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Modelling and Parameter Estimation of a Paper Machine Drying Section Using Modelica

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Modelling and Parameter Estimation of a Paper Machine Drying Section using Modelica (Modellering och parameterskattning av torkpartiet i en pappersmaskin)

Abstract
In this thesis a model of the drying process in a paper mill has been adapted to paper machine 3 at Hylte Mill. The model is mainly based on a previous work by my supervisor Ola Slätteke PhD (at the Department of Automatic Control).
New models have also been developed for the condensate system, e.g. condensate tanks, pumps, pipes and siphons. Models with a control system for the drying process have been implemented in the modelling based language Modelica and simulated in Dymola. Due to several unknown modelling parameters, optimisation of parameters has been a part of the work, where different optimisation routines have been investigated. Also sensitivity analysis of uncertain model parameters have been made. Step response experiments have been performed online at Hylte Mill and the results have been used for parameter optimisation and validation. Validated results show that stationary results can be modelled in a good way, even if single parameters have too high or low values. The results also show that it is difficult to use simplified physical models to describe the dynamic behaviour correctly, especially condensate removal and the dead time for paper moisture.

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I also want to thank Johan Åkesson that together with Ola have developed the Modelica Library DryLib which has been frequently used. Åkesson also deserves an acknowledgement for helping me with optimisation questions.

I also want to thank Stefan Snygg and Choy-Hsien Lin at Hylte Mill. I am especially grateful to Choy for taking time for helping me with process descriptions, measurements and answering all my frequently questions about the process structure.

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Contents

Chapter 1

Introduction

The paper industry is an enormous industry with a turnover of 72 billions euros in Europe in 2003 [13]. It is also an industry exposed for high competition and low prices. Therefore it's essential to be able to control and optimise the process. In the paper process, the drying process is the part that consumes most energy, approximately 70 % for newsprint according to [9]. Due to the high energy consumption it's important to understand the process, so that the speed of the production and energy consumption easier can be optimised. A good optimisation usually requires a model. In this thesis a model of the drying process, based from previous work done in[13], is developed. The model is implemented in the simulation computer program Dymola[1] using the object-orientated model based language Modelica[2].

1.1 Problem definition

The goal for this project was to build a model that describes the gross physical behaviour of the drying process for PM3, paper machine 3, at Hylte Mill and implement the model in Modelica. The model was mainly designed to be used for operator training, where an operator could learn more about the process under simulations. For example how a different operating point for a valve connected to a steam group affects temperature and moisture in the paper due to changing cylinder pressure. Other fields of applications could be controller design to improve the performance or a help of assistance for a reconstruction.

The steam and condensate system at Hylte is a cascade system, further explained in section 3.3. A change in a reference value or a control signal at one place can therefore affect the system at other places. This makes its very difficult for an operator to change the control system if needed. Therefore typically some parameters are never changed due to difficulties on predict-

[1] www.dynasim.com
[2] www.modelica.org

ing the process behaviour and the quality parameters. A simulator could therefore be used for training operators to handle more difficult scenarios.

1.2 Methodology

Developing a model of the drying system, simulate and validate it and doing optimisation handles a lot of different physical and mathematical domains. Therefore the first step was to collect material , read it through and get an overview of physics behind paper making and flow systems, mathematics behind optimisation and modelling using Modelica language. Also, time has been spent at Hylte Mill to understand the process better. The model building and the thesis work can be divided in four different sub parts.

- Modelling the drying section based on the Modelica library Drylib.
- Extend DryLib library with fluid components as pipes, pumps, siphons and condensate tanks, to be able to model the condensate system.
- Performing measurements and experiments at Hylte Mill for validation.
- Validate simulations against measurements and calibrate parameters using optimisation methods.

1.3 Outline

The outline of this thesis is following:

Chapter 2 gives a short summary of paper making history and paper manufacturing.

Chapter 3 gives a process description of the drying section.

Chapter 4 explains the control system configuration.

Chapter 5 goes into details of deriving physical models.

Chapter 6 describes measurements and experiments at Hylte Mill.

Chapter 7 presents parameter sensitivity analysis and parameter optimization.

Chapter 8 shows and analysis validation results.

Chapter 9 gives a short overview of the Modelica language and modelling in Dymola.

Chapter 10 presents the conclusion and ideas of future work.

Chapter 2

Paper manufacturing

2.1 History

History of manufacturing paper is over 2000 years old. The first discovery of paper was from China [8] ,were the paper was made of hemp. It was not until the 11th century that the knowledge came to Europe through Arabians. At that time paper were made from liner rags by manually forming a paper on a straining cloth.

Around year 1800, there was a breakthrough in the manufacturing when the paper machine was invented in England and France [8]. Today's manufacturing is a result of constant technical progress where the process have been more automatized and the production speed has increased . Europe's total production capacity 2003 was 105 million tons of paper [13].

2.2 Pulp

Paper consists of networks of fibres [8]. Fibres is usually extracted from wood, but can be extracted from many materials, e.g. straw. The source of fibre gives the paper a unique characteristic. Also the method used to extract fibres affects the paper properties. Pulp is the base for producing paper. It is a liquid that contains a mixture of fibres and water. There are two ordinary methods to produce pulp:

- Mechanical
- Chemical

2.2.1 Mechanical pulp

Mechanical pulp is produced by mechanical means. Woods are split into fine pieces by some mechanical construction.

An advantage with mechanically produced pulp is that the exchange is high compared to chemically produced pulp, approximately 93-96 % [9]. Two disadvantages are that fibres been cut off and losing strength and that the amount of lignin is high, which makes the paper yellow after some time. Which can be seen in old newspaper.

To improve quality and strength usually a part of chemical pulp is mixed into the mechanical pulp.

2.2.2 Chemical pulp

Chemical pulp is produced from a chemical process. Small pieces of wood are boiled together with chemicals.

A disadvantage with chemically produced pulp is the low exchange of wood, only 45-55%. Advantages are that fibres retain their length and therefore are stronger than mechanically produced fibres. The amount of lignin is also lower, which increases quality of the final product.

2.2.3 Fibre structure

Producing paper without water would not be possible [8]. This is due to the papers chemical structure. Fibres produced from a vegetable source contains cellulose and it's cellulose chains capacity of building hydrogen bindings that makes paper making possible. This is also the explanation why paper only can be produced of vegetable fibres and not of e.g. plastic fibres.

2.3 Production from pulp to paper

The process from manufacturing pulp to paper can be divided into a series of several sub processes. The process can differ from factory to factory and what final product that is produced. A short overview of the different sub processes for a normal production is here presented.

2.3.1 Wire section

At the beginning of the wet end the paper is produced by spraying pulp on a fabric. After the paper sheet have been formed, it's essential to remove free water fast, to prevent fibres to cluster [8]. Dewatering of the free water is done by force of gravity and by introducing a negative pressure under the fabric.

2.3.2 Press section

When paper leaving the wet section to press section the moisture content is $\sim 80\%$. When leaving the press section it has decreased to $\sim 50\%$.

The water is mainly removed mechanically, by pressing paper between steel rolls. This is a very cost efficient method for water removal compared to thermal method used in the drying section. Therefore it is desirable to press out as much water as possible. However quality aspects give constraints of how hard the paper can be pressed.

2.3.3 Drying section

In this thesis the drying section is the part that has been modelled and therefore more investigated. (See chapter 3 for a detailed description of the process.)

Incoming paper to the drying section have a moisture content of $\sim 50\%$ and outgoing paper $\sim 10\%$. Steam heated cylinders that paper has to pass over are used for water removal.

2.3.4 Calendering

At Hylte Mill calendering is the last process. It contains of smaller steal rolls, that paper passes between. Where the steel rolls diameter and position can be changed by a hydraulic and a pneumatic control system. The purpose of the calendering are to give the paper a uniform thickness and smooth surface.

Chapter 3

Process Descriptions

3.1 Principles of drying section

In the drying process, water removal from paper is done in a thermal way. The wet and cold incoming paper passes over steam heated cylinders. Heat from hot cylinder shells are transferred to the paper, its temperature is increased and evaporation occurs. A typical drying section contains of:

- high pressure steam source
- enclosed steel cylinders
- condensate system

Valves are connected between the pressure source and cylinders. This makes it possible to control steam pressure inside the cylinders and indirectly also heat flows and moisture content in the paper.

Also several valves are included in the condensate system for controlling condensate flows. Condensate is formed inside the cylinders when steam releases latent energy to the colder cylinder shell and needs to be removed for efficiency reasons, see further section 5.6 for a more detailed description.

3.2 Cylinder configuration

There are mainly two different cylinder configurations. Steam group and drying group configuration.

3.2.1 Steam groups

Cylinders are normally divided into steam groups. A steam group contains of a number of cylinders connected to the same valve. This makes cylinders in a steam group to operate on the same steam pressure. The operating

Steam Group 4	cyl. 1-7	cyl. 1,2,4,6 = c
Steam Group 3	cyl. 8-17	even cyl. numbers = c
Steam Group 2	cyl. 18-37	cyl. 18,20,22,24,26 = c
Steam Group 1	cyl. 38-49	cyl. 39,40,42,43 = c

Table 3.1: Steam group configuration at PM3, c= cold cylinder i.e not steam heated.

steam pressure normally increases with a typical value of $\sim$ 50 kPa [13], for the next coming steam group.

The first steam group operates on a steam pressure around atmospheric pressure. This is not optimal in terms of short drying time and amount of cylinders. But it is necessary for the quality of the paper. A high difference pressure between steam groups, increases the temperature gap. This can make, paper get stuck on cylinders and lead to web breaks. It can also make the paper curl and lead to other quality problems.

3.2.2 Drying groups

The cylinders are also divided into different drying groups. In PM3 there are 5 drying groups.

A drying group consists of cylinders having the same drive system for the fabric. Two common ways to structure drying groups are the one-tire configuration, see figure 3.1, and the two-tire configuration, see figure 3.1.

In the one-tire configuration the paper gets in contact with every second cylinder. Cylinders that are not getting into contact with the paper are typically cold, i.e. they are not steam heated. If a one-tire configuration drying group uses cold cylinders, only one side of the paper is heated.

The first two drying groups at Hylte Mill use one tire configuration. A reason for this is that at the beginning the paper moisture is high. With a high moisture content the paper's strength is low and therefore needs to be supported of a fabric in the free draws.

3.2.3 Cylinder configuration at PM3

The drying process at Hylte Mill PM3 consists of 49 steel cylinders in a series with two different configurations. Cylinder 1 to 27 have an one-tier configuration and cylinder 28 to 49 have a two-tier configuration. They are all of type multi-cylinders and have a diameter of 1.8 m and a length of 8.8 m. The 49 steel cylinders are divided into 4 steam groups. These steam groups are numbered in a reversed order i.e. steam group 1 is the last steam group. The cylinders are also divided into 5 drying groups. Tables 3.1 and 3.2 show the different cylinder configuration. At PM3 several of the cylinders are cold, not steam heated, which are indicated in the tables.

Drying Group 1	cylinders 1-7,	one-tier configuration.
Drying Group 2	cylinders 8-17,	one-tier configuration.
Drying Group 3	cylinders. 18-27,	two-tier configuration.
Drying Group 4	cylinders 28-37,	two-tier configuration.
Drying Group 5	cylinders 38-49,	two-tier configuration.

Table 3.2: Drying group configuration at PM3.

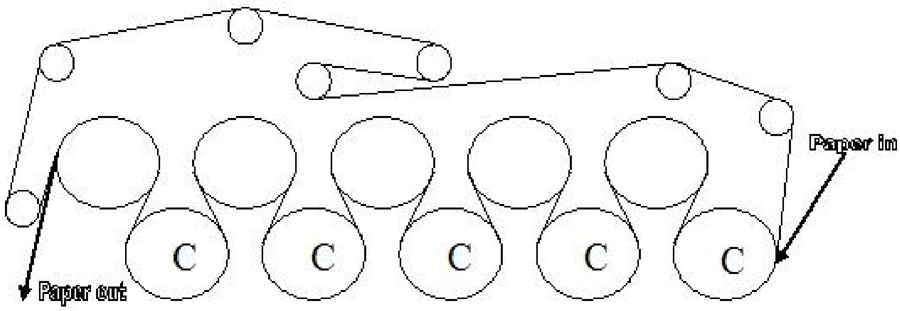

Figure 3.1: Drying group 2 uses a one-tier configuration, C=cold i.e passive cylinder.

3.3 Steam and condensate system

Producing steam is equal with high energy costs. Therefore it is essential to reuse energy from condensate and blow-through steam.

Due to the steam group configuration with different operating points, see section 3.2.1, it is possible to use a cascade structure for reusing steam and condensate from a steam group with higher pressure to a steam group with lower pressure. This configuration can be seen in figure 3.3. A drawback with the cascade structure is that it complicates the control design, due to increased interactions in the system.

3.4 Ventilation system

The ventilation system is not modelled. Instead the air properties, temperature and moisture content, are assumed constant values for each steam group based on average measured values.

Even if the ventilation system is not modelled an understanding of how the ventilation system works is important for doing analysis of measured data and the model. Therefore a short description of the ventilation system is here presented.

The evaporation rates for paper at different cylinders are highly affected by properties of the surrounding air as air humidity and temperature. High

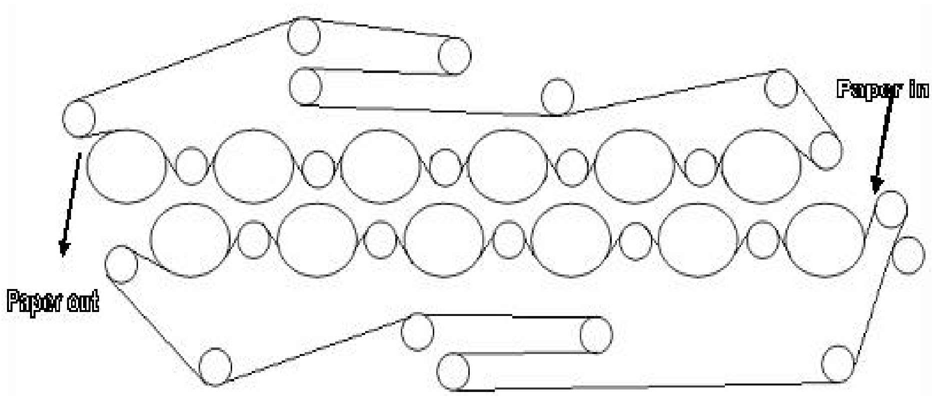

Figure 3.2: DryingGroup 5 uses a two-tier configuration. In the free draw, the paper has no fabric support.

energy losses and bad paper quality can be a result of poorly air conditions. For this reasons its essential to control the air around the drying section.

To be able to control the surrounding air, the drying section needs to be separated from the machine room. This is done be encapsulating it in a hood, see figure 3.4. The hood makes it possible to control the environment inside and outside independent of each other. It also collects the hot and moist air so it could be reused.

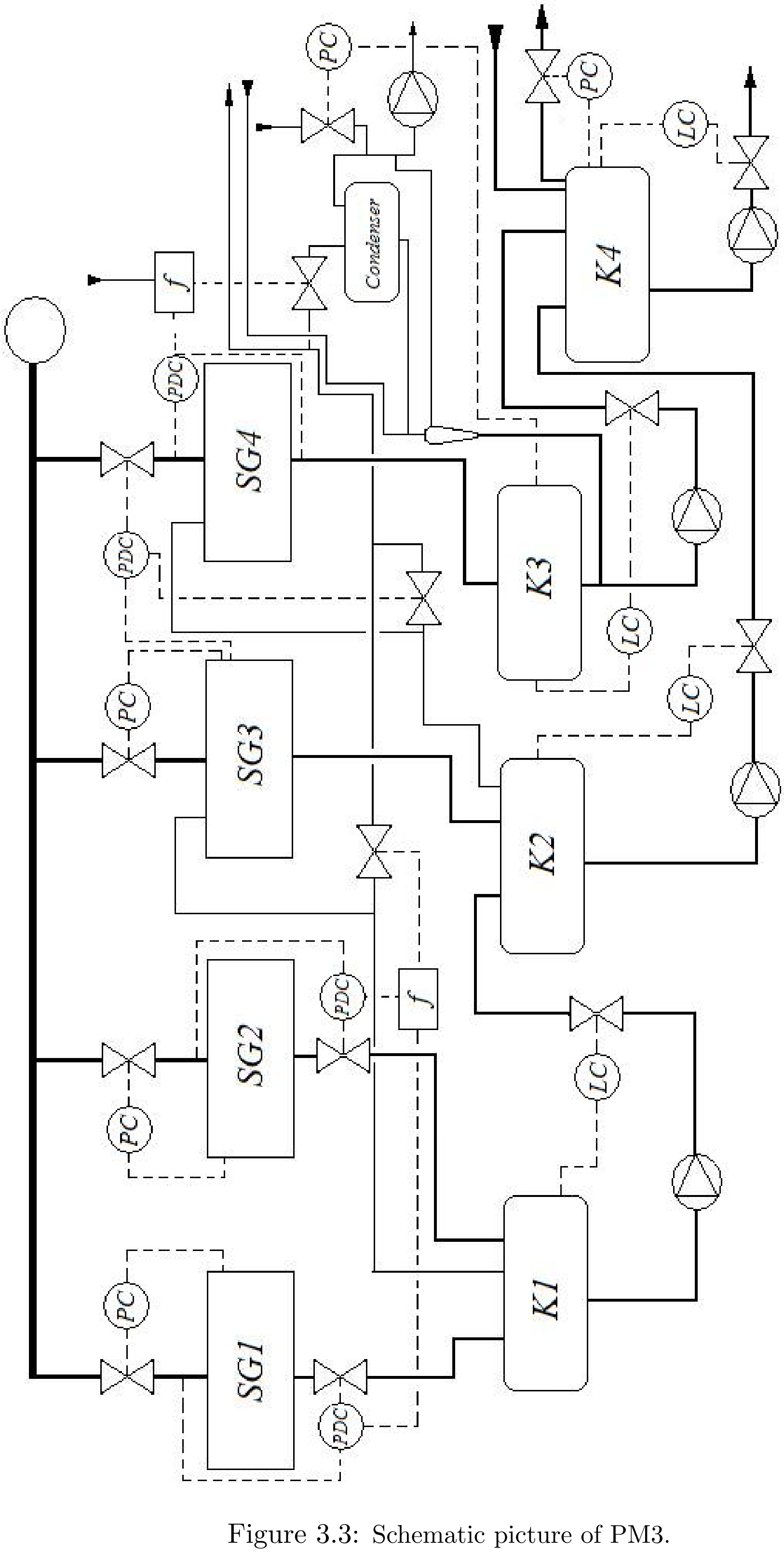

Figure 3.3: Schematic picture of PM3.

Figure 3.4: Dryer section hood at PM3. *Photo by Choy-Hsien Lin.*

Chapter 4

Control System

The control system for the drying process is large and complex due to many variables controlled and the cascade structure. Examples of controlled variables are: steam pressure, moisture profile, paper thickness , paper colour, differential pressures over steam groups and condensate tank levels. Due to simplification in model, see section 5.7, where the paper is treated as one control volume with a constant thickness, control systems for e.g. thicknesses, colour and moisture profile are neglected in the model and therefore not more investigated.

4.1 PI Controller

In the drying section almost every variable is controlled by a PI-controller, a controller with a gain and an integrator. An ordinary PI controller without anti windup can be described by following equation given in [13].

$$u_c(t) = k_c\Big(\beta r(t) - y(t)\Big) + \frac{k_c}{T_i}\int_0^t (r(\tau) - y(\tau))d\tau \tag{4.1}$$

where,
$u_c(t)$ is a control signal,
$r(t)$ is a reference signal,
$y(t)$ is a measured signal and
β, k_c, T_i are control variables.

