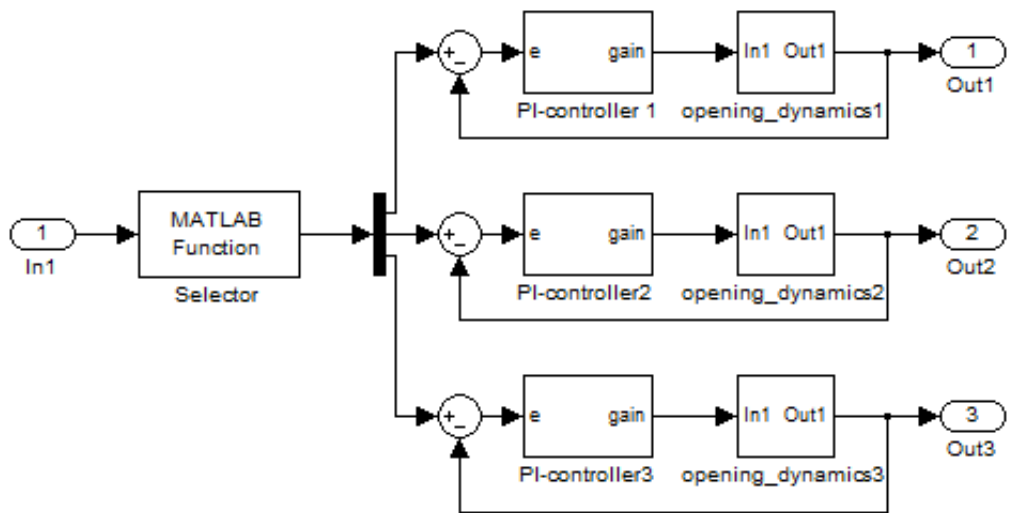


Figure B.3: Selector

Appendix C

Plots

C.1 Pump curve

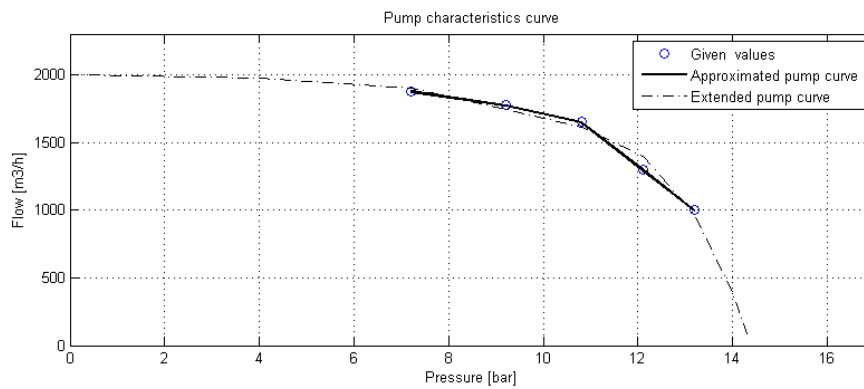


Figure C.1: Pump curve

C.2 Measurements from real equipment

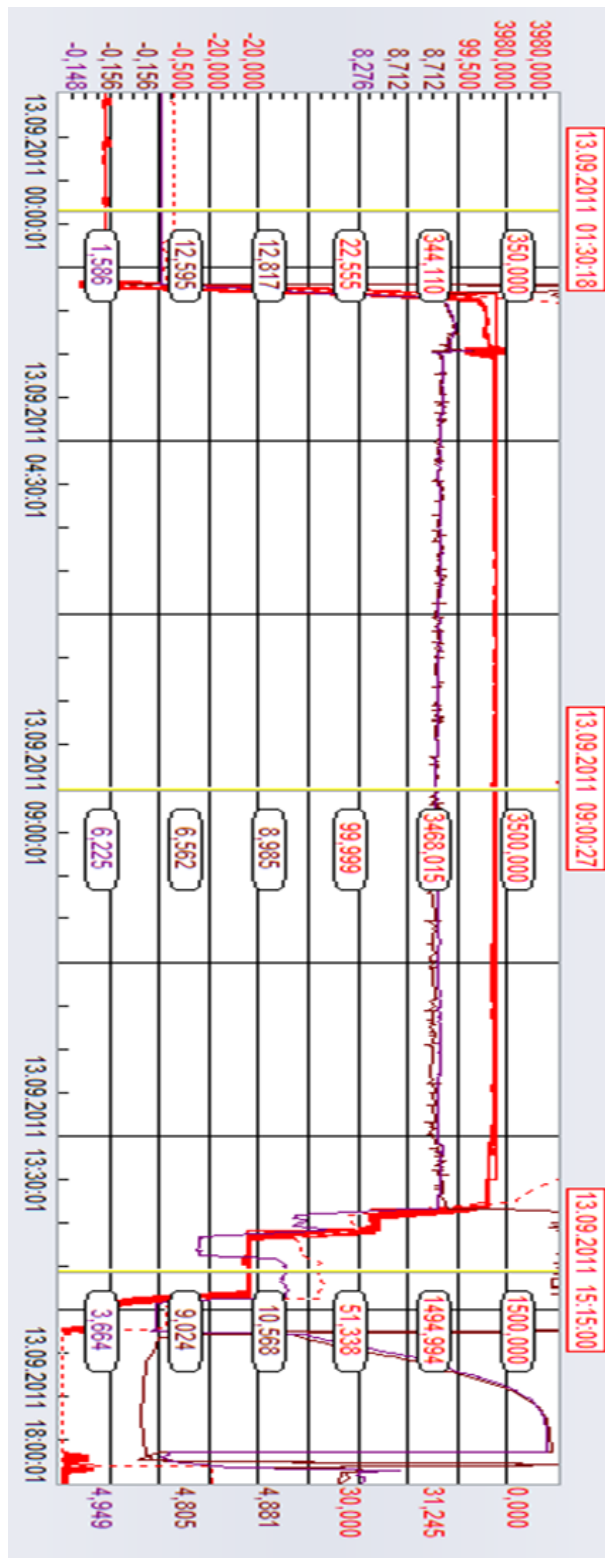


Figure C.2: Measurements from real equipment

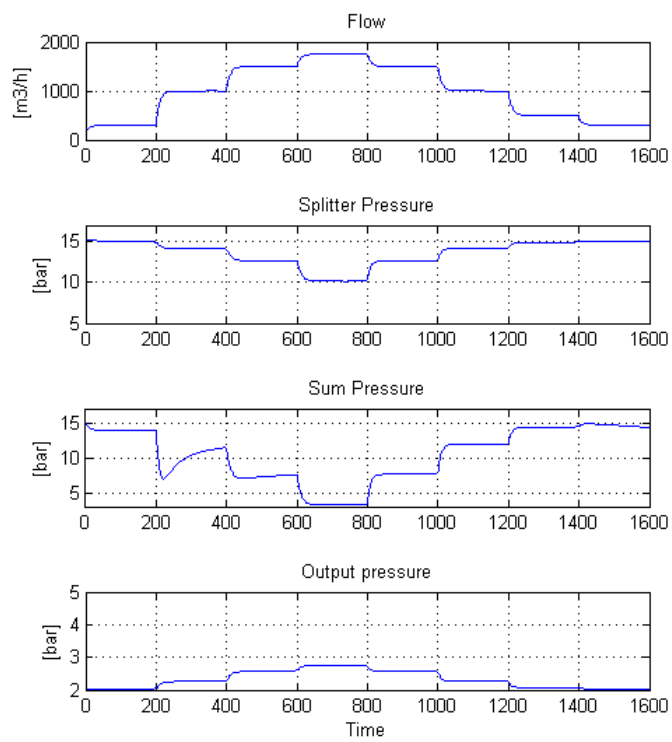


Figure C.3: Simulation of overall model

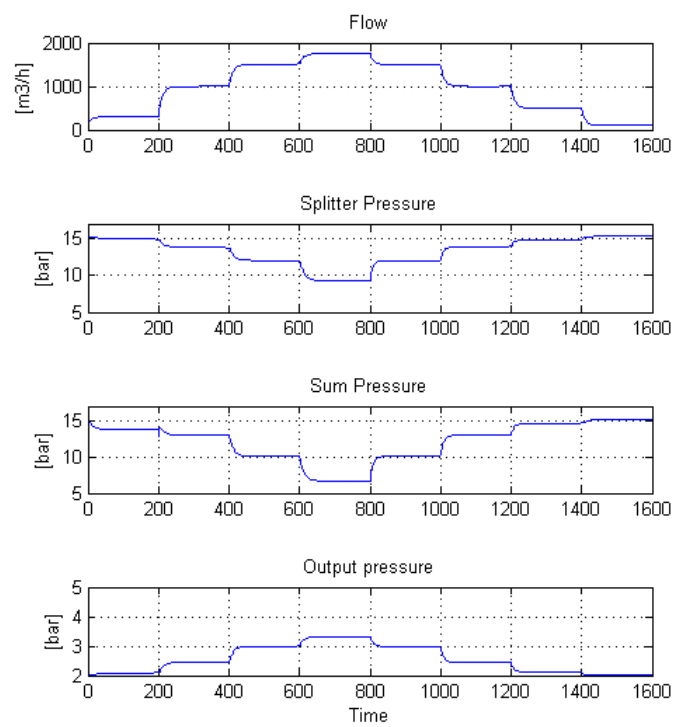


Figure C.4: Simulation with extra pressure drop at the end

Appendix D

Matlab code

D.1 Main

```
clc;
clear all;

controller;
%% DATA
global rho;
global fric_fac10;
global fric_fac20;
