Control of superheater for electrical steam boiler at Esbjerg power plant

Period: November 1st 2009 - January 7th 2010
Due date: January 7th 2010
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Titlepage

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Abstract: This project focuses on modeling of an electrical superheater, placed at DONG Energy's power plant in Esbjerg. Based on the model a controller for the superheater is made. The entire system is then tested and compared to data from the physical power plant.

The test made to the obtained system is done by using Simulink.

Due to the time considerations some of the model has not been linearised. However it has been shown how to linearize a model.

Supervisors: Zhenyu Yang

Student: Rasmus Holmgaard Rasmussen

Preface

This report is written as documentation for my final project at Aalborg University Esbjerg. The purpose of the report is to give the reader insight into which considerations and processes that was used during the project.

The report is divided into four parts. First an analysis of all the regulations loops on the electrical steam boiler. The purpose of this analysis is to find a single area which needs to be modeled.
The second part presents the work with modeling, system identification, control design and testing. The third part is conclusion. The fourth and last part is appendix.

In the back of the report a CD is enclosed containing a digital copy of the report along with the Simulink program.

DONG Energy should have thanks for the help and hospitality enjoyed during this project.

Aalborg University Esbjerg, fall 2009

Rasmus Holmgaard Rasmussen

Contents

1 Analyses

At the power plant in Esbjerg, DONG Energy has an electrical steam boiler. The steam boiler is used when the power plant is started up or is running at low load.

The steam boiler is made of an outer tank, inner tank and an electrical superheater. In the inner tank there are two times three electrodes which heats up the water. The outer tank gets water from a main tank. This water can be filled into the inner tank and back again. Since the water in the inner tank can go back into the outer tank, there has to be room for it else the boiler will be overflowed. To make sure that the boiler wouldn't be overflowed there are two maximum levels, which the level has to stay below. The more water in the inner tank the more effect will be use and therefore the amount of steam produced will increase if the amount of water in the inner tank is increased. When steam is produced a pressure inside the boiler will be build. The higher the pressure is the higher the steam temperature is. The pressure in the boiler is higher than the pressure in the steam pipe that is connected to the boiler, a controllable valve makes sure that the pressure doesn't get to high or too low in the boiler and the steam pipe. When the pressure drops the temperature will drop and the amount of dew in the steam will increase. The steam needs to be dry so the steam pipes won not get clogged by scale and more. To ensure dry steam and a high temperature there is a superheater.

For all of the above mentioned to happen in a regular manner some controllers has to be developed.

- The total amount of water:
  Must control the total amount of water in the two tanks and make sure that there is room in the outer tank for the water in the inner tank.

- The level of water in the inner tank.
  Controls the level in the inner tank based on the effect. However if the pressure is too high or proper there is no need for more steam and therefore the level in the inner tank has to be lowered or hold steady. So the pressure has to be taken as a factor in the control for the level in the inner tank.

- Temperature out of the superheater.
  A third controller must control the temperature of the steam coming out of the superheater.

- Pressure in the boiler and in the steam pipe.
  Final a controller has to control the valve that ensures that the pressure in the boiler or in the steam pipe doesn't get to high or low.

On Figure 1 all the regulation that is needed for the Electrical steam boiler, for auxiliary steam on Esbjerg power plant, can be seen.

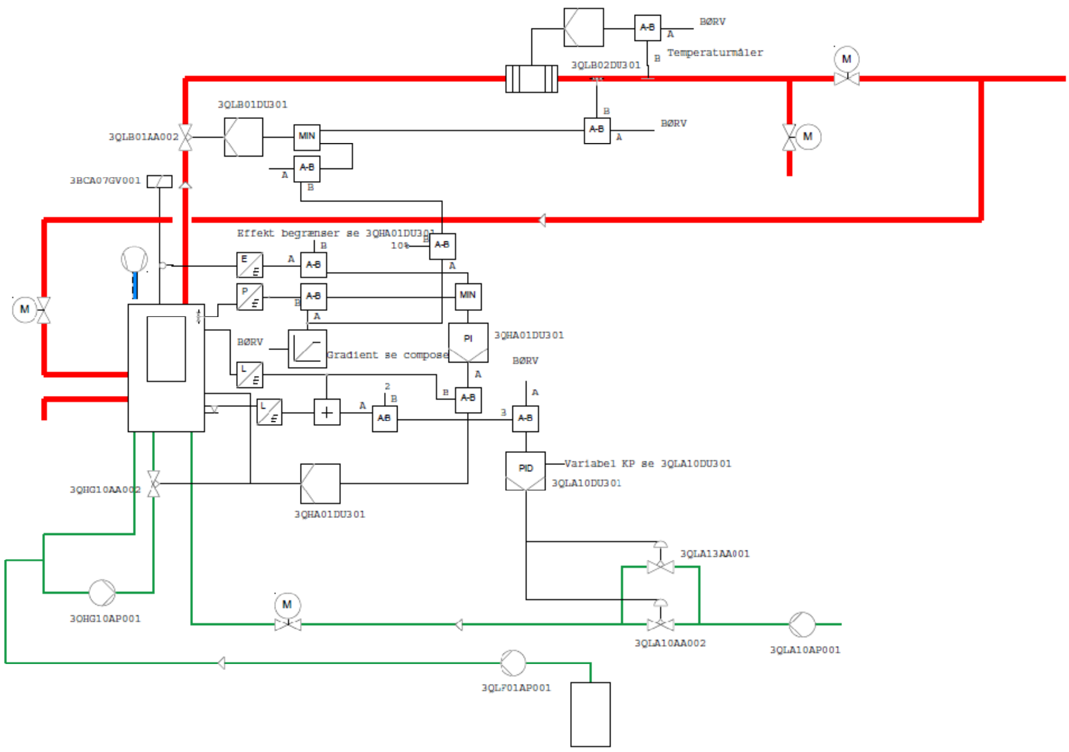


Figure 1 All regulation for the electrical steam boiler

The Projects goals are therefore:

- Establish a dynamic model for one of the areas that need to be controlled.
- Test and verify the dynamic model in similarity to the real system, with data from the real system.
- Develop a controller based on the dynamic model.

1.1 Physical influences

This section will give an overview of the things that will have an influence on the models and the controllers.

- The total amount of water:
  The levels in the two tanks are the main influence. The pressure doesn't have any direct influence one the levels because water is almost incompressible. However when steam is produced the level will virtual raise because there will be some absorption of the steam in the water. The higher pressure the more the steam will be forced

into/closer to the water. There are two different valves which deliver the water to the outer tank, the characteristics of these two valves must be included as well.

- The level of water in the inner tank.
  Again the steam has an influence and the pressure direct on the water can be ignored. The more water there is in the inner tank the more effect will be used, which means more steam will be produced. When the water is vaporized feed water has to enter the tank, and when steam is made the pressure will raise, which as previous mentioned will have an influence on the level. The pressure have also an influence on the level because if the pressure is to low there has to be produced more steam, if the pressure is correct there only have to be produced the amount of steam that is used, if the pressure gets to high then there shouldn’t be produced more steam. One valve controls how much water there is coming into the tank, another is controlling how much water there is coming out again. The two valves are connected so when one is open the other is closed and reversed. If the two valves are 50% open the same amount is coming in as there is being poured out and thereby the level will remain the same. The characteristics of the two valves are also having an influence on this model and this controller.

- Temperature out of the superheater.
  The superheater is electronic, therefore it is the effect that is control. When the temperature gets lower than the set point the effect has to increase. When the temperature get to high the effect decreases. The amount of steam going through the superheater has an influence on how much effect there will be used. If the amount of steam increase and the effect is kept steady, then the temperature on the steam going out of the superheater will decrease.