The input error e is usually multiplied by a scaling. This makes the error dimensionless and prohibits large values of the controller parameters. Also the output is normally scaled.

At Hylte Mill, and in the model PI controllers with anti windup are used.

4.1.1 Split range

Some of the differential pressure controllers have an extra special scaling on the output, called split range. Split range techniques are used to control

u	V1	V2
0	0	100
50	100	100
80	100	0
100	100	0

Table 4.1: Example of a split range control of two valves, V1 and V2. The table specifies the valve openings for a given control signal u.

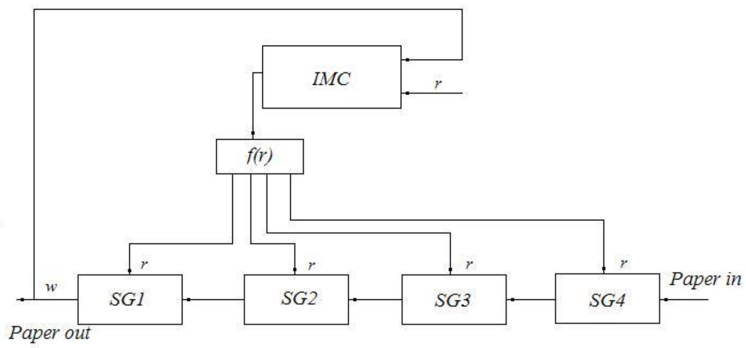

Figure 4.1: Schematic picture of control structure for moisture control.

several variables from a single output. A simple split range controller can be defined in a table. Example, table 4.1, which shows that the controller controls different valves depending on the control signal output.

4.2 Control of moisture and steam pressure

The moisture is controlled by changing the steam pressure inside the cylinders.

The control system for the moisture content can be divided in different levels. At the top level is a internal model controller, IMC. The papers moisture content at the drying process end is a input to this controller. The main output is a reference pressure value, see figure 4.1. This value gives implicitly the reference values in the different steam groups, see section 4.2.1. If the moisture is too high, the controller outputs a higher reference pressure value, and indirect also higher reference values in the different steam groups. Under the main IMC controller are the steam group pressure controllers. They control the pressure in the different steam groups. This is done by changing the openings of the valves connected to the steam groups, see figure 3.3.

4.2.1 Differential functions and quotient functions

The reference pressure values to the steam groups are functions of the output from the top level controller. Two common functions are differential functions and quotient functions. If quotient functions are used, the steam groups reference value is a quote of the output value from the main controller. This quote gets lower for steam groups close at the beginning of the drying section.

At PM3 differential functions are used to control the steam pressure. The output from these functions is the difference between output from main controller and a predefined differential pressure value. These values are at Pm3 normally fixed and not changed for a steam group.

4.3 Control of condensate- and flash system

The control system for the condensate and flash steam is more complex. That is because several of the controllers using a split range technique and that the output to a valve can be a function of different controllers output. The controllers for the modelled condensate and flash steam system can be divided in 3 groups, dependent of what they control.

- differential pressure
- tank level
- Steam flow to condenser and ventilation

4.3.1 Differential pressure

The differential pressure over steam groups are controlled by changing the openings to valves that are placed between a cylinder group and a flash tank. A too low differential pressure, results in an output from the controller that increases the valve opening. An increase in the valve opening should result in a higher flow rate and by that a higher differential pressure.

4.3.2 Tank level

The height of condensate in condensate tanks are controlled by changing the condensate output flow by controlling a valve. The valve is connected to a pipe with the inlet at the flash tank bottom, see figure 3.3.

4.3.3 Steam flow to condenser and ventilation

The steam flow to the condenser and ventilation are controlled by valves. These type of valves are normally closed. A typical opening of a valve is when the differential pressure over a steam group is to low, even if the valve that is supposed to control the differential pressure, is totally opened. To dump steam to the condenser is not an efficient way to reuse energy. That is why these valves normally are closed.

Chapter 5

Modelling

5.1 Physical modelling

Physical modelling is based on physical laws and equations. The advantage with physical modelling is that the interpretation between mathematical expressions in a model and the real physical object is easier to make. Examples are constants coupled to physical properties as e.g. length or mass.

When deriving a model it is important to know in which environment it should be used in. Optimal would be to have a model that is valid under all kinds of conditions. This is in practical impossible but it is usually sufficient to have a smaller operator region that the model should be valid in. Increasing the operator region usually makes the model more complex and gives longer simulation times.

The opposite to physical modelling is black box modelling, where a model is developed from input and output data using identification routines without further information of the process . This normally results in a transfer function that can be difficult to analyse due to lose of physical significance in parameters.

In this thesis the modelling is mainly based on physical modelling.

5.2 Mass and energy balances

Several of the models are based on mass and energy balances in control volumes.

5.2.1 Mass balance

Mass balances are based on the principle that a change of the total mass Δm in a system is equal to incoming mass Δm_{in} minus outgoing mass Δm_{out}.

$$\Delta m = \Delta m_{in} - \Delta m_{out} \tag{5.1}$$

Mass changes under an infinite short time interval, $\Delta t \to 0$, gives following relationship.

$$\frac{\Delta m}{\Delta t} = \frac{dm}{dt} = \dot{m}_{in} - \dot{m}_{ut} \tag{5.2}$$

5.2.2 Energy balance

Energy balances are based on the principle of conservation of energy. A change in energy for a system can be written as

$$\Delta E = \Delta E_{in} - \Delta E_{out} - \Delta Q - \Delta W, \tag{5.3}$$

where, ΔE_{in},ΔE_{out} are incoming respective outgoing energy to the system (J),
ΔQ is energy losses to surrounding environment (J) and
ΔW is the system work on the surrounding environment (J).
Incoming and outgoing energy can be divided into kinetic, potential and internal energy.

$$\Delta E_{in} = \Delta E_{in}^{kin} + \Delta E_{in}^{pot} + \Delta U_{in} \tag{5.4}$$

$$\Delta E_{out} = \Delta E_{out}^{kin} + \Delta E_{in}^{pot} + \Delta U_{out} \tag{5.5}$$

In the modelling of cylinders, see section 5.6, the potential and the kinetic parts have been neglected. For a solid cylinder or tank, ΔW is the work needed for the gas or liquid to leave and enter the control volume.

$$\Delta W = \Delta P_{out} \Delta A_{out} \Delta v_{out} \Delta t - \Delta P_{in} \Delta A_{in} \Delta v_{in} \Delta t, \tag{5.6}$$

Simplifications gives the following expression

$$\Delta W = \frac{\Delta P_{out}}{\rho} \dot{m}_{out} \Delta t - \frac{\Delta P_{in}}{\rho} \dot{m}_{in} \Delta t. \tag{5.7}$$

Using the definition of specific enthalpy, see equation 5.13, gives

$$\Delta E = \Delta m_{in} h_{in} - \Delta m_{in} h_{in} - \Delta Q. \tag{5.8}$$

Energy change during an infinite short time interval, $\Delta t \to 0$, gives

$$\frac{\Delta E}{\Delta t} = \frac{dE}{dt} = \dot{m}_{in} h_{in} - \dot{m}_{out} h_{out} - \dot{Q}. \tag{5.9}$$

5.3 Thermal modelling

The drying section uses thermal energy to decrease the moisture content in the paper. Therefore the modelling mainly consist of describing heat flows, temperature changes and phase transitions. Here follows some definitions and explanations of concepts used in the modelling.

5.3.1 Heat transfer

Heat transfer is normally divided into three categories.

- conduction
- convection
- radiation

5.3.2 Conduction

Conduction is heat transfer of energy on a molecular level [11]. Molecules with higher speed crash into molecules with lower energy and thereby transfer energy. Thermal expansion in a solid material is an example of heat conduction.

5.3.3 Convection

Convection is transport of heat due to bulk movements of a gas or liquid. Convection can be divided into natural/free and forced.

Natural convection is heat transfer due to movements from a density variation [16]. Example of natural convection is heating of air. Heated air increases its temperature and thereby decreases its density which results in a upward movement and transport of energy.

Forced convection is transport of heat due to an external force. Example of forced convection is when a fan or a heating system is used.

In this thesis heat flow due to convection is modelled as

$$Q = aA\Delta T, \tag{5.10}$$

where,
Q is the heat flow (W),
a is a lumped heat transfer coefficient ($\frac{W}{m^2K}$),
A is the contact area and (m^2)
ΔT is the temperature difference (K).

5.3.4 Radiation

Radiation is emission of electromagnetic waves [11]. The formula for the total power W radiated by a black body is

$$W = \sigma\epsilon AT^4, \tag{5.11}$$

where,
σ is the Stefan-Boltzmann constant ($5.67 \cdot 10^{-8}\frac{W}{m^2K^4}$) and
ϵ is the emissivity for a material, ϵ is equal to one for a perfect black body

and zero for a perfect reflective surface.

Due to the fact that the temperature in the model is relative low ~ 80℃, radiation is neglected in the modelling

5.3.5 Enthalpy and internal energy

Enthalpy is an energy term frequently used in thermal modelling. A systems enthalpy H is defined as

$$H = U + PV, \tag{5.12}$$

where,
U is internal energy (J),
P is pressure (Pa) and
V is volume (m^3)

A systems enthalpy is a sum of its internal energy and the work needed to create space for it. Division of equation 5.12 by the systems total mass m, gives the expression for the specific enthalpy

$$\frac{H}{m} = \frac{U + PV}{m} \longleftrightarrow h = u + \frac{P}{\rho}. \tag{5.13}$$

Specific enthalpy is frequently used in energy balances, see equation 5.9, and values for different medias are normally tabulated which makes is suitable for modelling.

5.4 Saturated steam

Drying of paper is based on the principle of steam condensing and releasing latent energy. This makes it important in the modelling to have a correct description of the steam properties. Saturated steam is steam at the phase curve, water and steam having the same temperature and thereby the temperature is only a function of pressure, see figure 5.1.

Super heated steam is steam that contains more energy and having a higher temperature at a specific pressure compared to saturated steam.

In the modelling of cylinders and condensate tanks, steam is approximated to be saturated which makes the models less complex.

There are a lot of data collected in different steam tables. For saturated steam, logarithmic functions of pressure have been adapted to describe temperature, density and enthalpy [13].

5.5 Modelling of the drying process

The goal in this thesis is to model the entire drying process PM3 at Hylte Mill, with its 49 cylinders, condensate system and control system.

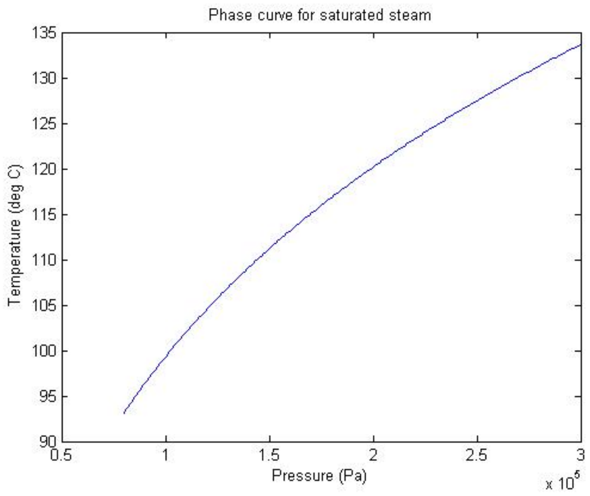

Figure 5.1: Phase curve for saturated steam. The pressure is given in absolute pressure.

The main purpose of the model is to use it to design a simulator for operator training. With that in mind the model can not be to complex and detailed due to constraints on simulation time. Instead a simplified model that is describing the gross physical behaviour is preferred.

The modelling approach has been following. First models of the different components in the drying section, i.e. models of cylinders, paper, valves, siphons, pumps, pipes and condensate tanks have been designed.

A lot of this modelling had already been done by Ola Slätteke and Johan Åkesson. Models of e.g. cylinders, paper, valves, and controllers have been collected in a Modelica library named DryLib, described in [18].

Next step in the model building was to adapt the model to the drying section PM3 and connect the different components. After that identification of uncertain parameters were done, it was followed by static and dynamic validation.

Due to incoming new data under the process the procedure from modelling to validation has not been straight forward. Instead it can be better described as a close cycle, see figure 5.2.

5.6 Cylinder

Multi-cylinders and Yankee-cylinders are two different types of cylinders used in drying processes at different paper mills. In PM3 at Hylte Mill only multi-cylinders are used and therefore they are the only ones that have been modelled and investigated.

A cylinder consists of four main parts, see figure 5.3:

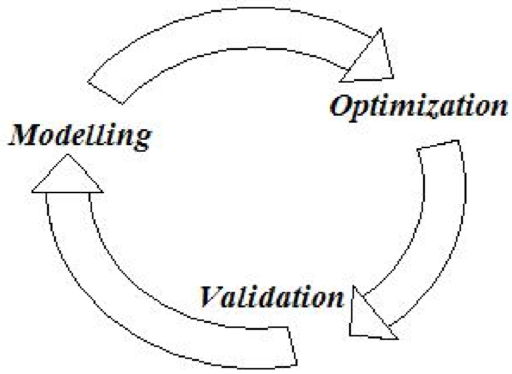

Figure 5.2: Schematic picture of the modelling procedure.

- cylinder shell
- input steam port
- siphon
- spoiler bars

The input port is connected via valves with a high pressure steam source, at PM3 $\sim$ 3 bar total pressure. The valves make it possible to control the steam pressure and indirect the heat flow to the paper.

The siphon can be described as a modified pipe that removes condensate inside the cylinder. See section 5.10 for a more detailed description.

Condensate is formed when incoming steam with high temperature is coming into contact with the colder steal cylinder shell. If the cylinders are driven fast enough, which is the case at PM3, the condensate is forming a rimming layer around the shell. This layer influences the heat flow between steam and cylinder shell negatively due to higher heat resistance. Removal of the condensate is therefore essentially important and besides using siphons to remove condensate, spoiler bars and blow-through steam are used.

Blow-through steam is incoming steam that goes directly to the siphon without condensing.

5.6.1 Approximations and assumptions

The cylinder is modelled as one control volume, i.e. temperature and pressure are assumed to be homogeneous and do not vary in space. The steam is modelled as being saturated, i.e. temperature, density and enthalpy are functions of pressure only. Approximation can be done because of the continuous condensation inside the cylinder. The advantage to treat all steam

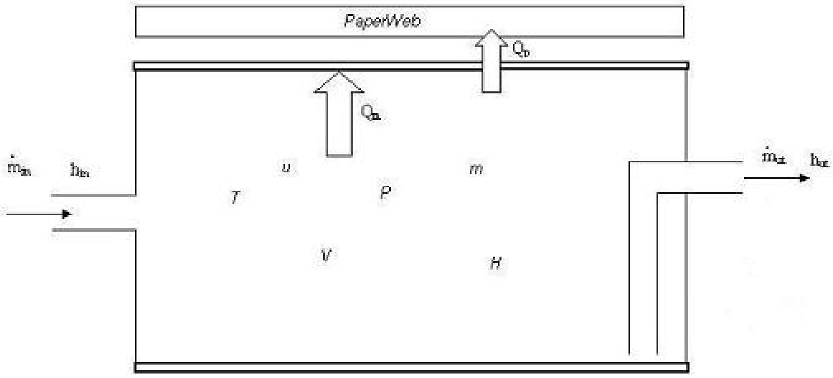

Figure 5.3: Schematic picture showing mass and energy flows in a steam heated cylinder.

as saturated is that it is reducing the complexity of the model and therefore makes it better suited for short simulations time.

The heat transfer coefficient α_c between steam and cylinder shell is not modelled. Instead it used as a fixed value, independent of e.g. condensate thickness.

For cylinders without spoiler bars, α_c depends strongly on condensate thickness and cylinder speed [9]. There it decreases with higher cylinder speeds and larger condensate thickness. At PM3 all cylinders are using spoiler bars.

Spoiler bars are lists on the inside of the cylinder shell. There function is to increase the heat transfer by creating turbulence of the condensate. For cylinders with spoiler bars, α_c is very hard to predict due to the turbulent behaviour [13]. Due to difficulties to predict its value, α_c is used as a tuning parameter. Under conditions when the condensate thickness is constant, as in stationary condition, this is a good approach. Under dynamic conditions, condensate thickness assumes to be fluctuating and therefore approximation α_c as a constant value is gross.

5.6.2 Equations

The following cylinder equations have been developed by Ola Slätteke in [13]. A small modification has been done, where ambient air losses has been included in the model.

Mass balance for a cylinder gives

$$\frac{d(\rho_s V_s) + d(\rho_w V_w)}{dt} = q_s - q_{bt} - q_w, \tag{5.14}$$

where,
ρ_s, ρ_w are density for steam and condensate $(\frac{kg}{m^3})$,

V_s, V_w are the total volume of steam respective condensate inside the cylinder (m^3),
q_s, q_w are the inlet mass flow of steam and outlet mass flow of condensate from cylinder ($\frac{kg}{s}$) and
q_{bt} is the blow-through steam ($\frac{kg}{s}$).

Energy balance for condensate and steam gives

$$\frac{d(\rho_w u_w V_w)}{dt} = q_c h_s - q_w h_w - Q_m, \tag{5.15}$$

$$\frac{d(\rho_s u_s V_s)}{dt} = (q_s - q_b - q_c) h_s. \tag{5.16}$$

Two different models of the cylinder shell dynamics have been used and tested in this thesis.

A simplified model treating the cylinder shell as one control volume with one temperature node that neglects the temperature gradient in the cylinder shell. And a more detailed model based on a discretization of finite differences of the one dimensional heat equation. The discretization have been done by Johan Åkesson and can be found in [20].

Advantages with the more complex model compared to the simplified model are that it describes the dynamic better and it is easier to do validation against cylinder surface temperature measurements. Disadvantages are that it increases the simulation time and makes the dynamic analysis more complicated.

Energy balance for the simplified cylinder shell gives

$$\frac{d(mC_m T_m)}{dt} = Q_m - Q_P - Q_{air}, \tag{5.17}$$

where,
q_c is the condensation rate ($\frac{kg}{s}$),
u_w is specific internal energy for condensate ($\frac{J}{kg}$),
h_s, h_w are specific enthaltpy for steam and condensate ($\frac{J}{kg}$),
m is the mass of the cylinder shell (kg),
C_m is the specific heat capacity for a cylinder shell ($\frac{J}{kg\ K}$),
T_m is the average temperature of a cylinder shell (K) and
$Q_m,\ Q_p,\ Q_{air}$ are the heat flows to cylinder shell, paper and ambient air (W).

Cylinder volume V_{tot} is constant, gives

$$V_{tot} = V_s + V_w. \tag{5.18}$$

Heat flows to cylinder shell and paper are described by,

$$Q_m = \alpha_c A_{cyl}(T_s - T_m), \tag{5.19}$$

$$Q_p = \alpha_{cp} A_{cyl} \eta (T_m - T_p), \tag{5.20}$$

$$Q_{air} = \alpha_{con} A_{cyl} (1 - \eta)(T_m - T_{air}), \tag{5.21}$$

where,
η is the fraction of paper covering the cylinder shell,
T_s, T_p are steam and paper temperature (K),
α_{con} is the heat transfer coefficient between cylinder shell and ambient air $(\frac{W}{m^2K})$,
α_{cp} is a function of moisture according to

$$\alpha_{cp} = \alpha_{p0} + \alpha_{pk} u, \tag{5.22}$$

where,
u is the sheet moisture and
α_{sc} is the heat transfer coefficient between condensate and cylinder shell $(\frac{W}{m^2K})$.

5.6.3 Passive cylinder

As described in section 3.2.3, PM3 uses several passive cylinders, not steam heated.

Due to that only temperature measurements of two passive cylinders were available, they have been modelled as constant temperatures. Introducing the heat transfer coefficient between cylinder, fabric to paper α_{cfp}. Gives a heat flow from passive cylinders to paper described by

$$Q_{cfp} = \alpha_{cfp} A_{cyl} \eta (T_{cyl} - T_p). \tag{5.23}$$

Observe that in general the cylinder temperature T_m are lower than paper temperature and therefore Q_{cfp} is negative.