global d_pipe10;
global d_pipe20;
global A_pipe10;
global A_pipe20;

rho=580; %kg/m3
% fric_fac10=0.0283; %friction factor 10 inch pipe
% fric_fac20=0.03; %friction factor 20 inch pipe
d_pipe10=10*0.0254; %diameter for 10 inch pipe
d_pipe20=20*0.0254; %diameter for 20 inch pipe
A_pipe10=pi*(d_pipe10/2)^2; %Areal for 10 inch pipe
A_pipe20=pi*(d_pipe20/2)^2; %Areal for 20 inch pipe

Epsilon=0.001;
p_storage=101400;
p_tanker=201400;
```



```

%% Minflow valve
fprintf( 'Minflow□valve ')
Cv_minflow=400;

%% %% Pressure node: Pump-Pipe
% fprintf( 'Pressure node: Pump-Pipe ')
% L_pump=2.0;
% A_pump=A_pipe20;
% m0_pump=rho*A_pump*L_pump
% p0_pump=9*10^5;

%% Pressure node: Splitter
fprintf( 'Pressure□node:□Splitter ')
L_splitter=2.0;
A_splitter=A_pipe20;
m0_splitter=rho*A_splitter*L_splitter
p0_splitter=9*10^5

%% Measurment unit values
fprintf( 'Measurment□unit ')
Cv_mUnit=1000;
Cv_mUnitSmall=400;

%% Pressure node: Sum
fprintf( 'Sum:□Pressure□node ')
L_sum=2.0;
A_sum=A_pipe20;
m0_sum=rho*A_sum*L_sum
p0_sum=6.5*10^5

%% FV-valve
fprintf( 'FV-valve ')
Cv_FV=2700;

%% Pressure node: FV-Pipe
L_FV=13;
A_FV=A_pipe20;
m0_FV=rho*A_FV*L_FV
p0_FV=6.5*10^5

%% Pressure node: End Pipe