- Pressure in the boiler and in the steam pipe.
  The valve’s, which creates the pressure drop, characteristic, is the main influence. Another influence is the pressure difference on the two sides of the valve.

1.2 Regulation specifications

- The total amount of water:
  For this regulation loop there is only one demand, which is there has to be room for the water from the inner tank in the outer tank.

- The level of water in the inner tank.
  Somehow this regulation has to find a level based on the effect and pressure. The effect is more a limitation; the boiler can at max use 30MW anything below is accepted. The pressure has to be under a maximum and at an ideal running pressure, which is at 20 bar.

- Temperature out of the superheater.
  This loop must hold the temperature on the steam out of the superheater at 230°C.

- Pressure in the boiler and in the steam pipe.
  As previous mentioned the pressure inside the boiler must be at 20 bar, besides holding that pressure the regulation must also hold a pressure at 11.5 bar in the steam pipe.

1.3 Analytic conclusion

Based on the analysis of the control loops I have decided to continue with the superheater, because the superheater is the only regulation that does not directly depend on one of the other regulations.

2 System description

As previous mentioned the superheater's assignment is to ensure dry steam and a temperature at 230˚C. To do this there are some electrodes which will heat the steam going through the superheater. To control the temperature the effect through the electrodes is regulated. The mass flow entering and the mass flow leaving has a big influence on how much effect is needed. As it can be seen on Figure 2 there is a valve before the superheater, this valve is controlling the pressure in the steam boiler and the pressure after the valve. So the control of the valve has nothing to do with the superheater, however the opening of the valve determines how much steam that will enter the superheater and therefore also how much that will leave. Furthermore it can be seen in Figure 2 that the measurement of the temperature is placed outside the superheater therefore it will take some time to register what kind of influence an increase or a decrease in the effect has on the temperature.

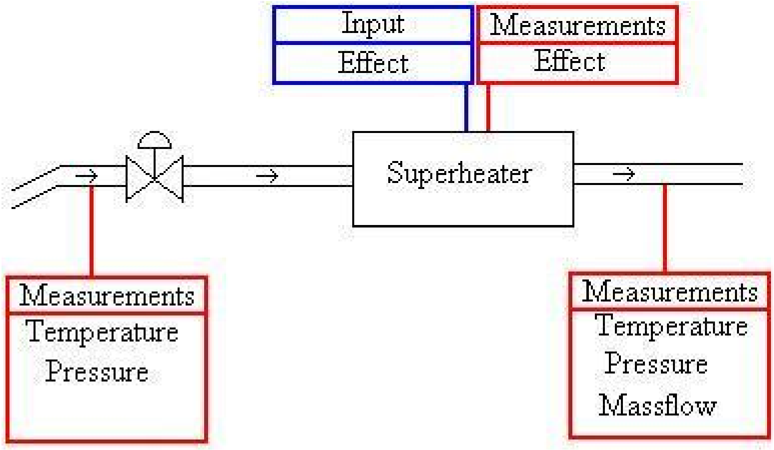


Figure 2 System overview

It is assumed that the controller for the valve is controlling the pressures on both sides of the valve perfectly. It is also assumed that the steam before the valve/coming out of the steam boiler is saturated steam.

Heat lost to the surroundings is ignored since it is hard to find because the system is isolated and it is not possible to get the temperature between the pipes and the isolation.

The superheater is only started when there is a flow above 1.0 kg/s.

3 Modeling

In Table 1(it is in Appendix) the main symbols for the following section is explained.

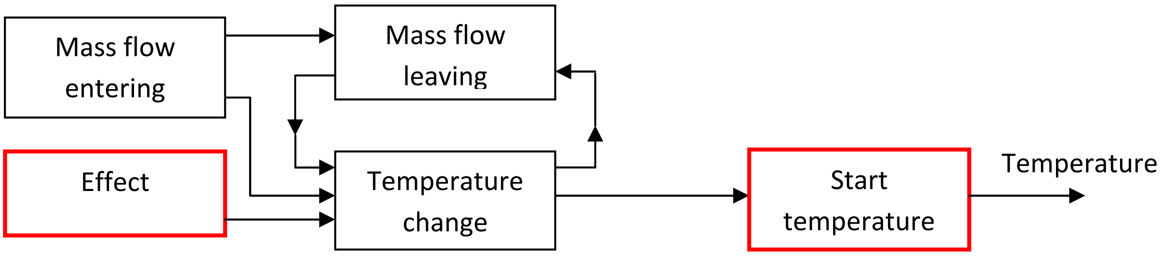


Figure 3 Overview of models

Figure 3 shows what needs to be modeled and what the inputs and outputs are. It is not necessary to model the effect and the start temperature, since it is the effect which has to be controlled and the start temperature is seen as a constant.

3.1 Mass flow entering

To find the mass flow entering the valve before the superheater has to be model. The mass flow entering can be rewritten as:

$$\dot{m}_{se} = \rho_{se} \cdot q_{outflow} \tag{3.1}$$

Where ρ_{se} is the density on the steam entering.

To find $q_{outflow}$, which is the energy in the mass, the Bernoulli principle is used.

The Bernoulli principle is a simplification of Bernoulli's equation, which states, that the sum of all forms of energy in a fluid flowing along an enclosed path (a streamline) is the same at any two points of that path. In fluid flow with no viscosity, and therefore, one in which a pressure difference is the only accelerating force; the principle is equivalent to Newton's law's of motion. The Bernoulli equation can be written as:

$$\frac{1}{2} \cdot v^2 + \emptyset + w = constant \tag{3.2}$$

v is the velocity, $\emptyset$ is the gravitational force and where

$$w = \varepsilon + \frac{p}{\rho} \tag{3.3}$$

p is the pressure and ρ is the density.

Then inserting this

$$\frac{1}{2} \cdot v^2 + \emptyset + \varepsilon + \frac{p}{\rho} = constant \tag{3.4}$$

Since ε is the fluid thermo dynamic energy per unit mass and is therefore a constant, it can be move to the right side of the equation, which therefore becomes:

$$\frac{1}{2} \cdot v^2 + \emptyset + \frac{p}{\rho} = constant \tag{3.5}$$

Because the mass consists of steam, which is most gas, the gravitational force (Ø) is very small and can be neglected. The equation now is:

$$\frac{1}{2} \cdot v^2 + \frac{p}{\rho} = constant\ along\ a\ streamline \tag{3.6}$$

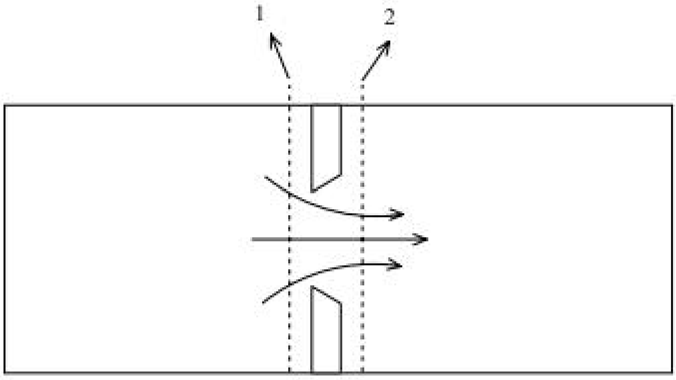


Figure 4 Flow through the valve

If this equation is used in two points (1 and 2) as shown in Figure 4, it will describe the flow through the valve and will lead to the following:

$$\frac{1}{2} \cdot v_1^2 + \frac{p_1}{\rho_1} = \frac{1}{2} \cdot v_2^2 + \frac{p_2}{\rho_2} \tag{3.7}$$

$$\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2} = \frac{1}{2} \cdot (v_2^2 - v_1^2)$$

$$2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right) = v_2^2 - v_1^2 \tag{3.8}$$

Thereby the relationship between the velocities and the pressures differences, between the steam pipe before the valve and the steam pipe after the valve/before the superheater. However the velocities are not known and the equation is only considering the energy balance regarding the valve.