5.7 Paper

Paper produced at Hylte Mill are going to be used as newspaper. Newspaper is a very thin paper with a dry weight around $45\frac{g}{m^2}$.

The main interest in the drying process is to model the moisture in the paper and see how it is affected by e.g. pressure changes in a steam group.

Another variable that is interesting to model is the temperature of the paper. There are several reasons why it can be interesting to model the temperature. The quality of the paper is affected, a to high temperature can lead to curl or even a web break. Another aspect is that it is easier to measure paper temperature than moisture. If it is not possible to do moisture measurements, validation can instead be done between modelled and measured temperatures.

5.7.1 Approximations and assumptions

The paper is modelled as one homogeneous layer. Paper temperature and moisture content are not varying in the cross- and thickness direction. As the paper is modelled as one homogeneous layer, the diffusion flow inside the paper is neglected.

Definition of moisture

The moisture in the paper can be expressed in two different ways, either by u or w. u is a ratio between water and fibre content and has following definition

$$u = \frac{m_w}{m_f}, \tag{5.24}$$

where,
m_w and m_f are the amount water and fibre in the paper sheet (kg).

w describes the share of water in percentage and are defined as

$$w = \frac{100 m_w}{m_f + m_w}. \tag{5.25}$$

From a mathematical point of view u is better suited to describe the moisture due to its linear form. w instead is the form the moisture at the end of the process is presented in and the form plant operators at the drying process are familiar with.

5.7.2 Equations

Following equations are also taken from [13]. A small modification have been done by introducing the fabric reducing factor, see Stefan's equation 5.29.

Mass balance for moisture gives

$$\frac{d(ugA)}{dt} = d_y v_x g u_{in} - u_{out} - q_{evap} A, \tag{5.26}$$

where,
v_x is paper speed ($\frac{m}{s}$),
A is the contact area between paper and cylinder ($\frac{m^2}{s}$),
g is the dry basis weight ($\frac{kg}{m^2}$) and
q_{evap} is the evaporation rate ($\frac{kg}{m^2 s}$).

An energy balance for paper gives

$$\frac{d(g(u+1)AC_{p,p}T_p)}{dt} = dv_x g(1+u_{in})T_{in,p}C_{in,p} - dv_x g(1+u)T_pC_{p,p} - \\ - Aq_{evap}(\Delta H + \Delta H_s) + Q_p - Q_{air} \tag{5.27}$$

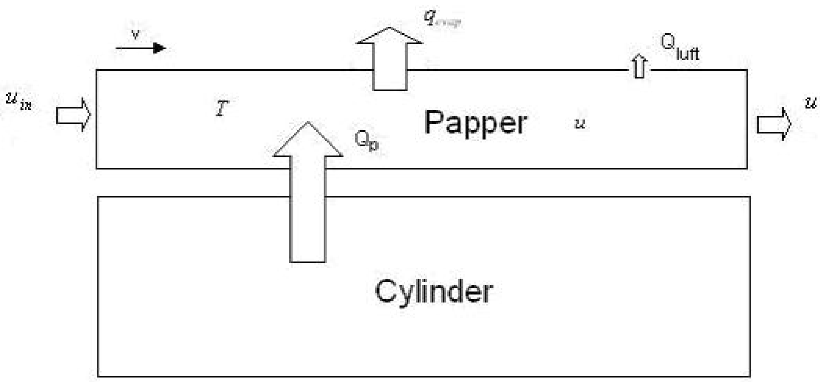

Figure 5.4: Schematic picture of different flows to and from paper

where C_p is a weighted average value of C_{fibre} and C_w ($\frac{J}{kgK}$), calculates as

$$C_p = \frac{C_{fibre} + uC_w}{1+u}. \tag{5.28}$$

The evaporation rate, q_{evap}, can be described by Stefan's equation

$$q_{evap} = \frac{p_{tot}K_{eff}M_w}{R_gT_p} ln(\frac{p_{tot} - p_{v,a}}{p_{tot} - p_{v,p}}), \tag{5.29}$$

where,
M_w is the molecular weight of water ($\frac{kg}{mole}$),
R_g is the gas constant ($\frac{J}{mole\ K}$),
p_{tot} is the total pressure (Pa),
$p_{v,a}$ is the partial pressure for water vapour in air (Pa),
$p_{v,p}$ is the partial for water vapour at paper surface (Pa) and
K_{eff} is the effective mass transfer coefficient $\frac{m}{s}$, defined as
$K_{eff} = Kg \cdot FRF$.

Introduction of FRF, fabric reducing factor, is due to that the evaporation rate is decreased when paper is covered by a fabric. In [17] this factor is experimentally investigated. Note that in [17] it is using a different definition of FRF.

Partial pressure for water vapour in air is a function of water content in air x. The relationship can be described by the following formula, a derivation can be found in [9],

$$p_{v,a} = \frac{x}{x + 0.62} p_{tot}. \tag{5.30}$$

Partial pressure for water vapour on paper surface can be described by Antoine's equation for free water multiplied by a correction term φ. The sorption isotherm φ, is a function that has a value close to one for high moisture values and decreases to zero as the moisture goes to zero. The sorption isotherm describes the relationship between the water content of a hygroscopic substance and the relative humidity of ambient air at a specific temperature [22].

$$p_{v,p} = \varphi \; p_{v0} \tag{5.31}$$

Different formulas of the sorption isotherm can be found in the literature. For mechanically produced pulp can φ be described as

$$\varphi = 1 - e^{(-47.58u^{1.877} - 0.10085(T_p - 273)u^{1.0585})}. \tag{5.32}$$

Antoine's equation is an empirical equation based on measured partial pressures over a temperature range for different substances. The general formula is according to [23]

$$log(p) = A - \frac{B}{T + C}, \tag{5.33}$$

where $A,\ B,\ C$ are fitted parameters for different substances. For free water this formula can be describes as

$$p_{v0} = 10^{10.127 - \frac{1690}{T_p - 43.15}} \tag{5.34}$$

The energy ΔH needed to evaporate water is given by

$$\Delta H = \Delta H_{vap} + \Delta H_s, \tag{5.35}$$

where ΔH_{vap} is the heat of evaporation. ΔH_{vap} varies with temperature, but has in the model been approximated to a constant value of 2260 $\frac{kJ}{kg}$. ΔH_s is the heat of sorption. It describes the extra amount of energy needed to evaporate water at low moisture content, and can be derived from the law of Clausius-Clapeyron to

$$\Delta H_s = 0.10085u^{1.0585} T_p^2 R_g \frac{\varphi - 1}{M_w \varphi}. \tag{5.36}$$

5.8 Valve

The drying section contains several valves. These can be divided in:

- security valves
- control valves

Security valves are valves that in normal operation are totally opened or closed. Valve openings are typically only changed during a stop or reparation Consequently these valves are not included in the model.

Control valves are used for controlling some variable, e.g. steam pressure and water levels in condensate tanks, by changing its opening. In the condensate and steam system almost all variables are controlled by valves.

Valves controlling differential pressure and steam pressure at PM3, have a flow characteristic that is close to equal percentage.

An equal percentage valve has a flow characteristic, where an equal increment of valve opening produces an equal change in flow [10].

According to [10] control valves can be modelled as an orifice with a variable opening. The flow equation is then

$$Q = K_v \sqrt{\frac{\Delta P}{\rho}}, \tag{5.37}$$

where,
Q is the volume flow ($\frac{m^3}{s}$) and
K_v is a function of the valve opening area. Different values of Kv are normally specified for different openings by the producer.

In [15] it is showed for an equal percentage valve that the Kv value can be described by an exponential function of the opening. This gives

$$Q = K_{v0} Rv^{u-1} \sqrt{\frac{\Delta P}{\rho}}, \tag{5.38}$$

where,
K_{v0} is the K_v value at full opening,
R_v is a parameter determining the valve characteristic and
u is an opening parameter. $u = 1$ and $u = 0$ corresponds to a full opened respective closed valve.

In the connector in the implemented model, mass flow instead of volume flow is used. Using following relationship between mass flow and volume flow,

$$\dot{m} = Q\rho. \tag{5.39}$$

Gives the implemented equation

$$\dot{m} = K_{v0} R_v^{u-1} \sqrt{\Delta P \rho}. \tag{5.40}$$

5.9 Pump

The pumps used in the condensate system are centrifugal pumps. The main parts are an electric engine, a pump house and an impeller. The electric

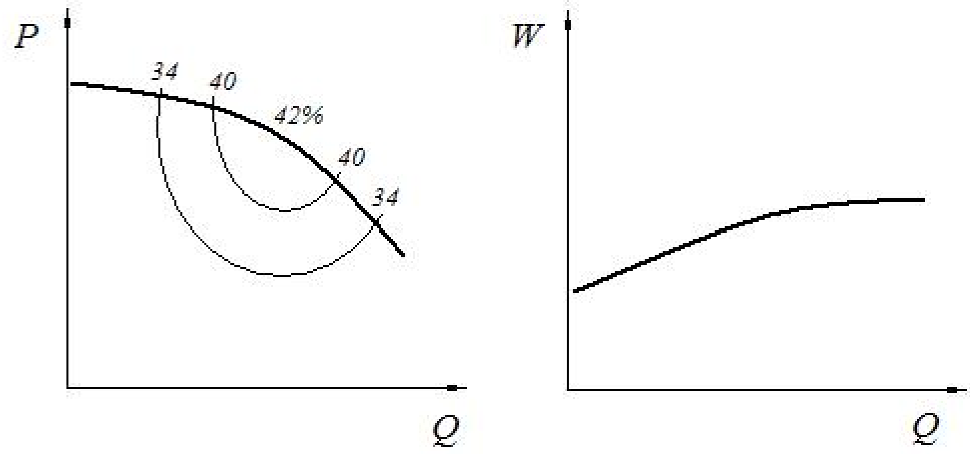

Figure 5.5: Example of a typical pump curve. The left figure shows the flow-pressure ($Q - P$) relationship for the corresponding input power W, shown in the right figure. The contour lines represent the efficiency.

engine is driving the pump wheel forward, which creates an increase in the pressure. The pressure increase is dependent on volume flow, input power and the pumps efficiency. These relations are from the producer normally specified in a diagram called pump curve. A typical pump curve can be seen in figure 5.5.

In figure 5.5 it can be seen that the pump efficiency gets low for high and low volume flows. For that reason it can be useful to simulate flows and from that data choose an appropriate pump with a high efficiency in that region

The pumps in the condensate system are normally manually controlled, by specifying the current in percentage of the nominal value. Therefore a model with the same input is developed.

5.9.1 Model

The relation between pressure gain and volume flow in the pump curve is approximated to be linear at a constant input power, which is a gross approximation.

$$\Delta P = P0(1 - \frac{Q}{Q0}) \tag{5.41}$$

where,
ΔP is the pressure gain (Pa),
$P0$ is the pressure gain at zero volume flow and nominal input power (Pa),

Q is the volume flow ($\frac{m^3}{s}$) and
$Q0$ is the volume flow when $\Delta P = 0$ with nominal input power ($\frac{m^3}{s}$).

A changing input power affects the relationship between ΔP and Q in equation 5.41 and can be modelled according to the affinity laws [24].

Affinity laws:

- Q is $\propto$ to impeller speed.
- ΔP is $\propto$ to $(impeller\ speed)^2$.
- Power is $\propto$ to $(impeller\ speed)^3$.

The affinity laws can be applied if the new operating point having the same efficiency, which is not general true. As it is hard to include changing efficiency, the affinity laws are approximated to be valid for a new operating point.

The input to the model is chosen to be a percentage value of the nominal current. Using following relationship,

- I is $\propto$ to power.

A relationship between Q, ΔP and I can then be set up using the affinity laws:

- Q is $\propto$ to $(I)^{\frac{1}{3}}$
- ΔP is $\propto$ to $(I)^{\frac{2}{3}}$

Include this into equation 5.41 gives the implemented expression

$$\Delta P = P0(\frac{u}{100})^{\frac{2}{3}}(1 - \frac{Q}{Q0(\frac{u}{100})^{\frac{1}{3}}}), \tag{5.42}$$

where u is the current in percentage of the nominal value.

5.10 Siphon

Condensate created inside the cylinders needs to be removed. Otherwise the thickness of the condensate layer around the inside of the cylinder shell would increase. A too high condensate thickness would lead to a decrease of the heat transfer coefficient between steam and cylinder shell.

To remove condensate siphons are placed inside every cylinder.

A siphon is a steel pipe with a rectangular opening at the end, see figure 5.6. Siphons can either be rotating or stationary. A rotating siphon rotates together with the cylinder while a stationary siphon is fixed inside the cylinder. The siphons at PM3 in Hylte Mill are stationary why only a model

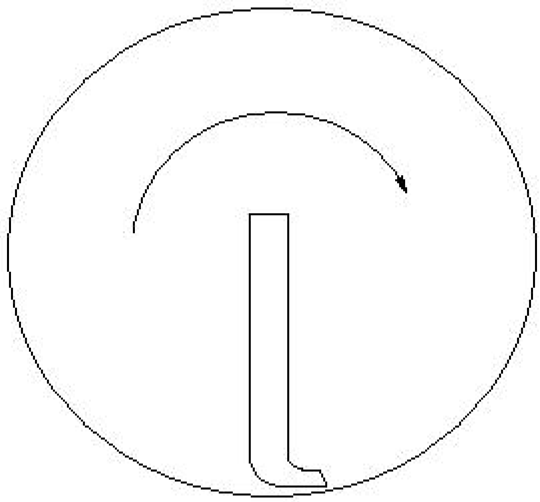

Figure 5.6: Stationary siphon.

of a stationary siphon is developed. Also an orifice plate is connected to the siphon end to reduce the blow-through steam. This affects the behaviour and needs to be included in the model.

The stationary siphons opening is placed a few millimetres from the cylinder bottom and perpendicular to the rotation axis. This has the advantage that condensate's kinetic energy is used to remove condensate, which enables lower difference pressure and consequently lower amount of blow-through steam for higher machine speeds [9].

Blow-through steam

Blow-through steam is steam that goes directly through the cylinder to the siphon without condensing. The main driving force for the blow-through steam is the difference in pressure between cylinder and siphon. A certain amount of blow-through steam is wanted as it reduces inequalities in the condensate layer and removes air and non condensable gases [9].

An obvious disadvantage with a too high blown through rate is that it increases the steam consumption. Therefore it's controlled by changing the differential pressure, see section 4.3.1.

Model

Modelling the siphon can be separated in two problems.

- Model the total pressure loss over siphon orifice and connected pipes.

- Find an expression of removed condensate.

At the entrance of the siphon the blow-through steam entrains and accelerate condensate [14] .The flow inside the siphon is therefore a mixture of steam and gas, a two-phase flow. This makes it difficult to derive a good model of the siphon.

In [14] siphon models are developed. Both models, based on treating the two phase flow as a homogeneous flow and as a separated flow, are investigated. These models can not directly be used because they are developed for stationary siphons and are not including an orifice. But in [14] it says that for a stationary siphon in principle the dynamic pressure can be recovered and the pressure loss is dominated by friction losses. According to [2], pressure losses for orifices and friction, are for an incompressible fluid both proportional to

$$\Delta P \propto w^2 \rho, \tag{5.43}$$

where,
w is the fluid velocity ($\frac{m}{s}$) and
ρ is the density $\frac{kg}{m^3}$.

Treating the two phase flow as a homogeneous flow and approximate formula 5.43 to be valid also for the siphon flow, gives the formula for the implemented equation, using relationship $wA\rho = q$ as

$$\Delta P = k\frac{q^2}{\rho}, \tag{5.44}$$

where,
k is a lumped parameter treated as a tuning parameter,
q is the total mass flow of steam and condensate through the siphon ($\frac{kg}{s}$),
ρ is the average density ($\frac{kg}{m^3}$) and
A is the pipe section area (m^2).

An additional equation is needed to describe the siphon flow. It could either be an equation describing the amount of blow-through steam or an equation for the removed condensate. Several alternatives have been investigated.

Treating the blow-through mass flow as a certain amount of the condensate flow is one of them. The disadvantage is that the outgoing condensate then only is dependent of the unknown parameter k in the siphon equation and the differential pressure. And would therefore not lead to a stationary solution of the condensate volume inside the cylinder, i.e. the condensate volume would be constantly increasing or decreasing.

Another alternative would be to set the outgoing condensate equal to a function of condensate volume inside the cylinder.

The solution that has been used is a more simplified alternative, where the outgoing condensate is equal to the condensation rate filtered through a first order low pass filter

$$qc_{out} = \frac{1}{s\tau + 1} qc, \tag{5.45}$$

where τ is the time constant.

5.11 Condensate tank

Condensate and blow through steam sucked up by the siphon are collected in condensate tanks, enclosed stationary steel cylinders, see figure 5.7.

Due to the condensate tanks lower pressure than the incoming flow, a part of the incoming condensate *flashes* , i.e. it transforms to steam. Of economic reasons flash steam and blow through steam are reused in another steam group with lower pressure. This is practically done by connecting an open pipe between the top of a flash tank and a steam group, see figure 3.3.

The hot condensate is also reused. At the bottom of the tank the condensate is flowing into a pipe connected to a pump. The pump is pumping the condensate to the top of another flash tank, where some of the incoming condensate flashes and the steam are reused in another steam group.

5.11.1 Modelling

Modelling of a flash tank is made by setting up an overall energy and mass balance. Due to the different configuration, flash tanks at PM3 have different inputs and outputs. They have to be modelled individually.

Interesting variables to model are

- pressure
- condensate level
- amount of flashed condensate

Approximations

Steam inside condensate tanks is treated as being saturated and homogeneous, steam and condensate have the same temperature and are not dependent of space. Steam inside cylinder models is treated as being saturated, ingoing condensate and steam to siphon are assumed to have same temperature. Assuming that the temperature dependence is maintained through the siphon. The approximation of treating steam inside condensate tanks as saturated should therefore be not so gross. Another reason to make this

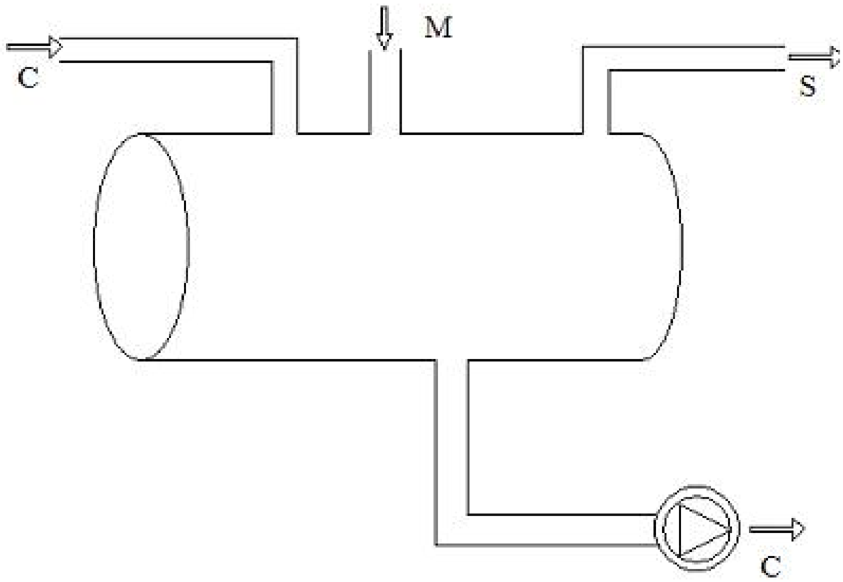

Figure 5.7: A schematic picture of a typical flash tank. S stands for steam, C for condensate and M for mixture of steam and condensate. Condensate tank 2, K2, has this configuration where condensate from condensate tank 1, K1, and a mixture of steam and condensate from steam group 3 are coming into the tank.

approximation is that outgoing flash steam is incoming steam to cylinders that treat the steam as being saturated.