```

```

L_pipe=10;
m0_pipe=rho*A_pipe20*L_pipe
p0_pipe=6.82*10^5;
%% Safety valve
fprintf(' Safety valve ')
Cv_safety=1800;
d_safety=20*0.0254;
L_safety=1.3;
A_safety=(pi)*(d_safety/2)^2;
m0_safety=rho*A_safety*L_safety

```

```

%% %% EndPipe
% p0_endPipe=6*10^5;
% d_endPipe=20*0.0254;
% L_endPipe=20;
% A_endPipe=(pi)*(d_endPipe/2)^2;
% m0_endPipe=rho*A_endPipe*L_endPipe
% Cv_endPipe=5000

```

D.2 Pump

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                               Pump module                               %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Returns flowrate from a given pressure differential. %
%
% originally given characteristics curve (pressure-flow)
% P_pump=[13.2 12.1 10.8 9.2 7.2];
% V_dot=[1000 1300 1650 1774 1876];
% extended to handle lower flow rates
% P_pump=[14.3 14 13.2 12.1 10.8 9.2 7.2 4 0];
% V_dot=[0 500 1000 1300 1650 1774 1876 1980 2000];
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

function [w_out] = pump(u)
global rho;
dp=u/10^5;
P_pump=[14.3 14 13.2 12.1 10.8 9.2 7.2 4 0];
V_dot=[0 500 1000 1300 1650 1774 1876 1980 2000];
polyn = polyfit(P_pump,V_dot,5);
n=length(polyn);

```

```

flow=polyn(1,1)*dp^(n-1)+polyn(1,2)*dp^(n-2)+...
      polyn(1,3)*dp^(n-3)+polyn(1,4)*dp^(n-4)+...
      polyn(1,5)*dp^(n-5)+polyn(1,6);
w_out=flow;
end

```

D.3 Controller parameters

```

%% Flow controllers
% Parameters for the flow controllers in the system

%% FV-valve controller
T_il=10;
K_pl=1;

% valve opening time used for all valves
tau_opening= 1;

%% Selector
Kp_selector1=.1;
Kp_selector2=.1;
Kp_selector3=.1;
Ti_selector1=10;
Ti_selector2=10;
Ti_selector3=10;
%initial values in the integrators(opening dynamics block)
init_selector1=0.1;
init_selector2=0.1;
init_selector3=0.1;

```

D.4 Flow element

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                               Valve module
%
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Calculates flow rate q_out based on pressure difference
% across the valve. Equation for calculating q, suits
% with definition of the used C_v constant. The valve
% flow coefficient is the number of US gallons per minute
% of 60°F water that will flow through a valve at

```

```

% a specified opening with a pressure drop of 1psi
% across the valve.
%
%  $q=C_v/(11.7*(SG/dp)^{(1/2)})$ 
%  $q$ -flow rate [m3/h]
%  $SG$ -special gravity. ( $\rho_{propan}/\rho_{water}$ )
%  $dp$ -pressure difference [kPa]
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

function [q_out] = flow_element(u)
global rho;
C_v=u(1);
z=u(2);
p_in=u(3);
p_out=u(4);
q_out=z*C_v/11.7/(rho/1000/((p_in-p_out)/1000))^(1/2);
end

```

D.5 Selector

```

%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%                               Selector                               %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Recieves measurement of the current flow
% and decides which loop/valve in the
% measurement station to be fully open (60%).
% If flow [m3/h]:
%           <400 => loop three is active
%           >400 % <1800 => loop one is active %
%           >1800 => loops one and two is active %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

```

```

function [signal] = selector(u)
global rho;
flow=u;
if flow <400 && flow >=0
    signal=[0 0 0.6];
elseif flow >400 && flow <1800
    signal=[0.6 0 0];
elseif flow >1800
    signal=[0.6 0.6 0];

```

```
    else
        signal =[0 0 0];
    end
end
```