To find the velocities the cross-sectional area of the valve has to be taken into account.

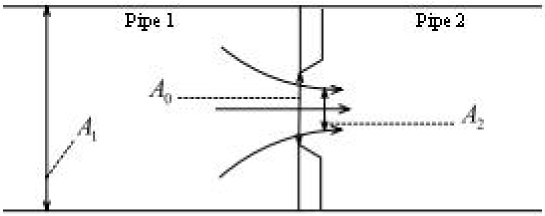


Figure 5 illustration of the opening of the valve

In Figure 5 it can be seen that the opening creates several cross-sectional areas A_0, A_1 and A_2.

The difference between A_0 and A_2 is called vena contracta and will be referred to as the contraction coefficient. The contraction coefficient has to be found, which can be done by the following:

$$C_c = \frac{A_2}{A_0}, A_2 = C_c \cdot A_0 \tag{3.9}$$

To finding the velocities through the valve, the mass balance will be used.

$$\dot{m} = \rho \cdot q \tag{3.10}$$

where

$$q = v \cdot A \tag{3.11}$$

therefore equation (3.10) becomes:

$$\dot{m} = \rho \cdot v \cdot A \tag{3.12}$$

Since the mass going into the valve is equal to the mass going out of the valve they can be set up as following:

$$\dot{m}_1 = \dot{m}_2 \tag{3.13}$$

$$\rho_1 \cdot v_1 \cdot A_1 = \rho_1 \cdot v_2 \cdot A_2 \tag{3.14}$$

Then isolating v_1

$$v_1 = v_2 \cdot \frac{\rho_1 \cdot A_2}{\rho_1 \cdot A_1}$$

And inserting A_2 from equation (3.9)

$$v_1 = v_2 \cdot \frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1} \tag{3.15}$$

Now that v_1 is found it can be inserted into the equation attained from using the Bernoulli principle, equation (3.8), which then gives:

$$2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right) = v_2^2 - \left(v_2 \cdot \frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2$$

Isolating v_2

$$2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right) = v_2^2 \cdot \left(1 - \left(\frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2\right)$$

$$\frac{2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right)}{\left(1 - \left(\frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2\right)} = v_2^2$$

$$\frac{\sqrt{2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right)}}{\sqrt{\left(1 - \left(\frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2\right)}} = v_2 \qquad (3.16)$$

The velocity out of the valve and into the steam pipe is obtained, giving a relationship between the orifice/opening of the valve and the velocity v_2.

Now using equation(3.16) on equation(3.11) as it is assumed that equation (3.13) is valid.

$$q = A_2 \cdot \frac{\sqrt{2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right)}}{\sqrt{\left(1 - \left(\frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2\right)}}$$

Once again the expression for A_2 is inserted.

$$q = C_c \cdot A_0 \cdot \frac{\sqrt{2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right)}}{\sqrt{\left(1 - \left(\frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2\right)}} \qquad (3.17)$$

Equation (3.17) is then inserted into (3.1)

$$\dot{m}_{se} = \rho_{se} \cdot C_c \cdot A_0 \cdot \frac{\sqrt{2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right)}}{\sqrt{\left(1 - \left(\frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2\right)}} \qquad (3.18)$$

Where ρ_1 is the density of the steam before the valve, $\rho_2 = \rho_{se}$ is the density of the steam after the valve/before the superheater, p_1 is the pressure before the valve, p_2 is the pressure after the valve.

Thereby the mass flow into the superheater is found.

3.2 The temperature change

Mass balance:

$$\frac{dm_s}{dt} = V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt} = \dot{m}_{se} - \dot{m}_{sl}$$

$$\Updownarrow$$

$$\dot{m}_{sl} = \dot{m}_{se} - V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt} \qquad (3.19)$$

$\dot{m}_{sl}$ is the mass flow of the steam that leaves the superheater, V_s is the volume of the steam inside the superheater and where the density can be written as:

$$\rho_{sl} = \frac{p_s \cdot M_s}{(T_{slh} + 273.15) \cdot R_{gas}} \qquad (3.20)$$

Energy balance:

It is assumed that the pressure after the valve is constant therefore the chance in the inner energy can be written in as the following:

$$\frac{dU_s}{dt} = \frac{d(m_s \cdot h_{sl})}{dt} \qquad (3.21)$$

$$= \frac{d(V_s \cdot \rho_{sl} \cdot h_{sl})}{dt}$$

$$= V_s \cdot \rho_{sl} \cdot \frac{\partial h_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt} + V_s \cdot h_{sl} \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt}$$

$$= V_s \cdot \rho_{sl} \cdot c_p \cdot \frac{dT_{sl}}{dt} + V_s \cdot h_{sl} \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt} \qquad (3.22)$$

Furthermore the energy balance is given by:

$$\frac{dU_s}{dt} = \dot{q}_{se} - \dot{q}_{sl} + Effect - Q_{stemp} \qquad (3.23)$$

where

$$\dot{q} = h \cdot \dot{m} \tag{3.24}$$

Inserting this into equation(3.23)

$$\frac{dU_s}{dt} = h_{se} \cdot \dot{m}_{se} - h_{sl} \cdot \dot{m}_{sl} + Effect - Q_{stemp}$$

Since the electrical effect is measured in watts, which is $\frac{J}{s}$ the energy is equal to the effect.

Q_{stemp} is that energy that is used to heat up the steam entering the superheater to the temperature inside the superheater.

$$Q_{stemp} = m \cdot c_p \cdot \Delta T \tag{3.25}$$

where m is the mass, but the mass flow for the steam entering is used instead, c_p is the specific heat capacity and ΔT is the temperature difference from start to the end.

$$\Delta T = T_{end} - T_{start}$$

T_{end} can be found by looking at the steam inside the superheater and the steam entering

$$Q_{sh} = Q_{se}$$

$$m_{sh} \cdot c_p \cdot \Delta T_{\mathrm{sh}} = m_{se} \cdot c_p \cdot \Delta T_{\mathrm{se}}$$

$$m_{sh} \cdot c_p \cdot (T_{startsh} - T_{end}) = m_{se} \cdot c_p \cdot (T_{end} - T_{startse})$$

$$m_{sh} \cdot (T_{startsh} - T_{end}) = m_{se} \cdot (T_{end} - T_{startse})$$

$$m_{sh} \cdot T_{startsh} - m_{sh} \cdot T_{end} = m_{se} \cdot T_{end} - m_{se} \cdot T_{startse}$$

$$m_{sh} \cdot T_{startsh} + m_{se} \cdot T_{startse} = m_{se} \cdot T_{end} + m_{sh} \cdot T_{end}$$

$$m_{sh} \cdot T_{startsh} + m_{se} \cdot T_{startse} = (m_{se} + m_{sh}) \cdot T_{end}$$

$$\frac{m_{sh} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{(m_{se} + m_{sh})} = T_{end}$$

$m_{sh}$is found by rearranging the ideal gas formula

$$m_{sh} = \frac{p \cdot V}{M_s \cdot R \cdot T}$$

Therefore equation (3.25) becomes:

$$Q_{stemp} = \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start} \right)$$