The main advantage with treating the steam as saturated and homogenous is that only one temperature variable is needed, which makes the modelling easier.

Another assumption is that there is an ideal heat transfer between steam, condensate and the tank shell. This makes the shell temperature equal to the temperature of condensate and steam.

The fourth approximation is that heat losses from the outer cylinder shell surface are neglected.

Equations

To be able to model flash tanks and describe its gross behaviour, several equations are needed. Temperature, enthalpy and density are described from the same saturated steam equations used in the cylinder model. Pressure and flash rate are determined by setting up an overall energy and mass balance for the tank, see equations 5.46 and 5.47.

The total mass balance gives the tank changes in mass and indirect the volume. Controllers for the amount of condensate in these tanks are using tank level as control variable. Tank level is defined as the water level in percentage of the tank height. Therefore a mathematical relationship between water level and volume is needed. A derivation can be found in Appendix A, approximating the tank shape with a lying cylinder. This is a small approximation, end of tanks are not complete vertical. Treating the tank as cylindrical makes the calculations easier.

5.11.2 Energy and mass balances

An overall energy balance of a general condensate tank, see figure 5.7 for explanation of index, gives the equation

$$\frac{d(\rho_s u_s V_s + \rho_w u_w V_w + m_{tank} C_p T)}{dt} = \dot{m}_{in}^M h_{in}^M + \dot{m}_{in}^C h_{in}^C - \dot{m}_{out}^S h^S - \dot{m}_{out}^C h^C, \quad (5.46)$$

where m_{tank} is the tank mass (kg).

A corresponding mass balance gives the formula

$$\frac{d(\rho_s V_s + \rho_w V_w)}{dt} = \dot{m}_{in}^M + \dot{m}_{in}^C - \dot{m}_{out}^S - \dot{m}_{out}^C. \quad (5.47)$$

The total tank volume V_{tot}, can be expressed as

$$V_{tot} = V_s + V_w. \quad (5.48)$$

Pressure at the outlet pipe at the tank bottom, is a sum of the steam pressure and pressure from the condensate level according to

$$P_b = P + Lg\rho_c, \quad (5.49)$$

where,
P_b is the tank bottom pressure (Pa),
P is the steam pressure (Pa),
g is the gravitational constant,
L is the condensate height (m) and
ρ_c is the codensate density ($\frac{kg}{m^3}$)

5.12 Pipes

Pipes have been developed for the condensate and flash steam system, where the length of the pipes and the height differences creates pressure losses that are not insignificant.

Three different pipes models have been developed, dependent if the media is steam, condensate or a two phase flow. An alternative would be to develop one pipe model and extend extra information in the connectors. Due to different connector classes this has not been possible.

For two phase flow, pressure loss is calculated according to the same formula used for the siphon, see equation 5.44. And thereby the same approximations are done for the two phase flow as in the siphon.

If the media is condensate it is assumed that pressure loss from friction is insignificant compared to pressure loss from height differences, due to low velocities and high density. Pressure loss in a condensate pipe can then be described by

$$\Delta p = hg\rho_c, \tag{5.50}$$

where,
h is the height difference (m) and
g is the gravitational constant.

Pressure loss in a steam pipe is assumed to be dominated by friction losses, due to high velocities and low density. This gives following expression for pressure loss in a steam pipe

$$\Delta p = k\frac{q^2}{\rho_s}, \tag{5.51}$$

where,
k is a lumped parameter, used as a tuning parameter,
q is the mass flow ($\frac{kg}{s}$) and
ρ_s is the steam density ($\frac{kg}{m^3}$.

5.13 Unmodelled parts

There are several unmodelled parts in the drying section. As mentioned in section 3.4 the air system have not been investigated and modelled in this thesis. Instead air temperature and moisture are described by specified constant values for a steam group based on measurements, see section 6.

Only two of the condensate tanks see figure 3.3 have been modelled, K1 and K2. K3 and K4 are only modelled as constant pressures. K3 is not modelled because the pressure is controlled in a complicated and indirect way that have not been investigated. Assuming the pressure in K3 is constant is actually a good approximation as the pressure control is stable, see figure 5.8. K4 is not modelled due to unmeasured incoming codensate from several different parts of the paper mill. The condenser is also unmodelled and therefore given a constant value.

It can be noticed that these unmodelled parts are not that important, as flash steam from K3 and K4 does not affect any the steam groups.

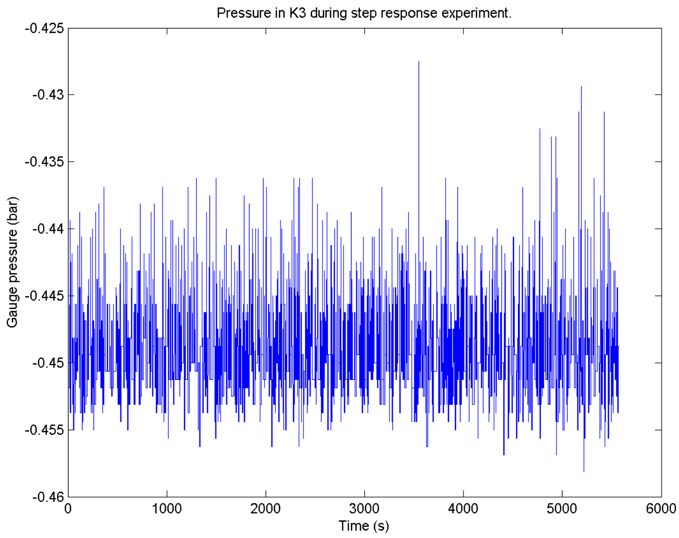

Figure 5.8: Steam pressure in condensate tank K3 during step response experiment, described in section 6.3.

Chapter 6

Measurements and Experiments at Hylte Mill

To build a model of the drying section and validate it, requires several kinds of measurements. Example of different measurements needed:

- Physical data, e.g. cylinder sizes and free draw lengths.
- Environment data, e.g. surrounding air temperature and moisture.
- Static validation data, e.g. steam pressure, paper moisture and temperature.
- Dynamic validation data, e.g. steam pressure, paper moisture and condensate levels variations under a dynamic experiment.

Therefore several different measurements have been done. Data used in static validation are from measurements done by the company Albany International, described in section 6.2.

6.1 Physical data

PM3 consist of 31 active and 18 passive cylinders, totally 49 cylinders. All cylinders except the first one have the same size and are made of the same material. Blueprints of cylinders were available and therefore no measurements on the actual cylinders were needed. They were having following geometry:

- Outer diameter: 1.8 m.
- Width: 8.6 m.
- Shell thickness: 3 cm.

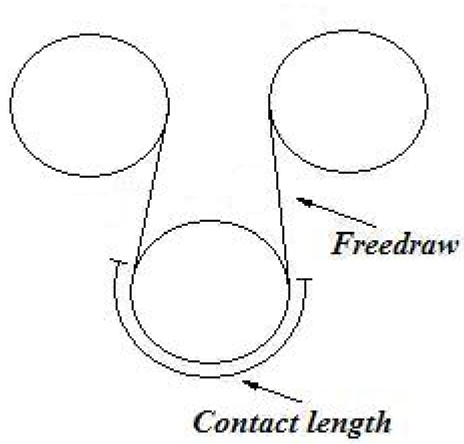

Figure 6.1: Schematic picture, showing measured free draw lengths and contact lengths.

In the blueprints there were no data on free draw lengths and contact lengths, see figure 6.1, available. These values affecting the process and are included in the model. Therefore measuring these values were necessary. This was done during a planned stop with a measuring tape and using simple geometry relations. During the stop all paper had been removed. Measuring length of free draws in steam group 1 and 2 did not give any problems , because paper follows the fabric in the free draws due to the one tier configuration, see section 3.2.2. In steam groups 3 to 5 this was done, using the fact that paper leaves cylinder perpendicular to the normal, see figure 6.1.

13 measurements on contact lengths and 10 free draw lengths were taken. The large amount of measurements were due to the fact that usually the first and the last cylinder in every drying group has a different configuration. Therefore a common measured length based on the symmetry could not be used for all cylinders in a steam group.

The uncertainty in the measurements are approximately up to 2dm.

6.2 Measurements used for static validation

There are no sensors measuring cylinder and paper temperatures. These values must instead be measured manually during normal operation. A company named *Albany International* has made these kinds of measurements 2004 and the result is presented in [1]. Due to that the moisture is only measured at the process end, temperature measurements become an important part when validating the model. This gives temperature measurements a strong influence on the final model and therefore methods and

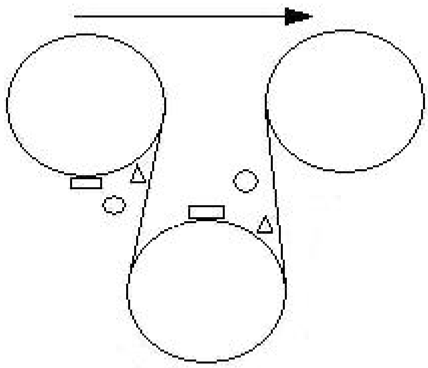

Figure 6.2: Different measurement positions, △, ○ and □ are positions for paper, air and cylinder measurements

result from Albany's measurements will be presented based on [1] .

Four types of measurements were done:

- Cylinder temperature
- Paper web temperature
- Dry and wet temperature of air

6.2.1 Cylinder temperature measurements

Cylinder measurements were made with a contact temperature device, see figure 6.2 for measurement position. All cylinders except the passive ones in drying groups 1-3 were measured.

6.2.2 Paper measurements

Paper temperatures were measured with an infrared thermometer in a position after paper leaving the cylinder, see figure 6.2. Measurements were not made after passive cylinders in steam group 1-3.

6.2.3 Surrounding air measurements

Presented values of properties for the surrounding air, are results based on measured dry and wet temperatures. From these data it is possible to calculate the relative moisture and the dewpoint. In the report the wet temperatures were not presented. Instead the relative moisture together with the dry air temperature were presented.

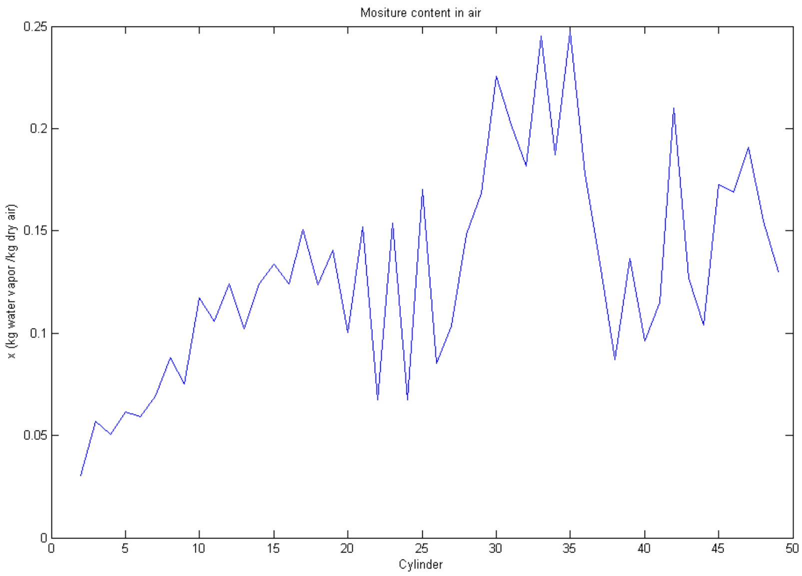

Figure 6.3: Moisture content of air.

The model has two input parameters for the surrounding air, dry air temperature and moisture content. Therefore measurements of the moisture needed to be recalculated.

According to [25], relative moisture is defined as: *The amount of water in the air relative to the maximum amount of water that the air can hold at a given temperature.*

Mathematically this is expressed as the ratio of water partial pressure and the saturation water vapour pressure at the prevailing temperature.

The saturation water vapour pressure can be calculated by Antoine's equation, see equation 5.34. Water partial pressure can then be calculated by

$$p_w = 10^{10.127 - \frac{1690}{T - 43.15}} w_{air}, \tag{6.1}$$

where,
p_w is the water partial pressure (Pa),
T is the air temperature (℃) and
w_{air} is the relative moisture in air (%).

Using equation 5.30 gives the relation between water partial pressure and moisture content of air. The result can be seen in figure 6.3.

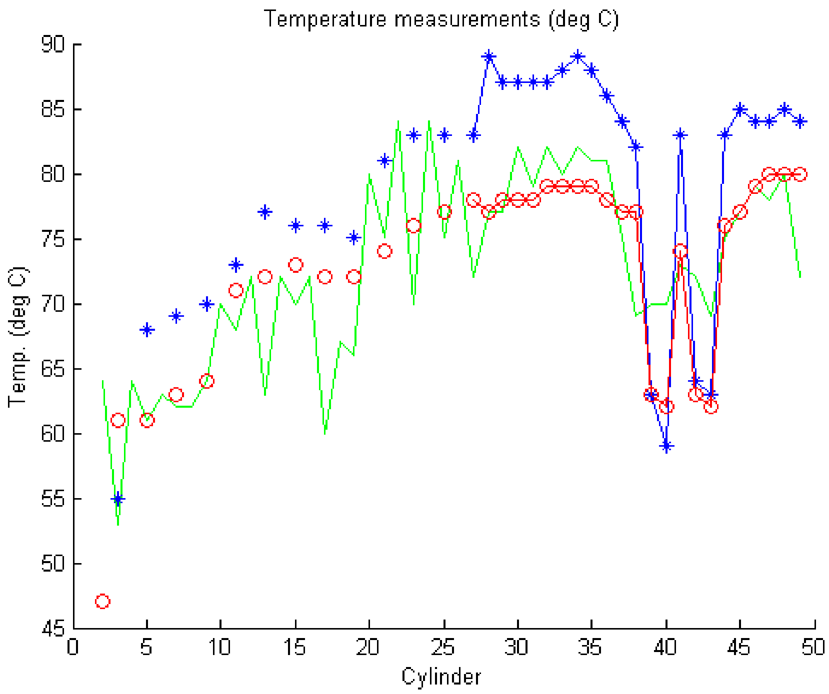

Figure 6.4: Temperature measurements. *, o, -, corresponds to cylinder, paper and air temperatures.

6.2.4 Results

Results from static measurements in [1] are presented in diagrams with low resolution. They are a little bit uncertain, because the measured values have been read manually. Results of cylinder-, paper- and ambient air temperature measurements can be seen in figure 6.4.

6.2.5 Analysis

Measured temperatures and air moisture contain information of the system. Even if the measured air properties are partly controlled by the ventilation system, conclusion of the evaporation rate can be drawn from these measurements. In fig 6.3, showing air moisture content over the cylinders, it can be seen how the air moisture is increasing from the first cylinder until cylinder $\sim$ 30, and also that the air moisture content is lower for the last steam group.

This correspond to the different drying zones. In the first cylinders, transferred energy to paper from cylinder, is mainly used to raise paper temperature, as can been seen in figure 6.4. Because of this the evaporation rate is low. In the middle section, the paper temperature is fairly stable.

This corresponds to the constant drying rate phase, where most energy is used to evaporate water.

The increase in air moisture content, in the middle of steam group 2, is due to changing cylinder configuration from single felting to double felting.

The small increase in temperature at the end of the drying process, and the lower air moisture content, is probably an effect of the low paper moisture content, where hygroscopic effects decreases the evaporation rate. The lower air moisture is also an effect of a lower steam pressure.

It would have been interesting to measure paper and cylinder temperatures over all cylinders, included passive ones. Due to that only two passive cylinder temperature measurements were done, made it very difficult to model them. Also the paper model would have benefitted by making these measurements, as it would have been easier to identify uncertain parameters, as some of them are affecting temperature dips more in free draws. Measuring paper temperatures before cylinders, and on both paper sides, would also be interesting from a modelling point of view, even if this model only uses one homogeneous paper temperature.

6.3 Dynamic measurements and experiments

During a visit at Hylte Mill, step response experiments and measurements were made to collect information of the dynamic behaviour of the system.

6.3.1 Step response preparations

The pressure set point for the leading steam group was set to manual mode. In automatic mode this set point is an output from a controller, see section 4.2, and therefore changes the set point to compensate for deviations in the final moisture content. Also the controller for the paper basis weight was set to manual mode. This controller changes the amount of fibre in paper due to deviations in the paper moisture content and was therefore set too give a constant density of $45\frac{g}{m^2}$.

6.3.2 Restrictions

The set point for the final paper moisture content was 9.5 %. Due to requirements of the product, the moisture content had to be in the interval $9-10\%$. These restrictions gave an upper bound of the step response amplitude.

6.3.3 Execution

The set point for the steam pressure was manually changed to a new value when the process seemed to be stable. After the moisture content seemed to reach its new steady state value, or if the moisture content was close, to its

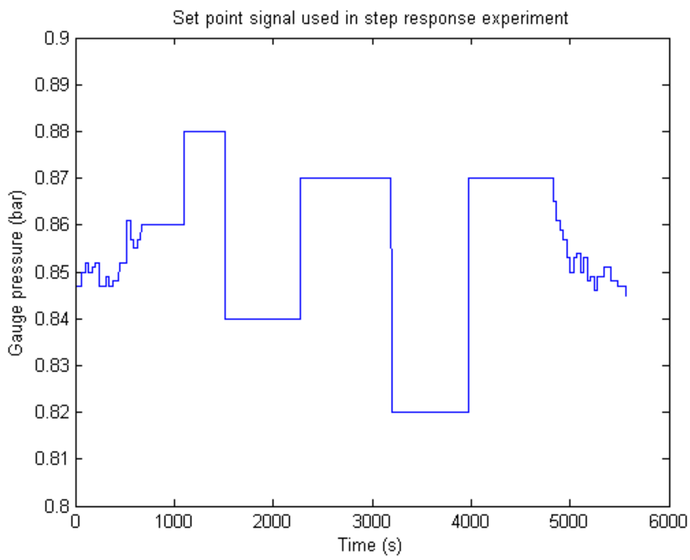

Figure 6.5: Set point signal for steam group 2 under a step response experiment.

maximum or minimum value, a new value for the set point was given. This procedure was repeated several times. The set point signal for the leading steam group, SG2, can be seen in figure 6.5.

6.3.4 Logging

During the step response experiment, interesting measured data was logged. About 90 different variables were saved on a PC. Examples of logged variables:

- final moisture content
- steam group pressure
- differential pressure
- condensate tank levels
- control signals
- steam flow to PM3

Even that ∼ 90 variables were logged, it would have been optimal if also following variables could been logged: Paper and cylinder temperatures, paper moisture content at different cylinders, pressure inside condensate tanks K1 and K2 and condensate and steam flows in the condensate system.

6.3.5 Results

Interesting logged data from these experiments are presented together with simulated results in section Validation.

Chapter 7

Parameter Optimisation

The model consists of several unknown and uncertain parameters. Before a simulation these have to be specified. Due to the large amount of unknown parameters some need to be fixed and other lumped into parameter sets.

Example of a parameter that can be lumped into one global is α_c, heat transfer coefficient between steam and inner surface shell. It is strongly dependent of condensate thickness inside the cylinder shell and therefore each cylinder have an individual value. It would be optimal to model α_c, but this is very difficult due to a turbulent and nonlinear behaviour. Instead it is treated as an unknown fixed parameter.

To give every cylinder an individual value would be very impractical and probably lead to an over parameterized model. Therefore it is more suitable to aggregate this parameter into parameter sets. A gross alternative would be to use a global common value of α_c for all cylinders. Another alternative is to have a common parameter for cylinders in a steam group. This could be a good approximation as cylinders in a steam group operates under similar conditions.

Due to the large amount of unknown parameters, a simple parameter sensitivity analyse is done before setting up the optimisation criteria.

7.1 Parameter analysis stationary model

To be able to set up a parameter optimisation criterion, optimisation parameters need to be specified. Optimal would be to use all uncertain parameters as optimisation parameters. The problem with this solution is the large amount of unknown parameters, which creates a big optimisation task to solve and probably an over parameterized model.

An over parameterized model gives a good fit to the optimisation data, but do not describe the system in a correct way. During different operator conditions the model will therefore give an incorrect description of reality. This can be discovered during validation. Due to lack of data during this

Parameters	Min	Max	Nominal value
Kg [m/s]	0.01	0.06	0.03
α_c $[W/m^2K]$	300	4000	700
α_{con} $[W/m^2K]$	0	300	700
α_{P0} $[W/m^2K]$	0	1400	300
α_{pk} $[W/m^2K]$	500	5000	2000
FRF	0.5	1	0.7
Air moisture [·]	-25%	+25%	(0.06,0.11,0.15,0.14)
Air temperature [°C]	-4°C	+4°C	(61,67,77,73)
Free draw lengths [m]	-25%	+25%	Measured values
α_{cfp} $[W/m^2K]$	0	900	300
Incoming sheet temp. [°C]	20 °C	50°C	30°C
Incoming sheet moisture [%]	42%	60%	53%

Table 7.1: Parameter values used in sensitivity analysis. Note that min and max values for air moisture, air temperature and free draw lengths are relative to the nominal values.

project, validation has been a big difficulty.

Another problem with an over parameterized model could be parameters affecting the model in a similar or opposite way. This could lead to unrealistic values for the parameters but could partly be solved by introducing constraints in the optimisation criteria.

Except describing realities in a good way the model should be as simple as possible. Therefore it is desirable to try to minimise the amount of parameters, specially the uncertain ones. This could be easier done with a good understanding about the process and therefore the need of a sensitivity analysis. Even if several parameters are dependent of each other, conclusions can be drawn from these simple analysis.

7.1.1 Conditions

Analysis of the model parameters have been made by changing one parameter and then simulating the model until a stationary solution has been reached. Then the parameter has been changed back to its nominal value and then the same procedure with a new parameter has been made.

This has been done under the same conditions, i.e. the same steam pressure has been used under all simulations. Due to efficiency reasons, a model without condensate system, outgoing condensate is equal to incoming steam filtered with a low pass filter, has been used. Also a finite difference discretized cylinder model with 3 dynamic states have been used, see section 5.6.2.

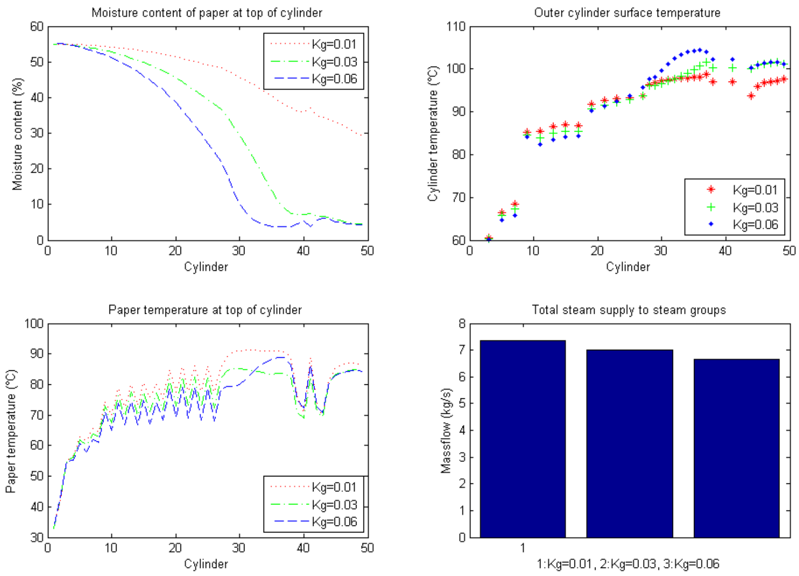

Figure 7.1: Results from sensitivity analysis of the mass transfer coefficient Kg.

7.1.2 Mass transfer coefficient Kg

The mass transfer coefficient Kg is proportional to the evaporation rate, see Stefan's equation 5.29, and therefore strongly affecting the moisture content in the paper. Kg is a function of several parameters and has in [17] been calculated for different environments. Calculated values have been in the interval 0.05-0.06.

Because the paper model used in this thesis is a homogeneous model neglecting diffusion inside the paper, the physical value of Kg would give a too high evaporation in the falling rate section according to [9] . Therefore Kg is used as a tuning parameter.

Paper temperatures for the lower value of Kg are in general some degrees higher than for the higher values of Kg. Also the temperature *dips* have general lower values. The higher paper temperatures are results of lower evaporation rate. Lower evaporation results in higher temperatures due to less energy, are used to evaporate water and instead used to raise paper temperatures .

For moisture contents under $\sim 15\%$, hygroscopic effects start to effect the paper. Then the temperature start to raise due to physical difficulties to evaporate water from an almost dry paper. A higher paper temperature decreases the heat flow from the cylinders, and consequently the cylinder temperatures start to increase.

The higher value of the total steam supply to the steam groups for the

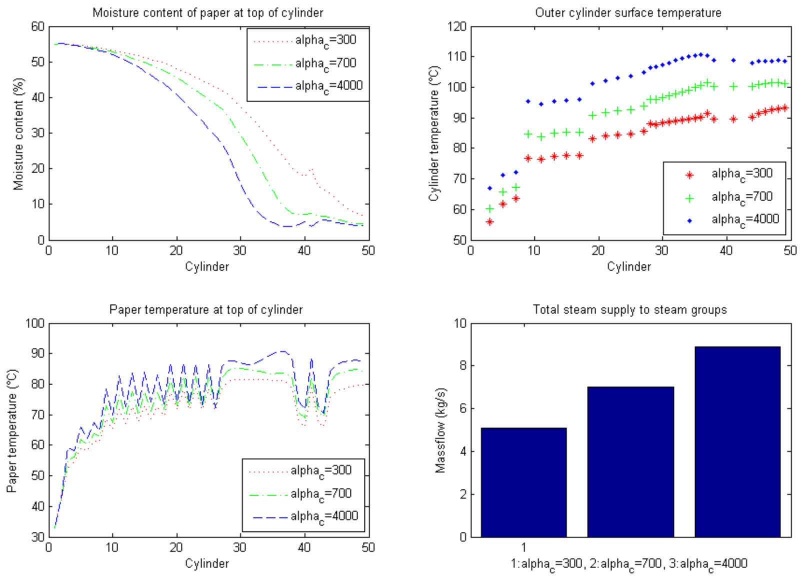

Figure 7.2: Results from sensitivity analysis of the heat transfer coefficient between condensate and cylinder shell α_c.

lower Kg value, is a result of higher paper- and cylinder temperatures. In the simulated model, ambient air temperatures are not modelled and therefore only set to fixed values. Higher paper temperatures therefore result in higher energy losses to ambient air and also higher steam consumption.

7.1.3 Cylinder-condensate coefficient α_c

α_c is the overall heat transfer coefficient between condensate and cylinder shell, see section 5.6.1. Due to difficulties to predict its value, α_c is used as a tuning parameter in the model and therefore needs to be investigated.

As expected it strongly affects all investigated values, see figure 7.2. A higher value increases cylinder temperatures, that affecting paper temperatures and evaporation rate.

The total steam supply also increases significantly with higher α_c values. The largest part of this increase is from ambient air losses, due to the constant air properties used in the model. Another part is due to a lower final sheet moisture, and by that also a larger influence of the heat of sorption.

7.1.4 Ambient convection coefficient α_{con}

α_{con} is a lumped parameter, describing the convection heat transfer coefficient between paper/fabric and air and cylinder shell and air. Its value

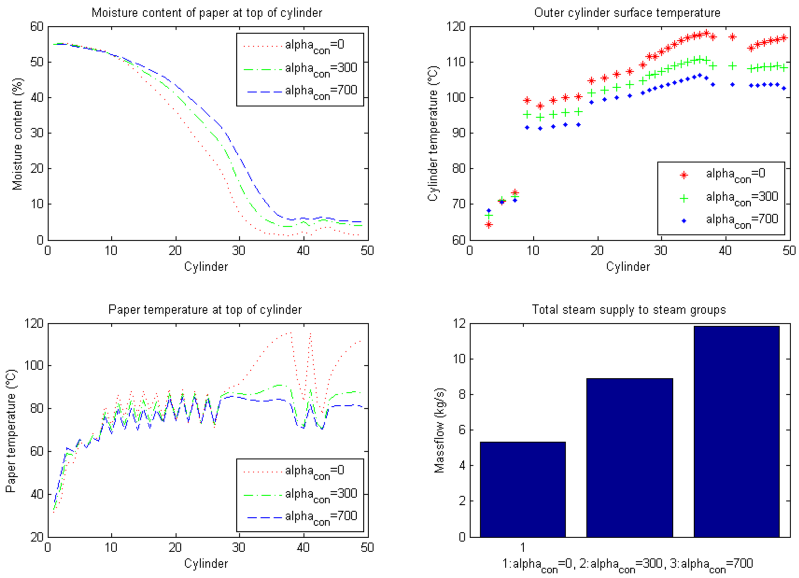

Figure 7.3: Results from sensitivity analysis of the heat transfer coefficient between air and paper/cylinder shell α_{con}

is unknown due to the air turbulence and forced convection that the ventilation system creates. The difference in cylinder temperature and paper moisture content, between the three simulated values, is extra obvious when the paper moisture is reaching the hygroscopic region. A higher value of α_{con} gives lower temperatures. Also the stationary moisture content is affected.

The total steam consumption is also strongly affected. This is due to increasing energy losses to ambient air for higher α_{con} values. According to [17] $\sim$ 70% of the total energy are used to evaporate paper moisture. For this reason 700 is an unrealistic value of α_{con}, as more than 50% of the total energy distribution is ambient air losses, see figure 7.3. A disadvantage with a too high value, except that the parameter loses its physical significance, is that the constant air temperatures strongly are affecting the model.

7.1.5 Cylinder-paper heat transfer coefficient α_{P0}

α_{P0} and α_{pK} are together describing the heat transfer coefficient between cylinder and paper, according to equation 5.22. A change in α_{P0} is therefore mostly affecting the system at lower moisture contents. This can be seen in figure 7.4, where the difference in cylinder and paper temperature for the three values of α_{P0} is increasing as the moisture content is decreasing.

A higher value is decreasing cylinder temperatures and increasing paper temperatures. The formula for the cylinder shell gives the explanation, see

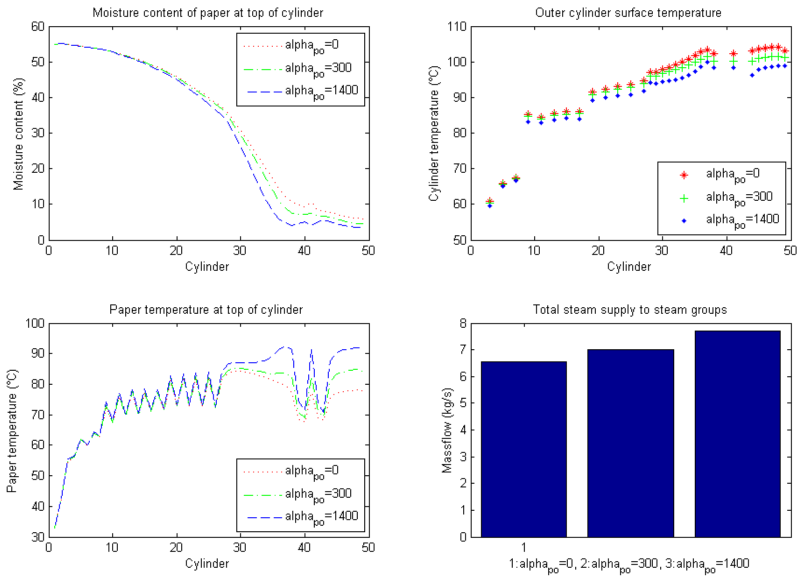

Figure 7.4: Results from sensitivity analysis of the heat transfer coefficient between cylinder shell and paper α_{P0}.

equation 5.20. Qp increases with higher value of α_{P0} and by then decreases T_m. Higher heat flows to the paper raise paper temperatures and also the evaporation. This increases the total steam consumption.

7.1.6 Cylinder-paper heat transfer coefficient α_{Pk}

The effect of α_{Pk} is the same as for α_{Pk} except that the biggest influence is at high moisture content values. An effect easier to see in figure 7.5, is that the temperature *dips* increase in amplitude with a higher value of α_{Pk}.

7.1.7 Fabric reducing factor Frf

Frf is the fabric reducing factor coefficient. It reduces the evaporation rate when fabric is between paper and surrounding air, by reducing Kg according to equation 5.29.

Different fabrics have been investigated in [17], and most of them were having a Frf value in the interval 0.5-0.8. Note that the definition of Frf is not the same.

The effect of Frf is very similar to Kg, but not the same. A change of Kg will affect the evaporation rate over the entire drying system, while a change of Frf only changes the evaporation where fabric is in contact with paper. For a two tier configuration a change of Frf only reduces evaporation over cylinders and not in free draws.

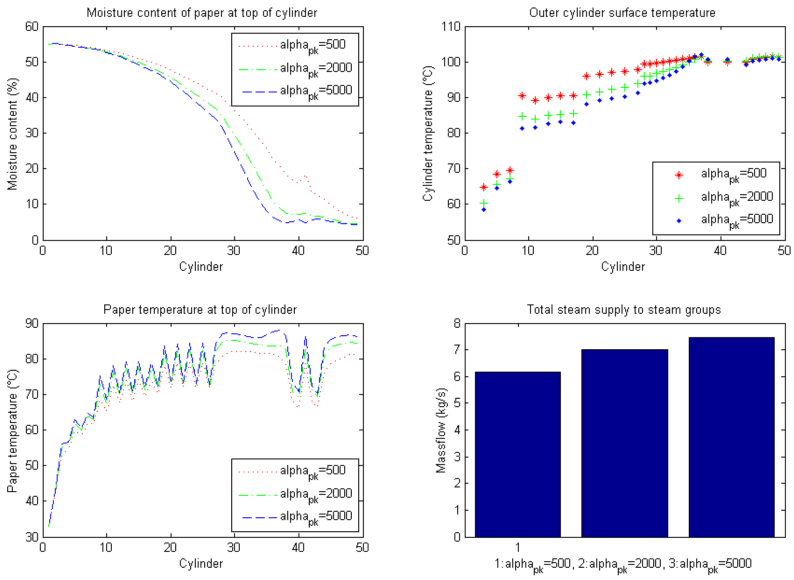

Figure 7.5: Results from sensitivity analysis of the heat transfer coefficient between cylinder and paper α_{Pk}.

In figure 7.6 it can be seen that the Frf value is not affecting temperatures and mass flow in a dramatic way, why a good approximation can be to set the Frf value to 0.7 and then instead use Kg as a tuning parameter.

7.1.8 Moisture content in ambient air

The driving force for evaporation is difference in vapour partial pressure between air and paper. Vapour partial pressure in air is dependent on temperature and moisture content in air, see section 5.7.2.

Neither air temperatures nor moisture contents are modelled. Instead constant values are used based on measurement, see section 6.2. These values change under different operator conditions and it is interesting to see how sensitive the model is for variations in these parameters.

An increase in the moisture content gives a lower evaporation rate as expected and can be seen in figure 7.7 which also shows that temperatures and the total steam supply are almost unchanged.

7.1.9 Ambient air temperature

As explained in section 7.1.8, ambient air temperatures are described by constant values based on measurements. Therefore it's interesting to see how sensitive the model is to these measurements.

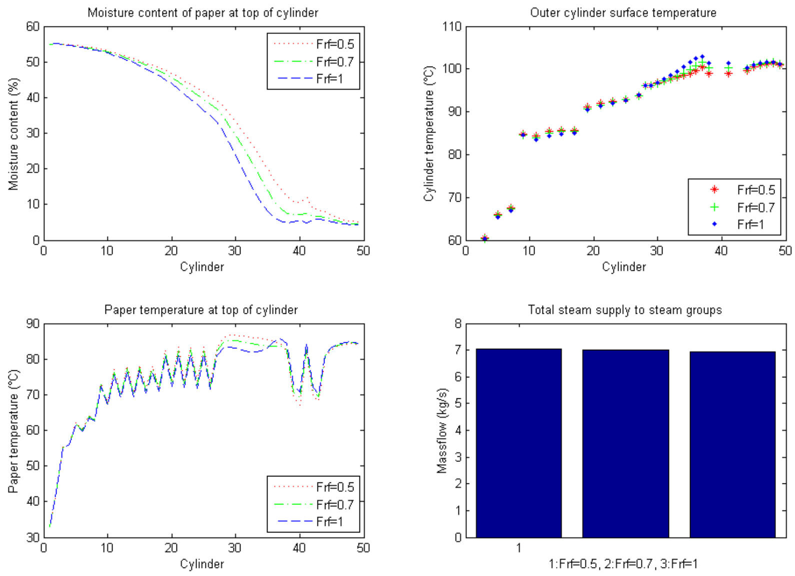

Figure 7.6: Results from sensitivity analysis of the fabric reducing factor Frf.

Figure 7.8 shows that a change of air temperature with 4 degrees ℃, affects both moisture content, temperature and total steam supply in a noticeable way. During this simulation a high value of α_{con} has been used. This explains the large variations for the different temperatures.

7.1.10 Length of free draws

Length of free draws were measured at Hylte Mill, see section 6.1. The uncertainty in these measurements were approximately up to 15% . Results from simulations were these lengths were changed +- 25% can been seen in figure 7.9. The result was expected, with higher evaporation and larger temperature *dips* for longer free draws. Due to increased evaporation time in free draws.

7.1.11 Cylinder-fabric-paper heat transfer coefficient α_{cfb}

α_{cfp} is the heat transfer coefficient between passive cylinder shell, fabric to paper. In [17] this value was calculated for a modern synthetic dryer fabric to 63 $\frac{W}{m^2K}$. In contrast to this value it was presented that a value of 300 $\frac{W}{m^2K}$ gave better simulation results.

Three different values of α_{cfb} were tested and simulated, see diagram 7.10. Their can it be seen that it mainly affects the amplitude of paper temperature *dips*.

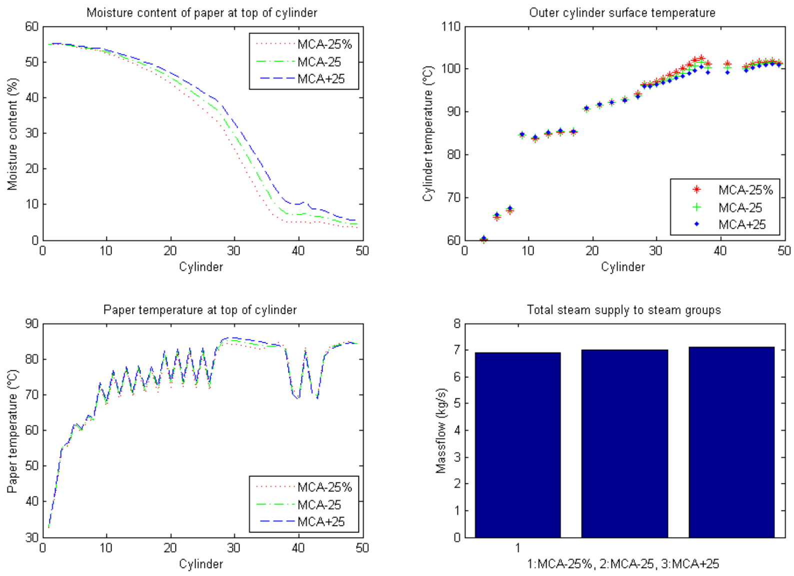

Figure 7.7: Results from sensitivity analysis of the moisture content in ambient air.