Inserting this into equation (3.23)

$$\frac{dU_s}{dt} = h_{se} \cdot \dot{m}_{se} - h_{sl} \cdot \dot{m}_{sl} + Effect - \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start} \right)$$

Then inserting $\dot{m}_{sl}$ from the mass balance, equation (3.19)

$$\frac{dU_s}{dt} = h_{se} \cdot \dot{m}_{se} - h_{sl} \cdot \left(\dot{m}_{se} - V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt}\right) + Effect - \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start} \right) \quad (3.26)$$

Combining the two formulas from the energy balance, equations (3.22) and (3.26).

$$V_s \cdot \rho_{sl} \cdot c_p \cdot \frac{dT_{sl}}{dt} + V_s \cdot h_{sl} \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt} = h_{se} \cdot \dot{m}_{se} - h_{sl} \cdot \left(\dot{m}_{se} - V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt}\right) + Effect - \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start} \right)$$

$$V_s \cdot \rho_{sl} \cdot c_p \cdot \frac{dT_{sl}}{dt} + V_s \cdot h_{sl} \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt} = -h_{se} \cdot \dot{m}_{se} - h_{sl} \cdot \dot{m}_{se} + \left(h_{sl} \cdot V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt}\right) + Effect - \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start} \right)$$

$$V_s \cdot \rho_{sl} \cdot c_p \cdot \frac{dT_{sl}}{dt} = h_{se} \cdot \dot{m}_{se} - h_{sl} \cdot \dot{m}_{se} + Effect - \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start} \right)$$

The specific enthalpy on the steam leaving (h_{sl}) can be found by the following formula:

$$h_{sl} = \frac{h_{se} \cdot Flow_{in} + Effect}{Flow_{out}}$$

Inserting h_{sl} gives:

$$V_s \cdot \rho_{sl} \cdot c_p \cdot \frac{dT_{sl}}{dt} = h_{se} \cdot \dot{m}_{se} - \left(\frac{h_{se} \cdot Flow_{in} + Effect}{Flow_{out}}\right) \cdot \dot{m}_{se} + Effect - \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start}\right)$$

Since the flow is measured in kg/s it is a mass flow which means $Flow_{in} = \dot{m}_{se}$ and $Flow_{out} = \dot{m}_{sl}$.

$$V_s \cdot \rho_{sl} \cdot c_p \cdot \frac{dT_{sl}}{dt} = h_{se} \cdot \dot{m}_{se} - \left(\frac{h_{se} \cdot \dot{m}_{se} + Effect}{\dot{m}_{sl}}\right) \cdot \dot{m}_{se} + Effect - \dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start}\right)$$

$$\frac{dT_{sl}}{dt} = \frac{h_{se} \cdot \dot{m}_{se}}{V_s \cdot \rho_{sl} \cdot c_p} - \left(\frac{h_{se} \cdot {\dot{m}_{se}}^2 + Effect \cdot \dot{m}_{se}}{V_s \cdot \rho_{sl} \cdot c_p \cdot \dot{m}_{sl}}\right) + \frac{Effect}{V_s \cdot \rho_{sl} \cdot c_p} - \frac{\dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start}\right)}{V_s \cdot \rho_{sl} \cdot c_p}$$

$$h_{se} = U_{se} + p_{se} \cdot V_{se}$$

where

$$p_{se} \cdot V_{se} = n_{se} \cdot R_{gas} \cdot T_{se}$$

$$n_{se} = M_{se} \cdot \dot{m}_{se}$$

so

$$h_{se} = U_{se} + M_{se} \cdot \dot{m}_{se} \cdot R_{gas} \cdot T_{se}$$

which means

$$\frac{dT_{sl}}{dt} = \frac{\left(U_{se} + M_{se} \cdot \dot{m}_{se} \cdot R_{gas} \cdot T_{se}\right) \cdot \dot{m}_{se}}{V_s \cdot \rho_{sl} \cdot c_p} - \left(\frac{\left(U_{se} + M_{se} \cdot \dot{m}_{se} \cdot R_{gas} \cdot T_{se}\right) \cdot \dot{m}_{se}{}^2 + Effect \cdot \dot{m}_{se}}{V_s \cdot \rho_{sl} \cdot c_p \cdot \dot{m}_{sl}}\right) + \frac{Effect}{V_s \cdot \rho_{sl} \cdot c_p} - \frac{\dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start}\right)}{V_s \cdot \rho_{sl} \cdot c_p}$$

$$\frac{dT_{sl}}{dt} = \frac{\left(U_{se} \cdot \dot{m}_{se} + M_{se} \cdot \dot{m}_{se}{}^2 \cdot R_{gas} \cdot T_{se}\right)}{V_s \cdot \rho_{sl} \cdot c_p} - \left(\frac{\left(U_{se} \cdot \dot{m}_{se}{}^2 + M_{se} \cdot \dot{m}_{se}{}^3 \cdot R_{gas} \cdot T_{se}\right) + Effect \cdot \dot{m}_{se}}{V_s \cdot \rho_{sl} \cdot c_p \cdot \dot{m}_{sl}}\right) + \frac{Effect}{V_s \cdot \rho_{sl} \cdot c_p} - \frac{\dot{m}_{se} \cdot c_p \cdot \left(\frac{\frac{p \cdot V}{M_s \cdot R \cdot T} \cdot T_{startsh} + m_{se} \cdot T_{startse}}{\left(m_{se} + \frac{p \cdot V}{M_s \cdot R \cdot T}\right)} - T_{start}\right)}{V_s \cdot \rho_{sl} \cdot c_p} \quad (3.27)$$

3.3 Mass flow leaving

There has already been mad an equation for the mass flow leaving the superheater in equation (3.19), which is:

$$\dot{m}_{sl} = \dot{m}_{se} - V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt}$$

4 Identification

4.1 Verifying of valve model

The maximum diameter of the orifice is 111.125mm

If the orifice is sharp a typical value of coefficient of contraction is 0.64.

$$A_{0max} = \pi \cdot r^2 = \pi \cdot \left(\frac{111.125mm}{2}\right)^2 = 9698.6978mm^2 = 0.00009699m^2$$

Then the maximum area of the valve orifice is $0.00009699m^2$.

$$A_0 = 0.00009699m^2 \cdot \text{valve opening[\%]}$$

The diameter of the steam pipe is 15cm, there fore the area of the steam pipe is:

$$A_1 = \pi \cdot r^2 = \pi \cdot \left(\frac{150mm}{2}\right)^2 = 17671.4587mm^2 = 0.0001767m^2$$

$$C_c = 0.64$$

$$p_1 = 20\text{bar} = 2000\text{kPa}$$

$$p_2 = 11.5\text{bar} = 1150\text{kPa}$$

$$\rho_1 = \frac{p_1 \cdot M_s}{(T_1 + 273.15) \cdot R_{gas}} = \frac{2000\text{kPa} \cdot 0.018\frac{kg}{mol}}{(214°\text{C} + 273.15) \cdot 8.314472\frac{J}{K \cdot mol}} = \frac{36000}{4050{,}40} = 8{,}888\frac{kg}{m^3}$$

$$\rho_2 = \frac{p_2 \cdot M_s}{(T_2 + 273.15) \cdot R_{gas}} = \frac{1150\text{kPa} \cdot 0.018\frac{kg}{mol}}{(188°\text{C} + 273.15) \cdot 8.314472\frac{J}{K \cdot mol}} = \frac{20700}{3834{,}22} = 5{,}3988\frac{kg}{m^3}$$

$$\dot{m}_{se} = \rho_{se} \cdot C_c \cdot A_0 \cdot \frac{\sqrt{2 \cdot \left(\frac{p_1}{\rho_1} - \frac{p_2}{\rho_2}\right)}}{\sqrt{\left(1 - \left(\frac{\rho_1 \cdot C_c \cdot A_0}{\rho_1 \cdot A_1}\right)^2\right)}}$$