7.1.12 Temperature of incoming paper

Incoming paper temperature from press section is not measured. It is assumed that it is in the range of 20-50℃. Three different values in the same temperature range were simulated. In figure 7.11 the results are presented. The incoming paper temperature is almost only effecting the paper temperature for the five first cylinders.

Therefore it can be seen as a good approximation to have the incoming paper temperature as a constant value of e.g 30℃.

7.1.13 Incoming sheet moisture.

At Pm3 the sheet moisture is only measured at the end of the drying process. Consequently the moisture content in incoming paper is unknown. It is assumed that it is in the range of 40-55%.

Three different values of incoming paper moisture have been simulated and this can be seen in figure 7.12. As expected a higher incoming moisture content increases the total steam supply, due to more evaporated water.

The differences in cylinder temperature are due to a combination of a higher α_p and difference in evaporation rate. A higher value of α_p increases the heat flow from the cylinder, provided that the paper temperature is constant.

A higher moisture content is equal to higher vapour partial pressure and

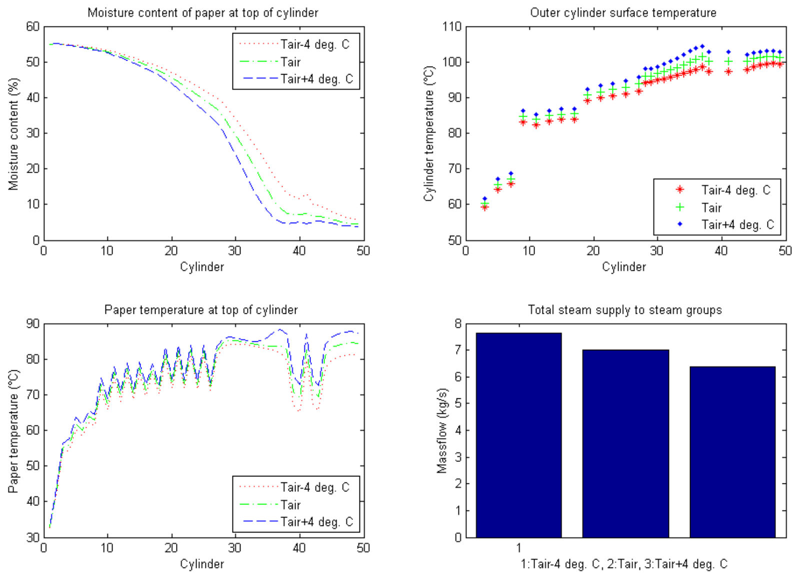

Figure 7.8: Results from sensitivity analysis of ambient air temperature.

according to Stefan's equation 5.29, higher evaporation rate. Thereby more energy is used for evaporation. A higher evaporation rate and α_p explains the small difference in paper temperature and the larger difference in cylinder temperature.

7.2 Parameter analysis dynamic model

It is not only the stationary conditions that the model is supposed to describe. Also the moisture dynamic is interesting, especially from a control point of view. For this reason the dynamics are investigated both theoretically and with simple parameter analysis.

7.2.1 Time constant calculations

Assuming that the cylinder shell is determining the time constant of the paper moisture, due to the large difference in mass between cylinder shell and paper. Then the time constant can calculated with equations 5.17, 5.19, 5.20 and 5.20.

$$\frac{d(mC_{sh}T_{sh})}{dt} = Q_m - Q_p - Q_{air}$$
$$Q_m = \alpha_{sc}A_{cyl}(T_s - T_m)$$
$$Q_p = \alpha_{cp}A_{cyl}\eta(T_m - T_p)$$

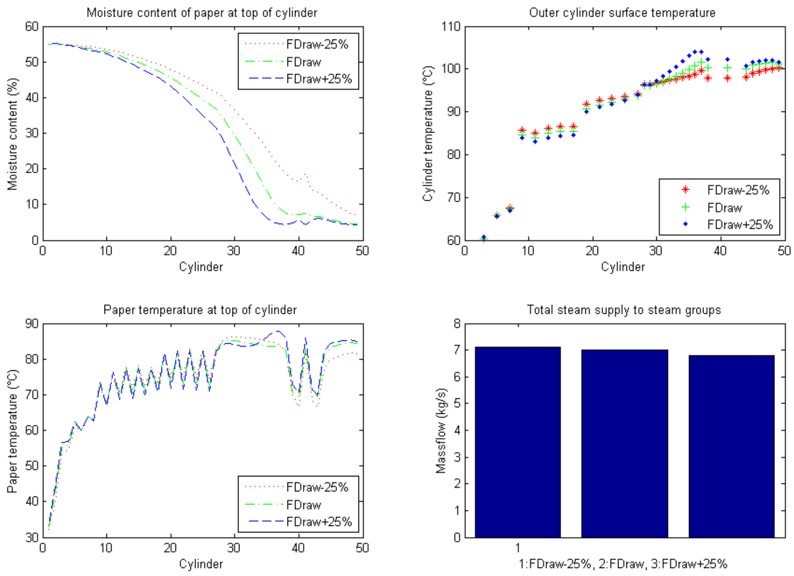

Figure 7.9: Results from sensitivity analysis of free draw lengths.

$$Q_{air} = \alpha_{con} A_{cyl}(1-\eta)(T_m - T_{air})$$

$$\Longrightarrow \frac{d(mC_{sh}T_{sh})}{dt} = \alpha_{sc}A_{cyl}(T_s - T_m) - \alpha_{cp}A_{cyl}\eta(T_m - T_p) - -\alpha_{con}A_{cyl}(1-\eta)(T_m - T_{air}) \Leftrightarrow \tag{7.1}$$

$$\frac{d(mC_{sh}T_{sh})}{dt} = \alpha_{sc}A_{cyl}T_s - (\alpha_{sc} + \alpha_{cp}\eta + \alpha_{con}(1-\eta))A_{cyl}T_m + +\alpha_{con}A_{cyl}(1-\eta)T_{air} \tag{7.2}$$

Laplace transformation gives

$$T_m = \frac{\frac{\alpha_{sc}}{\beta}}{\frac{mC_m}{\beta A_{cyl}}s + 1}T_s + \frac{\frac{\alpha_{cp}\eta}{\beta}}{\frac{mC_m}{\beta A_{cyl}}s + 1}T_p + \frac{\frac{\alpha_{con}(1-\eta)}{\beta}}{\frac{mC_m}{\beta A_{cyl}}s + 1}T_{air}, \tag{7.3}$$

where $\beta = \alpha_{sc} + \alpha_{cp}\eta + \alpha_{con}(1-\eta)$.

Assuming the paper temperature is constant gives the time constant τ between T_s and T_m as

$$\tau = \frac{mC_m}{\alpha_{sc} + \alpha_{cp}\eta + \alpha_{con}(1-\eta)A_{cyl}}. \tag{7.4}$$

Even if equation 7.4 is based on assumptions that the paper temperature is constant, the control system is fast and the cylinder shell can be described by one temperature. It gives an approximation of the time constant for the moisture content and which parameter that is affecting it.

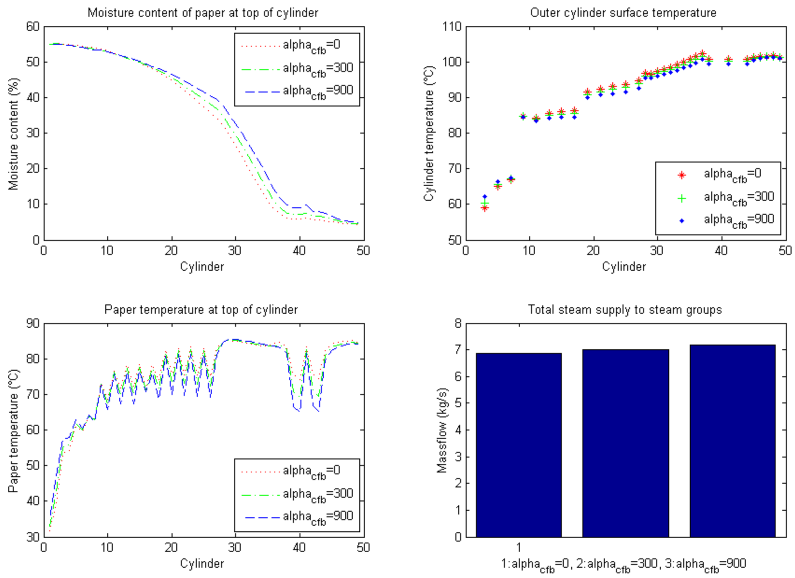

Figure 7.10: Results from sensitivity analysis of the heat transfer coefficient between passive cylinder shell, fabric to paper α_{cfp}.

7.3 Dynamic sensitivity analyse

From the calculation of the time constant, see equation 7.4, it can been seen that α_c, α_{cp} and α_{con} are affecting the dynamic behaviour. Therefore have simple dynamic sensitivity analysis of these parameters been done.

7.3.1 Conditions

Analysis of the model parameters have been done by changing one parameter and then simulating the model. All simulations have been done under same conditions. Their the same steam pressure and step response have been used. Two values were simulated for each investigated parameter.

Due to efficiency reasons, a model without condensate have been used. The outgoing condensate have therefore been equal to incoming steam filtered with a low pass filter.

The used cylinder was a discretized cylinder shell model with 5 interior nodes.

7.3.2 Analysis

Result from dynamic sensitivity analysis can be seen in figure 7.13, 7.14 and 7.15. Even if the time scales in the figures not are exactly same, it is obvious that α_c has a larger affect on the moisture dynamics than α_{con} and

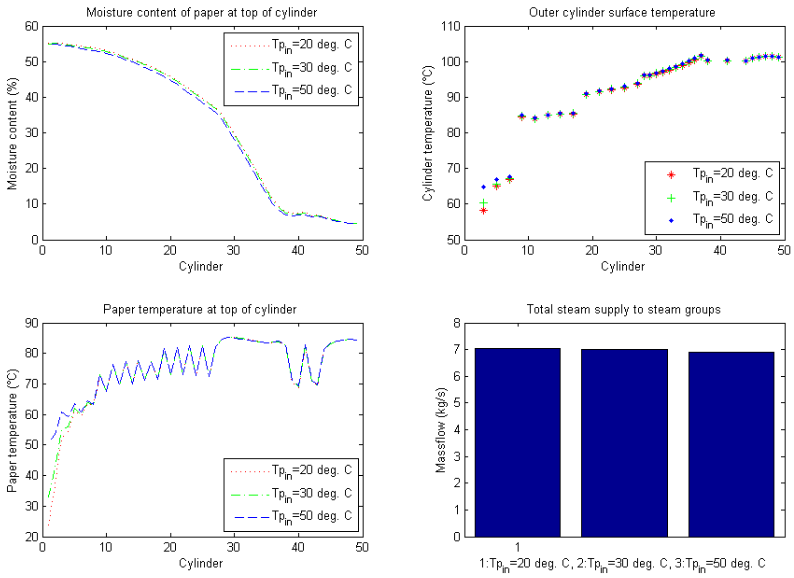

Figure 7.11: Sensitivity analyse of incoming paper temperature.

Parameters	Nominal Value	
α_{cyl} $[W/m^2K]$	750	1500
α_{con} $[W/m^2K]$	300	600
α_{P0} $[W/m^2K]$	300	600
α_{pk} $[W/m^2K]$	2000	4000

Table 7.2: Parameter values used in dynamic sensitivity analysis

α_{cp}. This observation is used in parameter identification, see section 7.4.1. The small influence α_{cp} has on the time constant is also noticeable.

7.4 Optimisation

Before an optimisation following parts need to be considered and specified:

- optimisation parameters
- loss function with weights
- algorithm

7.4.1 Optimisation parameters

In the sensitivity analysis it can be seen that the system contains several uncertain and unknown parameters. From the discussion in section 7 it

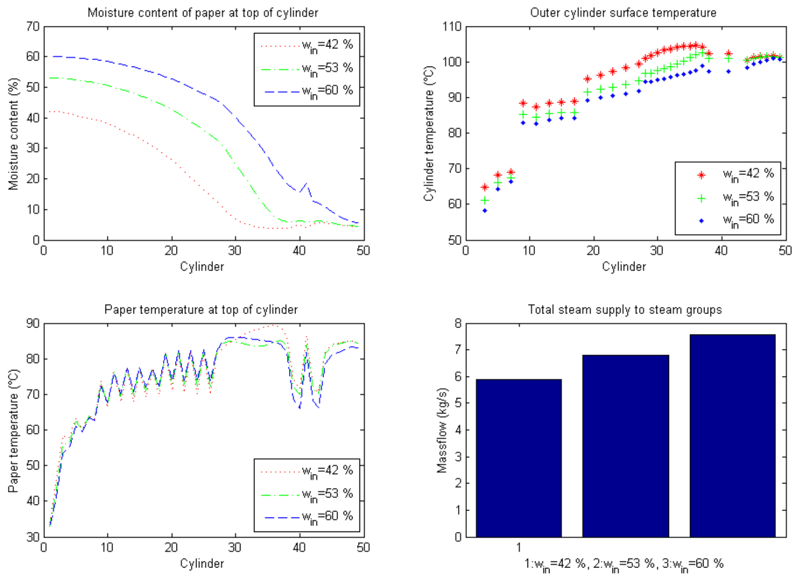

Figure 7.12: Sensitivity analyse of incoming sheet moisture.

is mentioned that some parameters also can have different values in different sections. Determining optimisation parameters was because of this not trivial.

The following parameters were considered to be used for optimisation: α_c, KG, α_{P0}, α_{PK}, α_{con}, Tp_{in}, w_{in}, Frf and α_{cfp}.

From the sensitivity analysis it could be seen that some of these only had a small effect on the system and were consequently not chosen.

Incoming sheet moisture w_{in}, was an uncertain variable that influenced the stationary solution strongly. But it was not chosen to be included in the optimisation criteria. A reason for this was that from two sources at Hylte Mill two different values were said to be correct. Different simulations of these values showed that the model gave better results if the higher value of the incoming moisture was chosen. If it was going to be used as a optimisation parameter, the incoming moisture would had got a value larger than the upper bound. It would also made the optimisation problem larger and more complex.

The following parameters were chosen to be used in the optimisation: α_c, KG, α_{P0}, α_{PK} and α_{con}.

Optimisation showed that with this parameter set, relative good results for the stationary condition could be achieved, even if certain values were too high or too low.

α_c and α_{con} were two parameters that was given a too low and a too high value. This resulted in a too long time constant and a too low amplitude of

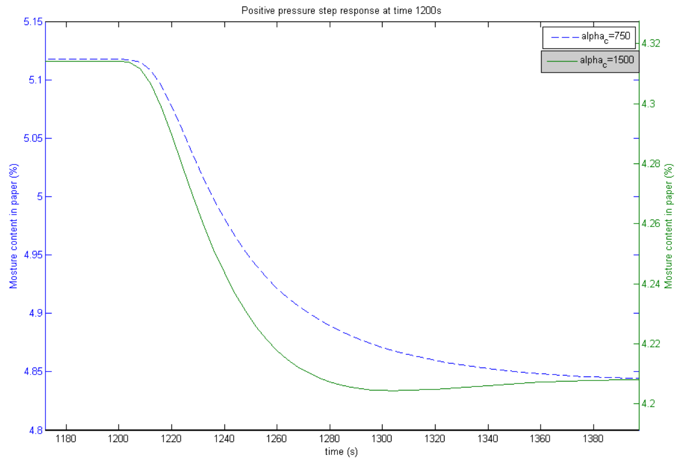

Figure 7.13: Dynamic sensitivity analysis for cylinder-condensate coefficient α_c.

the sheet moisture. Instead of having α_c and α_{con} in the optimisation criteria they were instead identified from the step response experiments visually.

As mentioned earlier, an alternative to achieve better results is to give each steam group a parameter set of its own. This was done in [19]. Due to uncertainty of under which conditions the real measurements have been performed and algorithm difficulties of handling more optimisation parameters, it was chosen to let the parameters be global.

7.4.2 Loss functions

The most interesting variables were considered to be sheet moisture, total steam supply, cylinder temperatures and paper temperatures. Therefore were these variables included in the loss function.

It is common in optimisation problems to use a quadratic loss function. It can be described in general mathematically by

$$J = \sum_{i \in S} (\lambda_i (x_i^m - x_i^s)^2), \tag{7.5}$$

where,
λ is the weights,
x^m is the measured values,
x^s is the simulated values and
J is the loss function value.

Another alternative is to use a loss function based on an absolute function. This alternative was used in the optimisation's, as it was considered a

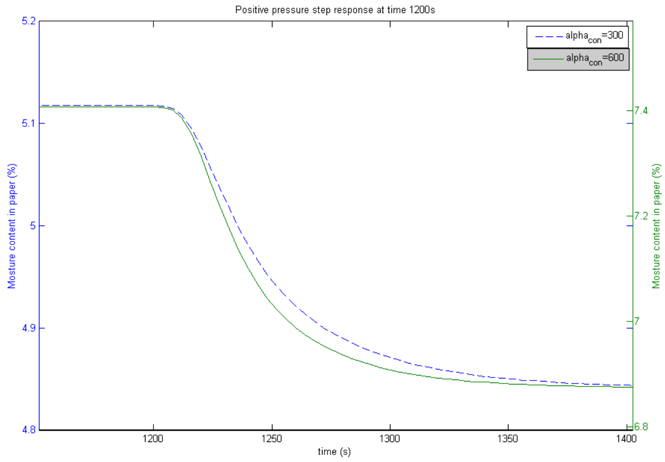

Figure 7.14: Dynamic sensitivity analysis for ambient air convection coefficient α_{con}.

little bit easier to specify magnitudes of weights. A general drawback with an absolute function is that its not continuous.

The implemented loss function can be described according to

$$J = \sum_{i=2}^{n}(\lambda_i(abs(Tm_i^m - Tm_i^s))) + \sum_{j=2}^{n}(\lambda_j(abs(Tp_j^m - Tp_j^s))) + \lambda_k(abs(qtot_k^m - qtot_k^s)) + \lambda_l(abs(w_l^m - w_l^m)), \quad (7.6)$$

where,
Tm is cylinder temperature,
Tp is paper temperature,
$qtot$ is the total steam consumption and
w is the final sheet moisture.

Because only one measured moisture content in paper was available and that this value was the most important, the weight for the sheet moisture was given a much higher value than the other weights. The second highest weight value was given to the total steam supply, due to its importance and that only one measurement was available.

The lowest weight values were given to temperatures in paper. This because paper temperature increases and decreases very fast and it is therefore very dependent on measurement position.

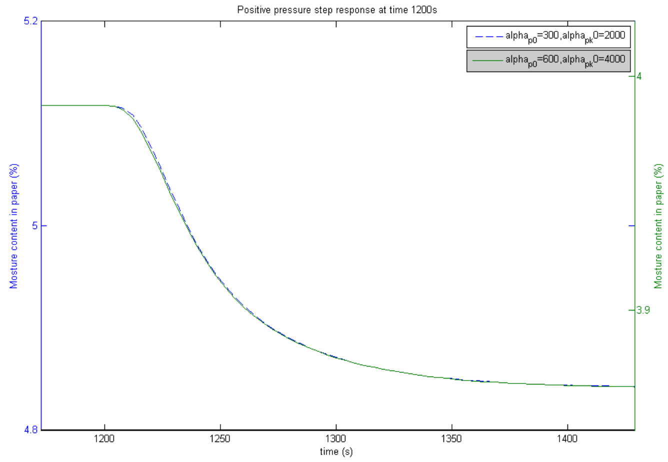

Figure 7.15: Dynamic sensitivity analysis for cylinder-paper heat transfer coefficients α_{P0} and α_{PK}.