$$\dot{m}_{se} = 1150\text{kPa} \cdot 0.64 \cdot (0.00009699m^2 \cdot \text{valve opening[\%]}) \cdot \frac{\sqrt{2 \cdot \left(\frac{2000\text{kPa}}{8.888\frac{kg}{m^3}} - \frac{1150\text{kPa}}{5.3988\frac{kg}{m^3}}\right)}}{\sqrt{\left(1 - \left(\frac{8.888\frac{kg}{m^3} \cdot 0.64 \cdot (0.00009699m^2 \cdot \text{valve opening[\%]})}{8.888\frac{kg}{m^3} \cdot 0.0001767m^2}\right)^2\right)}}$$

$$\dot{m}_{se} = 71.38464 \cdot \text{valve opening}[\%] \cdot \frac{\sqrt{2 \cdot (225022.5023 - 213010.2986)}}{\sqrt{\left(1 - \left(\frac{0.0005517}{0.001571} \cdot \text{valve opening}[\%]\right)^2\right)}}$$

$$\dot{m}_{se} = 71.38464 \cdot \text{valve opening}[\%] \cdot \frac{154.9981}{\sqrt{(1 - (0.3512 \cdot \text{valve opening}[\%])^2)}}$$

If the valve is 100% open

$$\dot{m}_{se} = 71.38464 \cdot 100\% \cdot \frac{154.9981}{\sqrt{(1 - (0.35098 \cdot 100\%)^2)}}$$

$$\dot{m}_{se} = 71.38464 \cdot \frac{154{,}9981}{0.87665856}$$

$$\dot{m}_{se} = 71.38464 \cdot 176.8056$$

$$\dot{m}_{se} = 12621.2006 \frac{g}{s} = 11.8162 \frac{kg}{s}$$

In the data sheet the maximum flow out of the valve can be $43200 \frac{kg}{h}$ which is $12 \frac{kg}{s}$. Therefore the model is assumed to be correct.

However the equation (3.18) is non-linear and therefore it is linearised using Taylor, which gives:

$$\dot{m}_{se} = \frac{273915832783988861321301338457 01}{247588007857076054979824844800 0} \cdot \text{valve opening}[\%]$$

$$\dot{m}_{se} = 11.0634 \cdot \text{valve opening}[\%] \tag{4.1}$$

Figure 6 shows a plot of equation (3.18), the blue, and a plot of the linearised equation (4.1), the red. It can be seen that around 0.5 or 50% a deviation is starting, after some calculation the linearised equation is satisfying from 0 to 52% where the deviation is $0.0984 \frac{\text{kg}}{\text{s}}$.

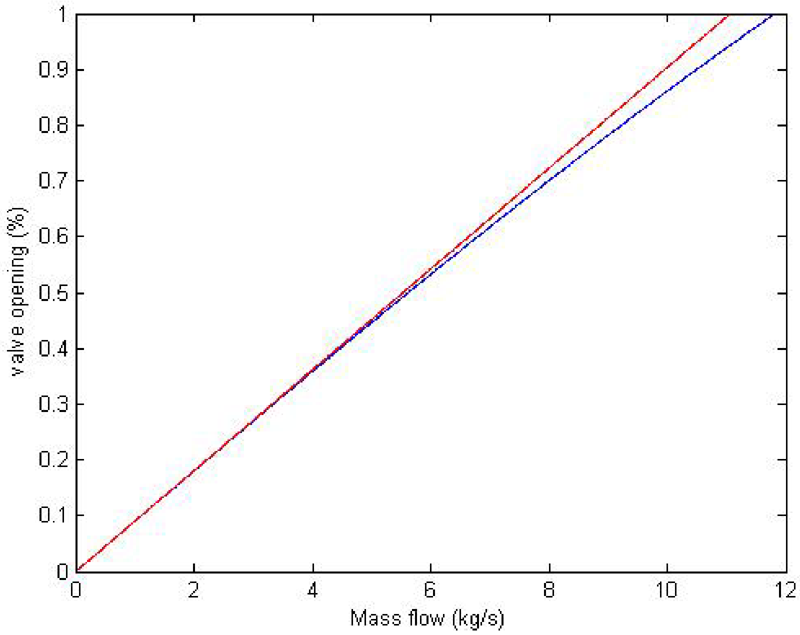


Figure 6 Relationship between valve opening and mass flow

4.2 The temperature change

It is assumed that the internal energy before the valve is the same after the valve. Therefore the U_{se} can be found, as it is assumed that the steam before the valve is saturated steam at a constant pressure on 20bar.

$$U_{se} = 2599.5\frac{kJ}{kg}$$

$$R_{gas} = 8.314472\frac{J}{K \cdot mol}$$

$$M_s = 18\frac{g}{mol} = 0.018\frac{kg}{mol}$$

$c_p = 2590\frac{J}{kg\cdot°C}$ this is found in a steam table.

The volume of the steam (V_s) is assumed to be the same as the volume of the superheater, because there has been running steam through the superheater some time before the superheater is started. The volume of the superheater is 404 liters which is 0.404m^3.

ρ_{sl} is calculated by the formula from the mass balance where it is assumed that T_{slh} is 230˚C since this is the temperature that is the set point.

$p_s = 11.5bar$ which is the pressure in the superheater.

$$\rho_{sl} = \frac{11.5bar \cdot 0.018\frac{kg}{mol}}{(230^\circ C + 273.15) \cdot 8.314472\frac{J}{K \cdot mol}} = \frac{0.207}{4183.427} = 4{,}95 \cdot 10^{-5}\frac{kg}{m^3}$$

$$T_{se} = T_{in} + 273.15$$

where

T_{in} is set to be a constant at 188˚C. The value of T_{in} is obtained from the temperature measurement after the superheater just before the superheater is turned on.

$$T_{se} = 188^\circ\mathrm{C} + 273.15 = 461.15\ K$$

When these values are inserted into equation (3.27) the following is obtained:

$$\frac{dT_{sl}}{dt} = \frac{\left(2599.5\frac{kJ}{kg}\cdot \dot{m}_{se} + 0.018\frac{kg}{mol}\cdot \dot{m}_{se}{}^2 \cdot 8.314472\frac{J}{K\cdot mol}\cdot\ 461.15\ K\right)}{0.404\mathrm{m}^3 \cdot 4{,}95\cdot 10^{-5}\frac{kg}{m^3}\cdot 2590\frac{J}{kg\cdot {}^\circ C}} - \left(\frac{\left(2599.5\frac{kJ}{kg}\cdot \dot{m}_{se}{}^2 + 0.018\frac{kg}{mol}\cdot \dot{m}_{se}{}^3\cdot 8.314472\frac{J}{K\cdot mol}\cdot\ 461.15\ K\right) + Effect\cdot \dot{m}_{se}}{0.404\mathrm{m}^3\cdot 4{,}95\cdot 10^{-5}\frac{kg}{m^3}\cdot 2590\frac{J}{kg\cdot {}^\circ C}\cdot \dot{m}_{sl}}\right) + \frac{Effect}{0.404\mathrm{m}^3\cdot 4{,}95\cdot 10^{-5}\frac{kg}{m^3}\cdot 2590\frac{J}{kg\cdot{}^\circ C}} - \frac{\dot{m}_{se}\cdot 2590\frac{J}{kg\cdot{}^\circ C}\cdot\left(\frac{\frac{11.5bar\cdot 0.404}{0.018\frac{kg}{mol}\cdot 8.314472\frac{J}{K\cdot mol}\cdot 230^\circ C}\cdot 230^\circ C + \dot{m}_{se}}{\left(m_{se} + \frac{11.5bar\cdot 0.404}{0.018\frac{kg}{mol}\cdot 8.314472\frac{J}{K\cdot mol}\cdot 230^\circ C}\right)} - 188^\circ C\right)}{0.404\mathrm{m}^3\cdot 4{,}95\cdot 10^{-5}\frac{kg}{m^3}\cdot 2590\frac{J}{kg\cdot{}^\circ C}}$$

It can now be seen that the temperature change $\frac{dT_{sl}}{dt}$ is a function of the mass flow entering, the mass flow leaving and of the effect.