7.4.3 Parameter optimisation using calibration toolbox in Dymola

The calibration toolbox in Dymola is a part of the Design Library provided by Dynasim. It is easy to use as it reads data from a specified file. In the calibration GUI model variables are coupled to measurements and optimisation weights are specified. A drawback with the calibration toolbox is that it is not possible to specify loss function and optimisation algorithm.

Several different optimisation tests were made with different weights and optimisation parameters. When using global parameters it converged to a better solution, but when introducing more parameters it could not handle it.

Therefore parameter optimisation using calibration toolbox was abandoned and was instead done from Matlab.

7.4.4 Parameter optimisation using Matlab

Dymola provides the stand-along program Dymosim, where special support is given to use it together with Matlab. This makes it possible to use optimisation toolbox in Matlab on the Dymola model. See Appendix B for a description of the optimisation routine.

Two different optimisation functions have been used from identification toolbox.

- fmincon
- fminsearch

Parameters	Opt. nr. 1	Opt nr 2.
α_c $[W/m^2K]$	211	(590)
α_{con} $[W/m^2K]$	562	(160)
α_{P0} $[W/m^2K]$	112	351
α_{pk} $[W/m^2K]$	2106	2014
Kg [m/s]	0.0272	0.0134
J	434	1170

Table 7.3: Results from parameter optimisation. Values in brackets have been fixed during the optimisation.

Fmincon uses a gradient based algorithm and fminsearch a direct search method that does not use numerical or analytic gradients [21]. Better results were maintained with fminsearch, specially when introducing more parameters. A disadvantage with fminsearch is that it does not support parameter constrains.

7.4.5 Results

Several optimisation's have been done under different conditions. It has been noticed that the solution usually is dependent of the initial values. Another problematic issue was that the model had to be simulated to stationary conditions before values could be evaluated. This made the optimisation very time consuming and impractical.

Results from two optimisation's with a discretized cylinder model using fminsearch are presented in table 7.3 and graphically in diagrams 7.16, 7.17 and 7.18. Both optimisation's used weights 1, 2, 90 and 600 for paper-, cylinder temperature, total steam supply and final sheet moisture. The low value of α_c and high value of α_{con} from the first optimisation gave poor dynamic performance. Therefore a second optimisation with fixed values of α_c and α_{con} were made. Used fixed values are indicated in brackets in table 7.3. These values have been manually tested to achieve a good dynamic performance.

In figure 7.16 it can be seen that the simulated final sheet moisture has the same value as the measurement. This was expected due to the high weight value. The discontinuity around cylinder 40 can be explained by the fact that every steam group shared a fixed value of the air properties. Cylinder 39, 40, 42 and 43 are passive and for that reason this approximation is very gross for these passive cylinders and thereof the discontinuity.

Diagrams 7.17 and 7.18 show the paper- and cylinder temperature. It can be seen that the simulated values give a relative good description of the measurements, even though only global variables have been used.

The total steam consumption was however too low with a simulated value of 4.48 $\frac{kg}{s}$. This value is however not including the blow-through steam. The

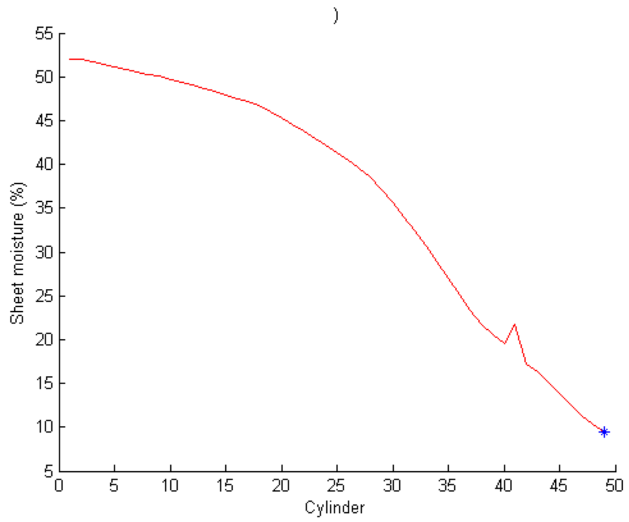

Figure 7.16: Sheet moisture simulated with optimised parameters.

real steam consumption was $\sim 7\ \frac{kg}{s}$.

Due to the unknown incoming sheet moisture and that only the total steam consumption to Pm3 was measured, where a part of the measured steam was used for e.g. ventilation and heating of the factory. It is difficult to draw any conclusions about the steam consumption. But possible explanations could be that the steam also contains a part of condensate or gases as e.g. air or that the mass flow of blow-through steam is higher than expected, which would increase the steam consumption. Another explanation could be that more energy is used in reality to evaporate water, and by that the heat of sorption need to be adjusted.

Neither of this suggestions have however not been investigated.

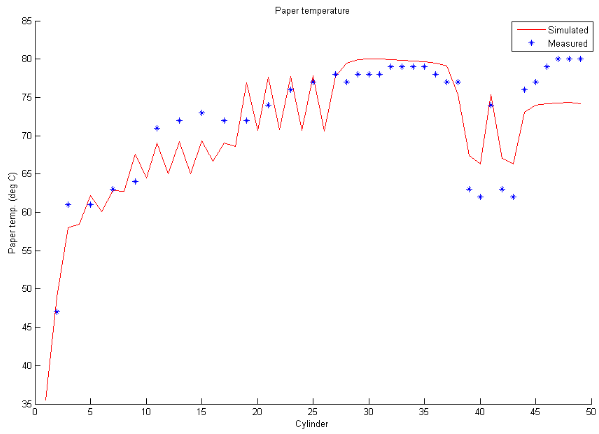

Figure 7.17: Sheet temperature simulated with optimised parameters.

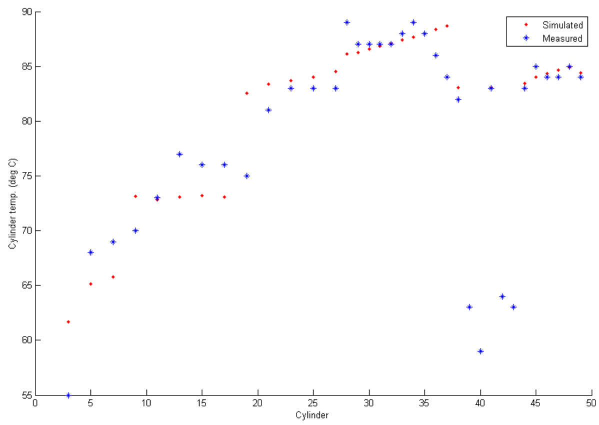

Figure 7.18: Cylinder temperature simulated with optimised parameters.

Chapter 8

Validation

A very important part of modelling is validation. During validation a model is tested under new conditions. This requires that sufficient data is available. Unfortunately lack of measurement has been a problem during this thesis. Therefore it is not possible to make a real validation. Instead the validation has to be replaced by a mixture of model optimisation and validation based on data from the step response experiment, see section 6.3.

8.1 Conditions and execution

The idea was to simulate the step response experiment and compare simulation results with logged data. Due to that the step response experiments were made in a closed loop, control system was active, an equivalent control system had to be implemented in the model.

Implemented control configuration was based on [4] and local process descriptions. As all interesting control variables were logged during the experiment it has been possible to verify the implementation.

Values from the static parameter optimisation in section 7.4.1 have been used in the drying section model. Due to difference in steam group pressure, the Kg value had to be adjusted to get a right stationary value of the moisture content.

The model have been simulated to a stationary solution and then an equivalent input with the step response experiment reference value has been used, see figure 6.5.

8.2 Pressure drop and disturbances

From the logged data it could be seen that pressure drop occurred in the steam supplier under step responses. Also a large pressure disturbance occurred at the end of the experiment, see figure 8.1. As it was interesting to model this disturbance and the pressure drops, the pressure of the steam

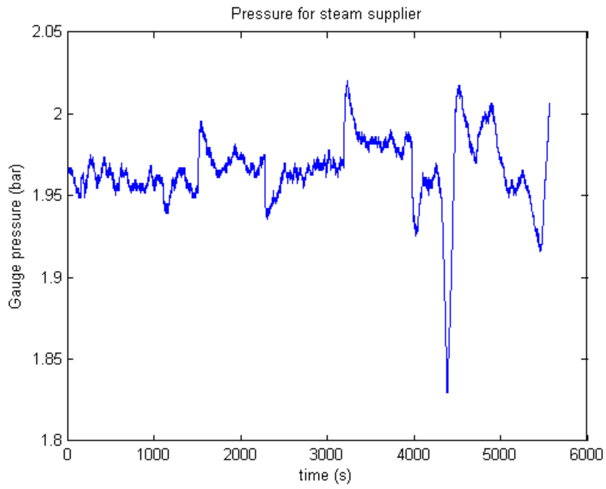

Figure 8.1: Pressure in steam supplier during the real step response experiment. Note the disturbance at time ~ 4300.

header was changed from a constant to be varying according to an interpolation table, adapted to the logged data. This was also done for the unmodelled condensate tank K4.

8.3 Steam group pressure

To be able to validate the paper moisture, it is important that the steam pressure for the different steam groups are correct. The dynamics of the steam pressure is mainly affected by the control system and the valve model. But it is also affected by the cylinder model.

As the valve parameters have not been found in valve specifications, they have been optimised against measured data. In the specifications it was mentioned that the valve characteristic was close to equal percentage. This makes the pressure dynamic only dependent of one valve constant, the R_v value, see equation 5.40. Provided that the K_v value is in a range where the control input does not exceed minimum or maximum.

A change of the R_v-value is equal to a scaling of the control signal. The adaptation of simulated steam pressure to the logged data, has been done by changing the R_v-values manually.

Results

Diagram 8.2 and 8.3 shows the steam pressure in steam group 1 and 2 together with input signals to their valve. As can be seen simulated pressure follows real pressure in a good way. The control signal also has a similar shape which indicates that correct controller parameters are used.

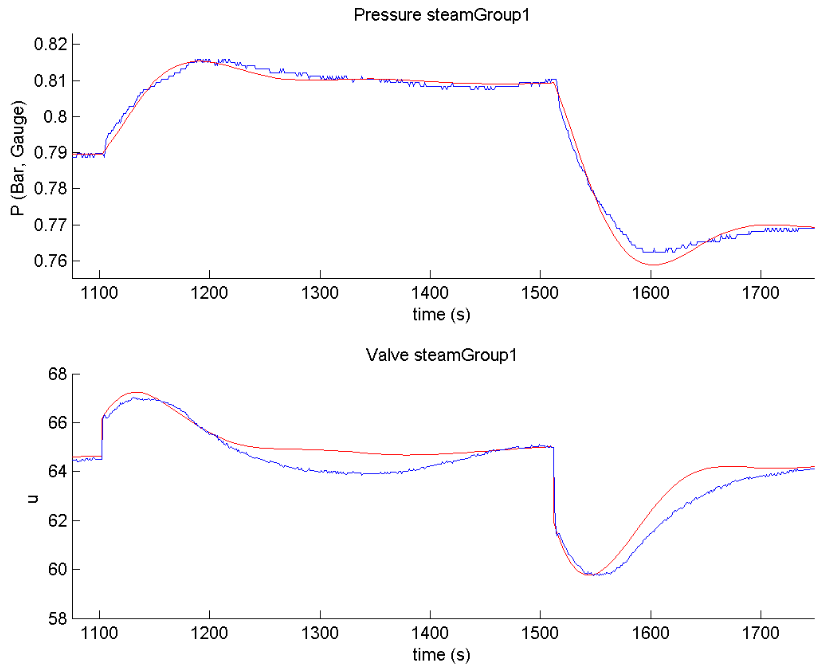

Figure 8.2: Simulated and measured steam pressure in steam group 1 with corresponding control signal.

Also the steam pressure dynamics for steam group 3 and 4 are described well by the model, even if simulations showed a too large overshoot. The effect of the steam supplier disturbance can also be seen in figure 8.4 and 8.5. It is noticed that the disturbance is well described by the model.

8.4 Paper moisture content

From the dynamic sensitivity analysis in section 7.3, it could be seen that moisture dynamics mainly was affected by α_c and α_{con}. Therefore these values have been manually optimised against the step response experiment to describe the dynamic correctly.

Results

From figure 8.6, it can be seen that the moisture content measurements are very noisy, which makes the interpretation of the results more difficult. It is however possible to see trends in the diagram. The amplitude and the time constants are described well. The problem is the dead time. The simulated model has a dead time of a few seconds, while real measurements indicate a value of $\sim$ 80 seconds. The value is very uncertain due to the high noise

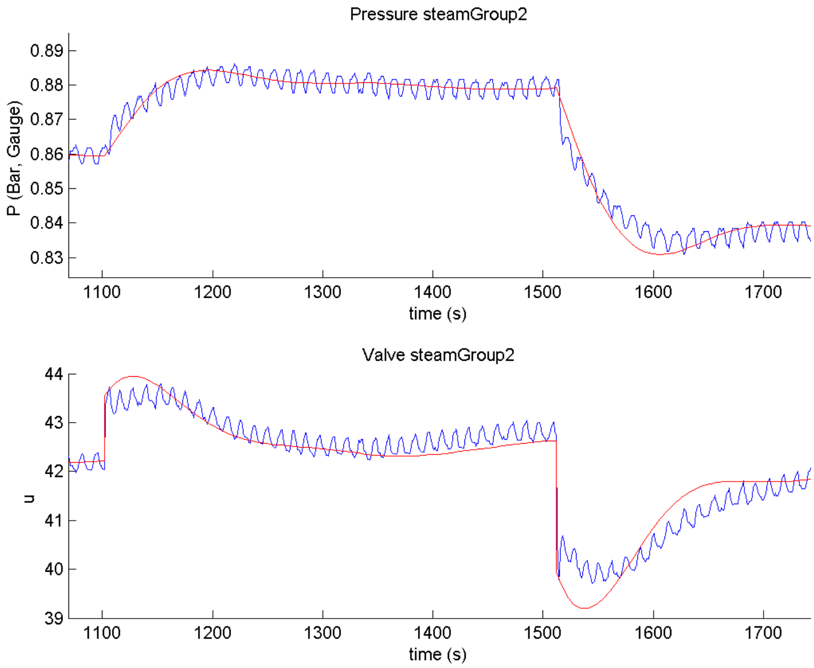

Figure 8.3: Simulated and measured steam pressure in steam group 2 with corresponding control signal.

level. From figure 8.6 it is still obvious that the process has a significant longer dead time than the model.

A possible explanation of the different results, could be the approximation of steam and condensate as being saturated. The saturation temperature increases with the pressure. The condensate is therefore in reality having a temperature under the saturation temperature before it is getting heated up. As the heat flow to the cylinder shell is dependent of the temperature difference between condensate and inner cylinder surface. The saturation temperature approximation probably affects the dynamics of the moisture content.

Another approximation that affects the dynamics is the heat transfer coefficient α_c between steam and cylinder shell. This coefficient is used as a constant but is in reality strongly dependent on e.g. thickness of the condensate layer. Under a fast pressure it is assumed that the condensate layer is varying and therefore affecting the cylinder heat flow in a way that is not described by a constant α_c.

These suggestions of explanations have however not been investigated in this thesis. Modelling this phenomena would make the model much more complex which is not wanted from a real time perspective.

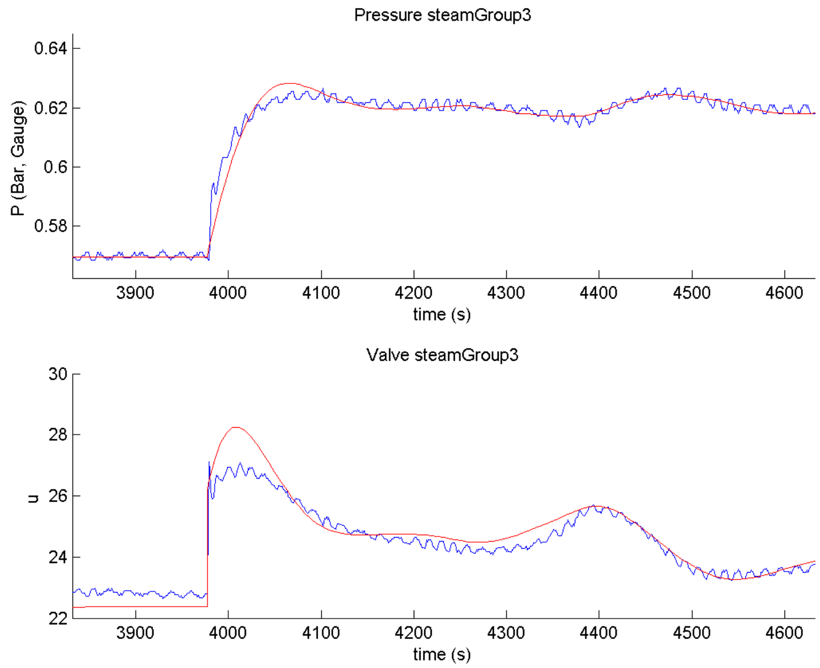

Figure 8.4: Simulated and measured steam pressure in steam group 3 with corresponding control signal.

8.5 Condensate system

Validation of the condensate system can not be done properly due to no condensate flow measurements. This makes it difficult to validate individual components, e.g. pumps, valves and condensate tanks.

Another important aspect is that the condensate system validation is dependent of correct steam group models. Incorrect cylinder models affect the flows to the condensate system and therefore result in a non correct validation.

Even the lack of data, the differential pressure over siphons and condensate tanks have been investigated.

8.6 Differential pressure

As mentioned, the validation of all condensate components is dependent of a correctly simulated flow. From the dynamic moisture analysis it could be seen that the model could not describe the dead time, and therefore probably not the condensation rate. It is therefore difficult to make conclusions about the siphon model describes the differential pressure correctly or not.

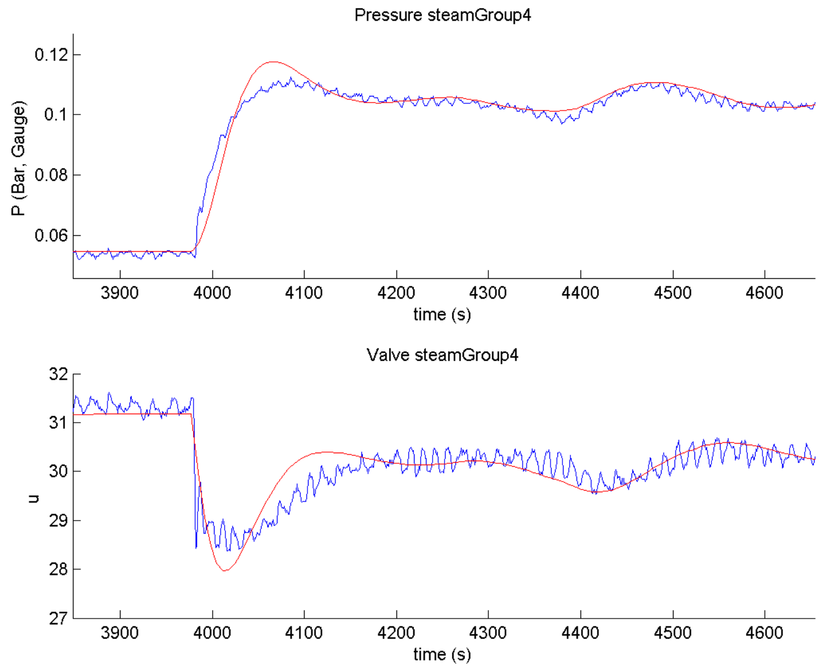

Figure 8.5: Simulated and measured steam pressure in steam group 4 with corresponding control signal.

Results

An interesting property that can be seen in figure 8.7, is that the differential pressure is going in different directions at the beginning of a step response. However at the pressure disturbance both differential pressures are going in the same direction and describing the disturbance in a good way.

8.7 Condensate tanks

From a modelling point of view, the most interesting condensate tank variables are

- Water level
- Pressure
- Flashed steam rate

The only logged variable from the two modelled condensate tanks are the water level. Except the incoming condensate, the condensate level is highly affected by the control system and also by the pump. Pump parameters

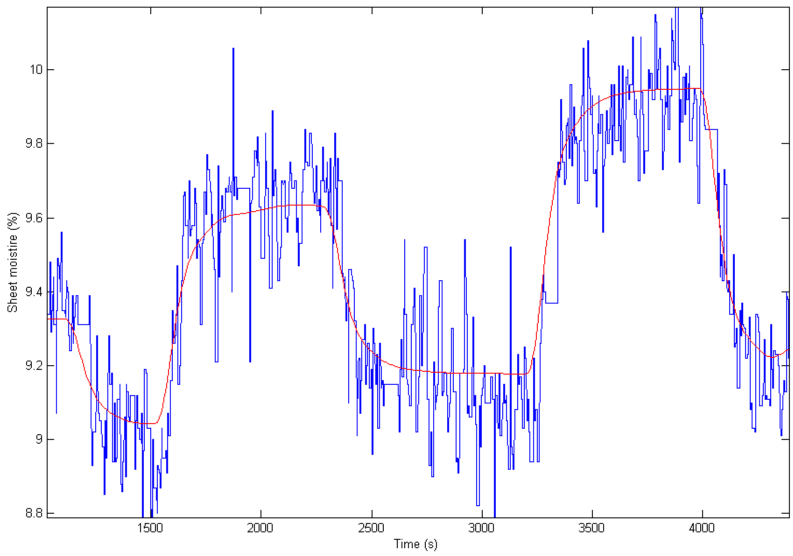

Figure 8.6: Simulated and measured sheet moisture.

have been taken from pump curves. The pump model is very uncertain but this probably is not affecting the dynamic behaviour, as the input current is constant and the flow is not varying much.

The flash steam rate is in stationary condition dependent of enthalpy difference between incoming condensate and the tank condensate, provided that incoming condensate has a higher temperature than the tank saturation temperature. Therefore the flash steam rate is dependent on the differential pressure. At Pm3 these values do not exceed 0.6 bar, which gives a flash steam rate of ∼1 %. Due to the low value it has not been further investigated.

Results

It is not possible to draw any conclusions from the validity of the condensate tank model, due to uncertain amount of incoming condensate. But information about outgoing condensate from steam groups can be obtained.

In diagram 8.8, condensate levels for K1 and K2 can be seen. The level in K2 is very noisy and it is consequently difficult to draw any conclusion at all. But in K1 an interesting behaviour is noticed, the condensate level in the beginning of a step response is going in the opposite direction. An explanation could be that dynamically the siphon is affected in a way that the amount of outgoing condensate is decreased.

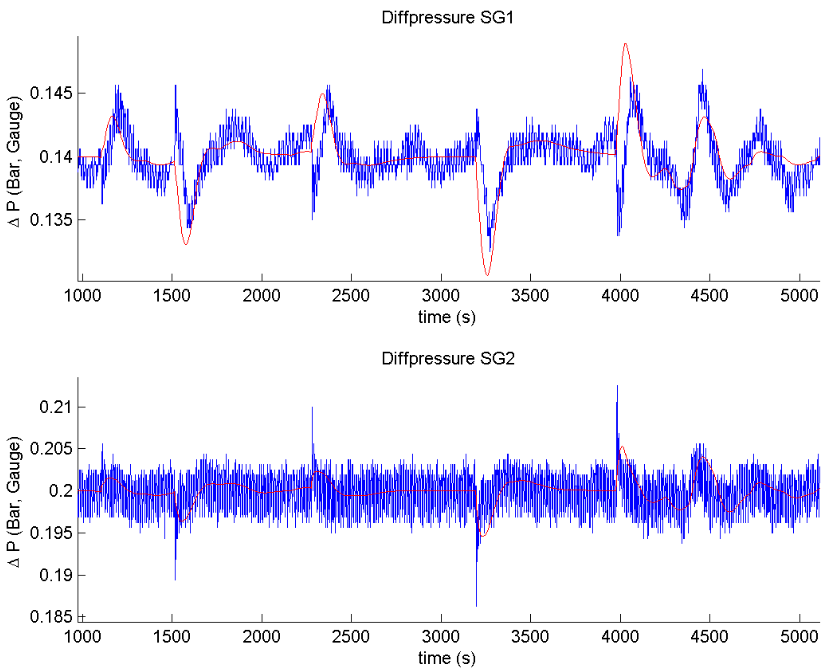

Figure 8.7: Differential pressure over steam group 1 and 2.

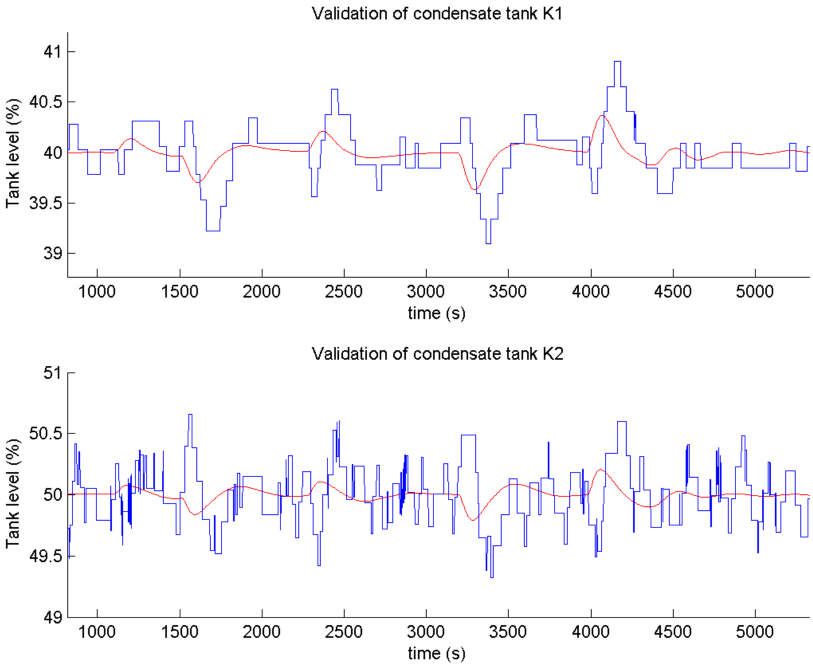

Figure 8.8: Condensate levels in condensate tank K1 and K2.

Chapter 9

Implementation

The model has been implemented in Modelica and simulated in Dymola. The implemented Dymola model can be seen in figure 9.1.

The model used in the validataion contained 16248 variables before translation, and 605 continues time states after translation.

9.1 Modelica

Modelica is a programming language designed for modelling physical systems. The language is based on acausal modelling. Models are set up by equations instead of assignments [6]. In a block oriented language like Matlab the structure of the components in a model is based of signal flows, i.e. input- output relations. In Modelica no input- output relations need to be defined. Instead input- output relations are determined by the equation solver. This has several advantages against block oriented modelling.

- Equations do not have to be transformed into state space models, which can be both time consuming and difficult.
- The corresponding structure between model representation and physical system is maintained.
- It makes it easier to build libraries and reuse models.
- Changes in models are easy to make. In a block oriented language a small change in the physical system can lead to a big difference of the block structured model.

Modelica is an object-oriented language which makes it possible to handle large models in a structured way. The support of inheritance is widely used when developing new libraries as in DryLib. The standard library includes library and models from several physical domains which can be connected together. This makes Modelica suitable for multi-domain modelling and consequently more complex systems can be modelled.

9.1.1 Basic principles of Modelica

A system is represented by a class, generally declared as *model*. Inside this class parameters, variables and equations are defined. The mathematical representation of the model is implemented under a line marked *equation*

To be able to connect models a connector class is used. A connector defines the conditions for linking models to each other. In a connector a variable can be declared in two ways, as flow or without flow. A declaration without flow sets up an equation where the connecting variables are set to the same values. If the variables are declared as flow the sum of the connecting variables are set to zero. In an electrical circuit, current is declared as flow and voltage without flow.

9.2 Dymola

Dymola, Dynamic Modelling Laboratory, is a program that interprets and creates Modelica code. The program is developed by the Swedish company Dynasim in Lund.

Dymola has two different working modes, simulation and modelling. In modelling mode models can either be built up in a text-editor or graphical by drag and drop pre-defined components.

After a simulation it is possible to get information about the numerical calculations, e.g. number of calculated Jacobin's, size of non linear equation systems and number of states. This makes it possible for an advanced user to get a better insight into the model and maybe make changes due to the information.

In this thesis Dymola has been used as the modelling environment

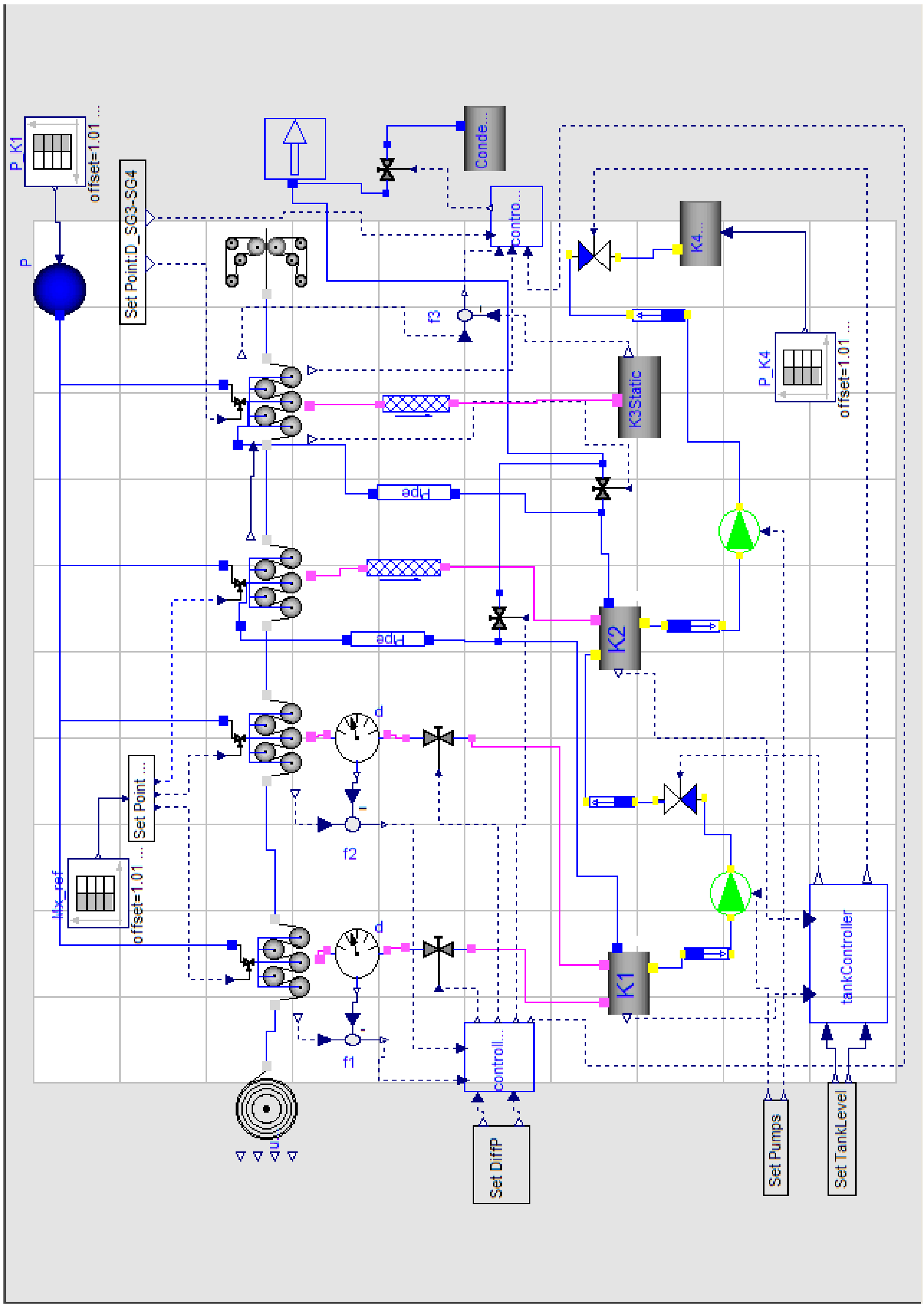

Figure 9.1: Implemented Dymola model.

Chapter 10

Conclusions

This thesis presents a model describing the drying process at PM3 at Hylte Mill. Both dynamic and stationary conditions for cylinders, paper and condensate system have been modelled and investigated.

A lot of effort has been spent on analysing model parameters and their static and dynamic influence on the system behaviour. To make the analysis more structured, simple sensitivity analysis have been made for unknown and uncertain parameters.

Validation against real dynamic measurements showed unexpected results for the condensate system. Condensate tanks levels decreased at the beginning of a positive step response in a steam group. This is probably due to dimensioning of siphons and pipes, since data from another drying section showed opposite results. However more measurements are needed to make certain conclusions.

There have also been other difficulties in the modelling. It has been problematic to both describe stationary and dynamic conditions at the same time. A good parameter estimation of the stationary conditions did not give any satisfactory results of the dynamics and vice verse. A possible explanation could be the validation data. Stationary and dynamic validation data came from two different measurements, where not all conditions from the stationary data were known. Also simulations showed to low values of the dead time between pressure changes in steam groups and the paper moisture.

The main goal with this thesis was to describe the gross physical behaviour of the drying section. It has been shown that this is possible with physical models mainly based on energy and mass balances, even if more validation and work is needed to be spent on the condensate system.

10.1 Future work

An interesting not modelled part is the air system. A drawback with extending the model is that it increases the simulation time. If the model is going to be used for real time simulations, a complex model of the air system can probably not be included. It is possible that the model already is too large for that. This has however not been investigated.

Other extensions could be to model the wire- and the press section and also connect the model to an operator interface.

More work is needed for validating the different components in the condensate system, as e.g. pumps and condensate tanks. Results from the dynamic validation showed that more job also is needed to explain and model the long dead time in paper moisture and the condensate removal inside cylinders. An alternative model approach to describe this complex behaviour, could be to use a grey box model.

Also more time can be spent on investigating the steam consumption and energy losses.

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[25] http://screensound.gov.au/glossary.nsf/Pages/Relative+Humidity+(RH)?OpenDocument

Appendix A

Volume-level derivation of a lying cylinder

Derivation of a relationship between water level and volume in a lying cylinder, see figure A.1.

$$V_{water} = AL, \tag{A.1}$$

Find relation between Area A, see figure A.1 and water level h.

In [12] is a relation given between angle α, h, r and A, see figure A.2.

$$A = \frac{r^2}{2}(a - \sin a) \tag{A.2}$$

$$Using\ geometry\ in\ figure\ A.2,\ a = 2\arccos\frac{r-h}{r}\ \Rightarrow, \tag{A.3}$$

$$A = \frac{r^2}{2}(2\arccos(\frac{r-h}{r})) - \sin 2\arccos\frac{r-h}{r} \tag{A.4}$$

$$Using\ \sin 2\alpha = 2sin(\alpha)cos(\alpha) \Rightarrow \tag{A.5}$$

$$A = \frac{r^2}{2}(2\arccos(\frac{r-h}{r})) - 2\sin\arccos\frac{r-h}{r}(\frac{r-h}{r}) \Leftrightarrow \tag{A.6}$$

$$A = \frac{r^2}{2}(2\arccos(\frac{r-h}{r})) - 2\frac{b}{r}\frac{r-h}{r} \tag{A.7}$$

$$Using\ geometry\ in\ figure\ A.3,\ b = \sqrt{2rh - h^2} \Rightarrow \tag{A.8}$$

$$A = r^2\arccos\frac{r-h}{r} - \sqrt{(2rh - h^2)(r-h)} \Rightarrow \tag{A.9}$$

$$V_{water} = Lr^2\arccos\frac{r-h}{r} - \sqrt{(2rh - h^2)(r-h)} \tag{A.10}$$

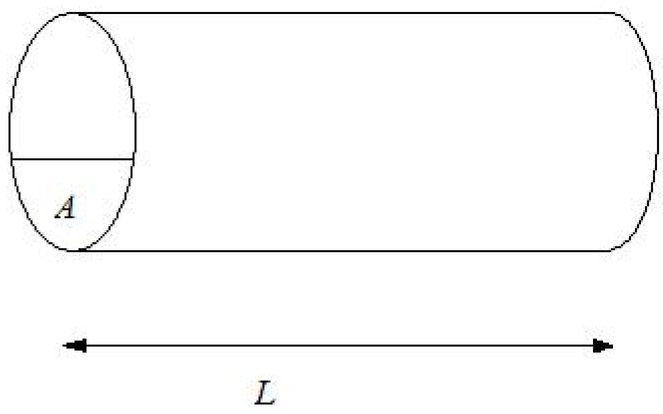

Figure A.1: Geometry of a flash tank.

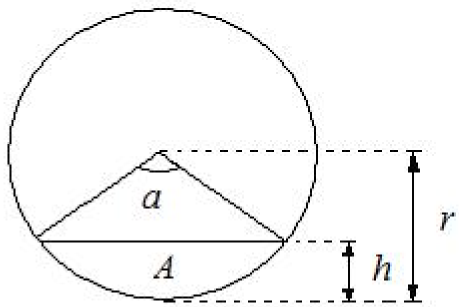

Figure A.2: End of a tank.

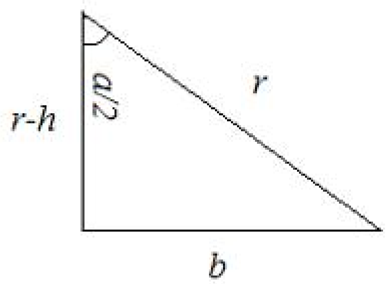

Figure A.3: Geometry relations.

Appendix B

Optimisation routines

Description of enumeration can be seen in figure B.1.

1. In main file, algorithm, tolerance level, optimisation parameters and initial values are specified.

2. The main file executes a Matlab optimisation function.

3. The Matlab optimisation function calls an own designed function, optimize, that takes optimisation parameter as input and returns a loss function value.

4. The optimize function calls the dymosim routine. Dymosim simulates the model with its new parameters until a stationary condition it reached and outputs a result file.

5. Optimize searches the state index from the result file , evaluates the states and saves them on a global variable, so they can be used as input values next time dymosim is called. This is done only during the first iteration.

6. Optimize calls a function that evaluates simulation results.

7. Loss function is called and returns the loss function value.

8.& 9. Optimize returns the loss function value to the Matlab optimisation function. Either it makes a new call to optimize, or if an iteration is done it check the tolerance values.

10. Depending on the tolerance values, it either runs a new iteration or the optimisation is completed and results are send to the main file.

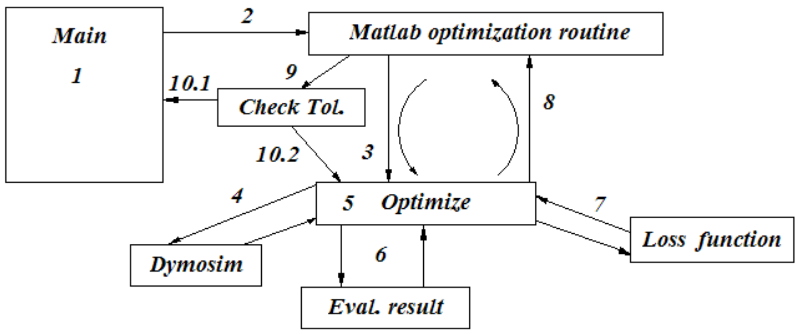

Figure B.1: Schematic picture of optimisation routine used in Matlab.