4.3 Mass flow leaving

$$\dot{m}_{sl} = \dot{m}_{se} - V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt}$$

$\frac{\partial \rho_{sl}}{\partial T_{sl}}$ can be written as:

$$\frac{\partial \rho_{sl}}{\partial T_{sl}} = \frac{\partial \frac{p_s \cdot M_s}{(T + 273.15) \cdot R_{gas}}}{\partial T_{sl}}$$

where $T = \frac{dT_{sl}}{dt} + T_{start}$

$$\frac{\partial \rho_{sl}}{\partial T_{sl}} = \frac{\partial \frac{p_S \cdot M_S}{\left(\frac{dT_{sl}}{dt} + T_{start} + 273.15\right) \cdot R_{gas}}}{\partial T_{sl}} \qquad (4.2)$$

A differential function can be rewritten as the following:

$$\frac{\partial \left(\frac{K_1}{z \cdot x + K_2}\right)}{\partial x} = -\frac{z \cdot K_1}{(x + K_2)^2}$$

Therefore equation (4.2) becomes

$$\frac{\partial \rho_{sl}}{\partial T_{sl}} = -\frac{R_{gas} \cdot p_s \cdot M_s}{\left(\left(\frac{dT_{sl}}{dt} + T_{start}\right) + 273.15 \cdot R_{gas}\right)^2}$$

$$\frac{\partial \rho_{sl}}{\partial T_{sl}} = -\frac{8.314472 \frac{J}{K \cdot mol} \cdot 11.5 bar \cdot 0.018 \frac{kg}{mol}}{\left(\left(\frac{dT_{sl}}{dt} + 188°C\right) + 273.15 \cdot 8.314472 \frac{J}{K \cdot mol}\right)^2}$$

$$= -\frac{1.7211}{\left(\left(\frac{dT_{sl}}{dt} + 188°C\right) + 2.2711 \cdot 10^3\right)^2}$$

5 Simulink

The equations obtained have been written into the program Simulink, which is a program in Matlab.

In Figure 7 the model of the superheater in Simulink can be seen.

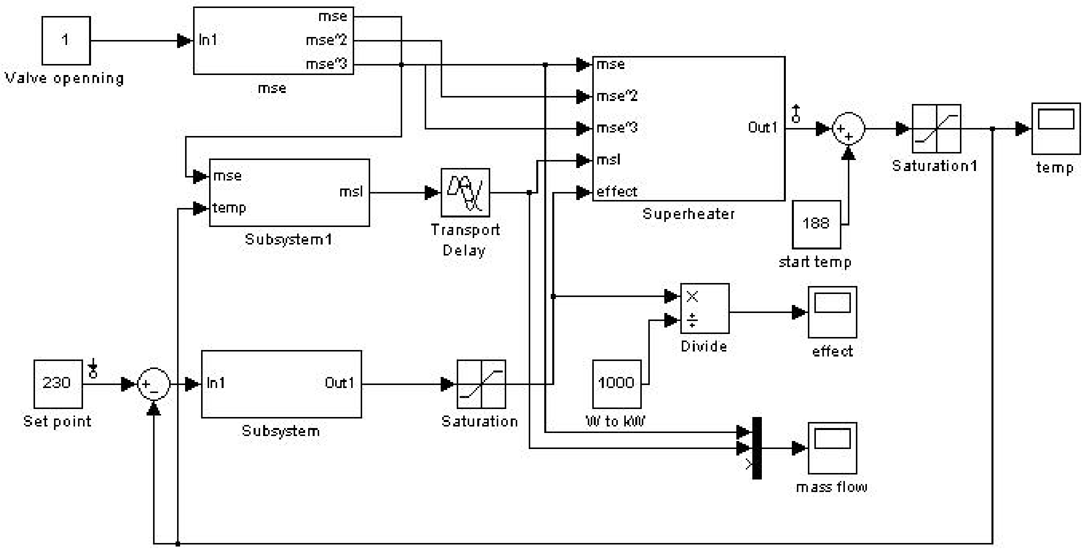


Figure 7 Simulink

Running the Simulink program with the Valve opening on 100 % the following graphs is obtained:

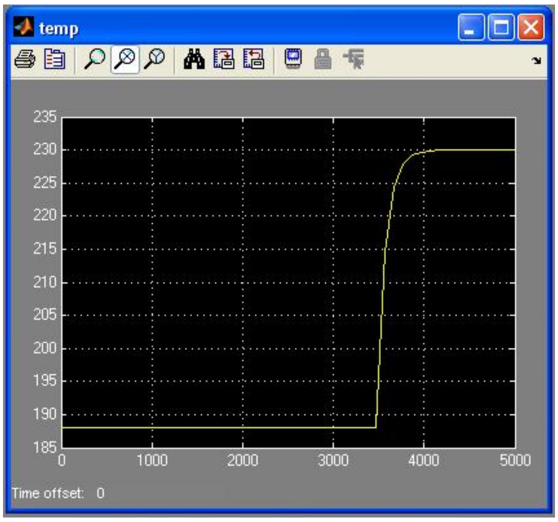


Figure 8 Temperature with the valve 100% open

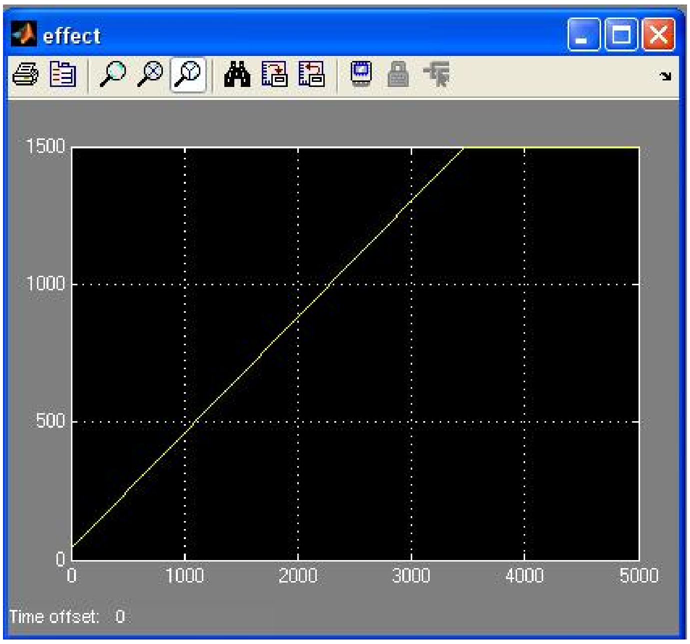


Figure 9 Effect used when the valve is 100% open

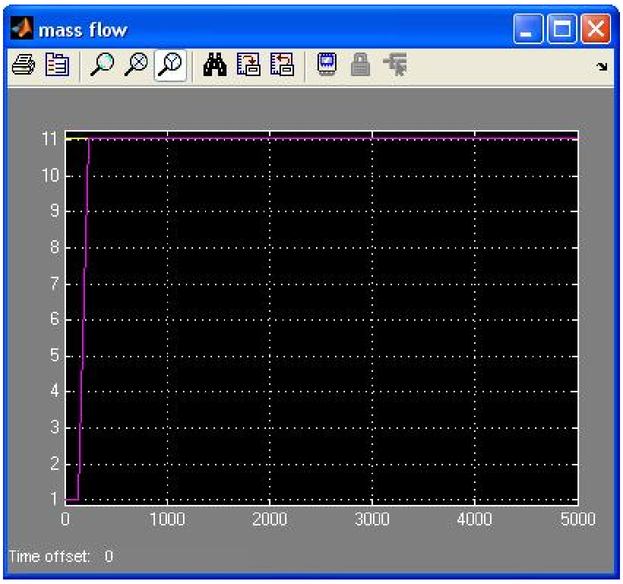
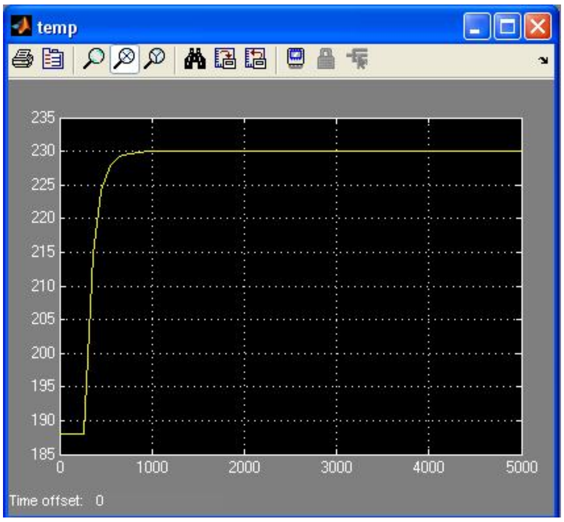


Figure 10 Mass Flow when the valve is 100% open

It can be seen that the effect is almost 1500kW and the mass flow for both entering (the yellow) and leaving (the purple) is a bit above 11 kg/s. It takes almost 4000 seconds to get the temperature at 230°C.

Then running the program whit the valve opening at 10% gives the following graphs:



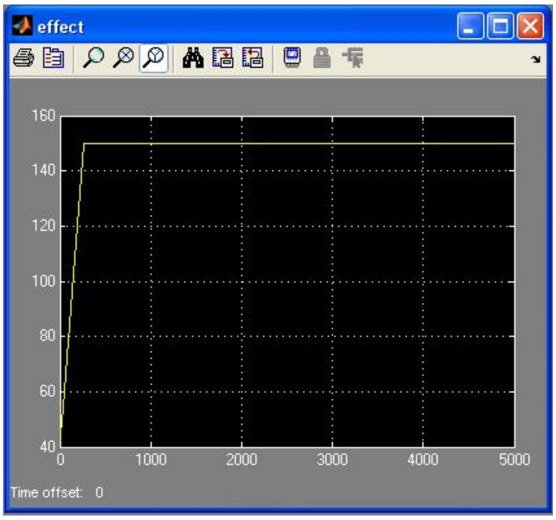


Figure 11 Temperature with the valve 10% open

Figure 12 Effect with the valve 10% open

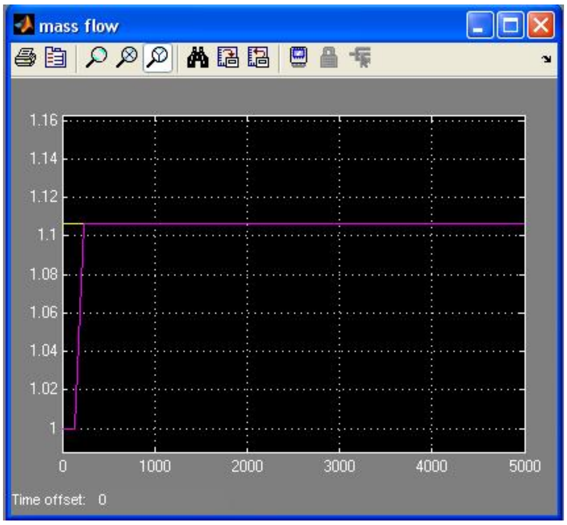


Figure 13 Mass flow with the valve 10% open

Now the mass flows and the effect has now gone down to around 1.1kg/s and 150kW. The time for the temperature to get to 230°C is now around 1000 seconds.

From these two runs of the program is can be seen that the more steam that needs to be heated the more effect will be used, which was expected.

6 Controller

The controller was manual tuned by setting all values to zero and then increasing the gain K_p until the output was starting to oscillate, the setting it to the half of that value. Next the K_i value was increased until any offset is correct in sufficient time for the process. It was not necessary to use a K_d value. Therefore the controller is a PI-controller, with the following values:

K_p = 1000

K_i = 15

7 Test and verification

There has made two types of tests. One where the effect was changed and the flow was kept stabile to see what the effect change would do to the temperature.

The effect was changed 5 %, from 48 % to 43 % which is 720kW to 645kW, the flow was at 1.5kg/s the temperature went from 230˚C to 220˚C on the measurement at the power plant. The measurements from the power plant have then been put into equation (3.26) which gave a temperature change:

720kW

$$\frac{dT_{sl}}{dt} = 91.7138$$

645kW

$$\frac{dT_{sl}}{dt} = 82.1603$$

This means that the temperature with 720kW will be 9.5535˚C higher than the temperature with 645kW. The measurement at the power plant cannot measure with decimals and therefore the test is seen as a success and the model for the temperature change is correct.

The same test was done with only 1 % change in the effect this gave at temperature change on 2˚C and if the data is put into the equation it gives a temperature change on 1.9107 again this is a success.

The other test was to keep the effect, the temperature and the valve opening constant because when the temperature is not changing the mass flow leaving is the same as the mass flow entering. This can be seen in equation (3.19):

$$\dot{m}_{sl} = \dot{m}_{se} - V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot \frac{dT_{sl}}{dt}$$

$$\frac{dT_{sl}}{dt} = 0$$

$$\dot{m}_{sl} = \dot{m}_{se} - V_s \cdot \frac{\partial \rho_{sl}}{\partial T_{sl}} \cdot 0$$

$$\dot{m}_{sl} = \dot{m}_{se}$$

The flow measured was 1.5 kg/s with a valve opening at 14 %

Then the opening of the valve was put into the linearised equation for the valve equation (4.1) which gave:

$$\dot{m}_{se} = 1.5489$$

The measurement at the power plant can not show more than one decimal. The test showed that the model of the valve is correct.

At the power plant the effect was stabile around 180kW when the valve was 13 % open. When 13 % valve opening is put into the Simulink program the graphs shown in Figure 14and Figure 15 is obtained.

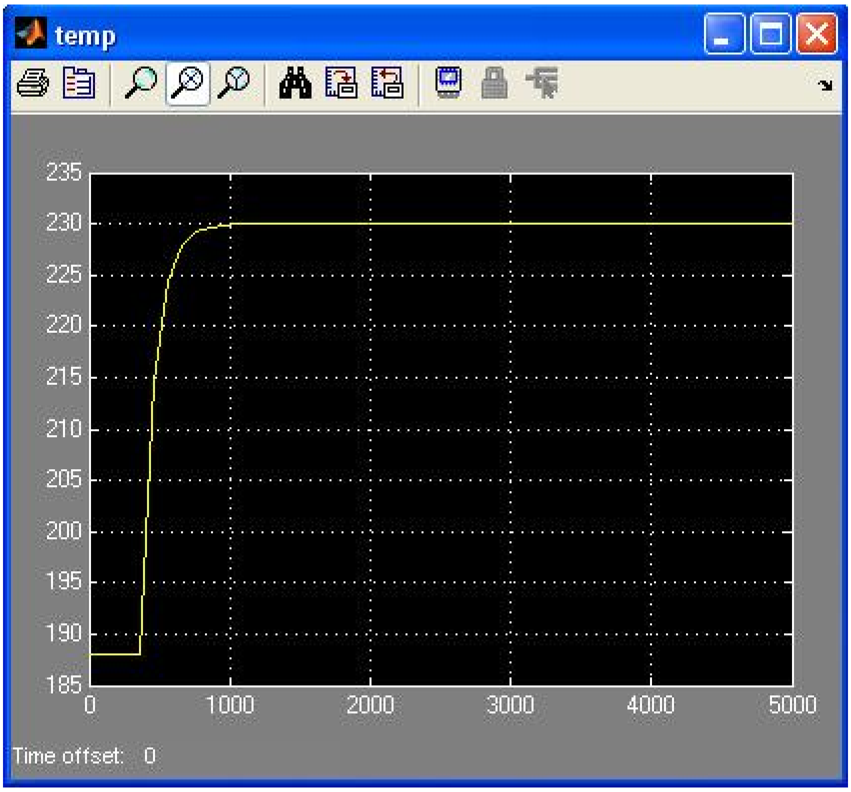


Figure 14 Temperature with valve opening at 13%

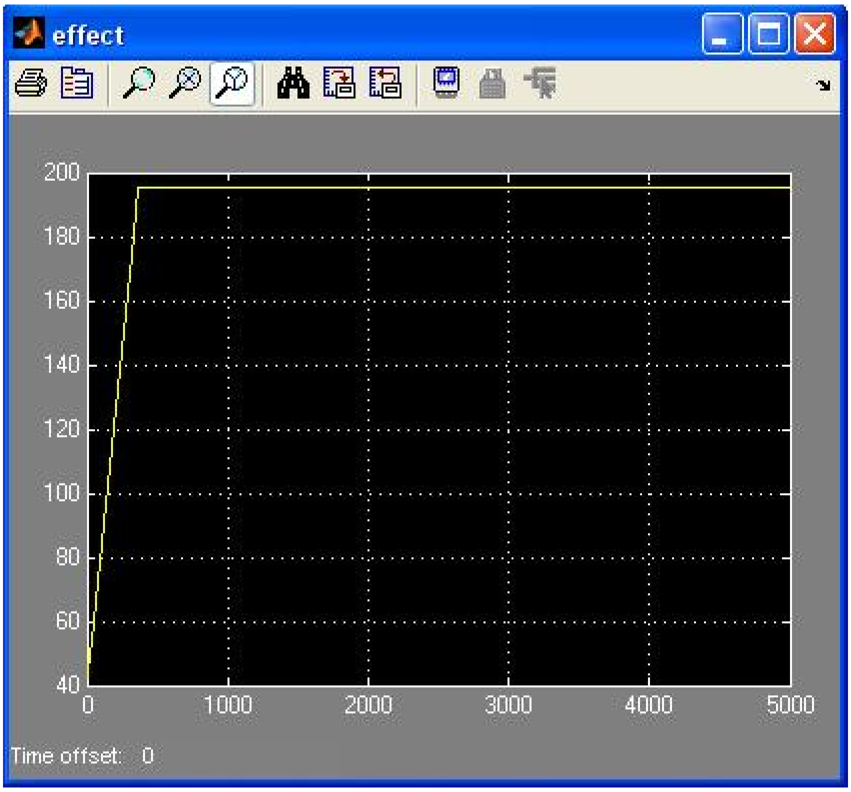


Figure 15 Effect with valve opening at 13%

It can be seen that the effect used in the Simulink program is a little higher than it was at the power plant, but it is acceptably.

8 Conclusion

In general it can be concluded that a controller for the electrical superheater at Esbjerg power plant has been made. The goals of the project has been achieved, a dynamic model has been made, a controller for that model has been found by manual tuning and data from the power plant has been inserted in to the model with success.

Not all models has been linearised this is due to the time consideration, but the model for the valve has been used to shown how a model could be linearised. Since the entire system is not linear the controller cannot be found/made in a theoretical way, like root locus and more.

There were some deviation between the measurement at the power plant and the effect used in Simulink. This could be due to some variations in my calculations, for instance the density of the steam could be calculated to be a little bit of what it really is, which will have a big influence on the temperature change. Another thing that could give deviations, is that some of the variables has been seen as constants for instance the temperature that there is inside the superheater. A third thing is that at the power plant the measurement is not correct, when the superheater is not started or it does not used any effect the measurement shows that 6kW is used. It has not been possible to test if this 6kW is constant or linear.

The controller made in this project and the controller at the power plant cannot be compared to each other because the controller at the power plant has an integration time where as the controller in this project has an integration gain.

The models made are not far from the real superheater since the effect used in both the Simulink program and at the power plant is almost the same. When looking at the mass flow's the models is almost the same as at the power plant.

9 Appendix

The table below shows the main symbols of the modeling part of the report.

Table 1 Nomenclature for Mass balance and energy balance.

Symbol	Unit	Meaning
C_c		vena contracta
c_p	$\frac{J}{kg \cdot {}^{\circ}C}$	Specific heat capacity of steam at constant pressure
$Effect$	$\frac{kJ}{s}$	The effect that is put into the super heater $1kW = 1\frac{kJ}{s}$
$Flow_{in}$	$\frac{kg}{s}$	Mass flow into the superheater
$Flow_{out}$	$\frac{kg}{s}$	Mass flow out of the superheater
h_{se}	$\frac{kJ}{kg}$	Specific enthalpy of the steam entering
h_{sl}	$\frac{kJ}{kg}$	Specific enthalpy of the steam leaving
M_s	$\frac{kg}{mol}$	Molar mass of gas in steam
m_s	kg	Mass of steam
$\dot{m}_{se}$	$\frac{kg}{s}$	Mass flow of steam entering the superheater
$\dot{m}_{sl}$	$\frac{kg}{s}$	Mass flow of steam leaving the superheater
p_s	bar	Pressure in the superheater
ρ_{se}	$\frac{kg}{m^3}$	Density of steam entering the superheater
ρ_{sl}	$\frac{kg}{m^3}$	Density of steam leaving the superheater
R_{gas}	$\frac{J}{K \cdot mol}$	Ideal gas constant
U_s	J	Internal energy of steam
ΔT	${}^{\circ}C$	The temperature difference from start to the end
T_{sl}	${}^{\circ}C$	Temperature of steam leaving
T_{slh}	${}^{\circ}C$	This is a constant where it is assumed that the temperature is 230˚C. It is used to calculated ρ_{sl}
v_{op}	%	Percent the valve before the superheater is open
V_s	m^3	Volume of the steam inside the superheater

10 References

Books

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2. Reguleringsteknik, 4th edition; Ole Jannerup, Paul Haase Sørensen; ISBN: 87-502-0982-5

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4. Introduction to Chemical Engineering Thermodynamiics, Sixth Edition, J.M. Smith/H.C. Van Ness/M.M. Abbott, ISBN: 0-07-118957-2

Web pages

1. http://www.spiraxsarco.com/resources/steam-tables/saturated-steam.asp

2. http://www.lru.dk/nvg/pdf/Opslag19b.pdf

3. http://en.wikipedia.org/wiki/Specific_heat_capacity#Heat_capacity

4. http://en.wikipedia.org/wiki/Vena_contracta

All web pages have been accessed the 06th January 2010.