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Dryer section control in paper machines during web breaks

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Dryer Section Control in Paper Machines During Web Breaks

Abstract
Web breaks in the dryer section of a paper machine cause loss of production and quality problems. After a web break, the steam pressure in the cylinders must be reduced to avoid overheating. The goal of this project is to determine optimal steam pressure trajectories during web breaks, so that the production is restarted with the same drying properties of the cylinder as before the break.

A detailed physical dynamic model of the drying cylinder has been developed. The model describes the relations between the steam valve position, the steam pressure, the cylinder temperature, and the paper temperature. The model is based on partial differential equations that describe heat conductivity for the cylinder and the paper web, and mass balances of water and dry material in the paper. The accuracy of the model has been verified through experiments made at the M-real paper mill in Husum, Sweden. Verifications are made both during normal operation and during web breaks.

The dynamic model has been reduced in order to derive simple transfer functions between the steam pressure and the cylinder temperature, and between a logic signal that is active during web breaks and the cylinder temperature, respectively. The transfer functions obtained were used to find the optimal steam pressure trajectory during web breaks.

A new feed-forward strategy for steam pressure control during web breaks is presented. The strategy has been tested on a paper machine with good results. The strategy is built on feed-forward compensation and has been well received at the mill.

Keywords
Dryer section, web breaks, paper machine, steam pressure control, physical modeling

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Contents

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Introduction

1.1 Background

The aim of a paper manufacturer is to produce paper to preset quality limits, preferably as close to the limits as possible. One of the most important quality variables used in the paper industry is the moisture content in the paper. The moisture content effects final properties such as strength, curl, and printability.

In the drying section of the paper machine, paper is dried on large steam heated cylinders. This makes the drying section an energy devouring process. Large variations in the moisture content of the paper web also entail variations in the steam supply and control. The more stable the process is, the easier it is to control.

After a web break, it is difficult to control the moisture content in the paper since the properties of the drying process change drastically during the web break. This is a serious problem that causes disturbances and reduction in production.

1.2 Motivation

Figure 1.1 shows the moisture content in the paper before and after a web break, as well as the steam pressure in the cylinders at the end

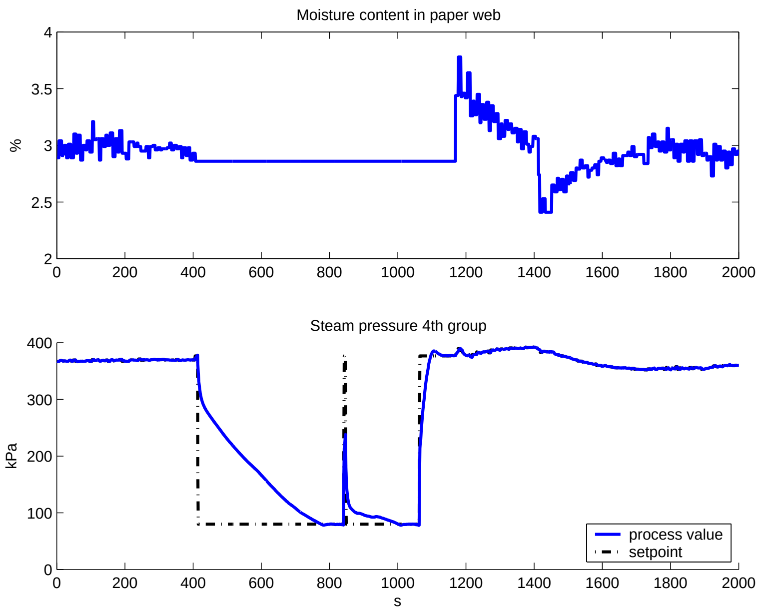

Figure 1.1 Moisture problems after a web break in the pre-drying section.

of the drying section. The web breaks after 400 seconds. At this time, the signal from the moisture sensor is kept constant, and the steam pressure is reduced from 370 kPa to 80 kPa. After 850 seconds there is an attempt to restart the production, but the web is broken again. The cause of this second break is probably that the paper web was far too moist and therefore very fragile.

The production of paper is restarted after 1100 seconds. However, by studying the moisture content in the paper web, it can be determined that the machine starts to produce salable paper first after 1400 seconds. This means that there are five minutes production of paper that does not meet the quality standards, and an additional 5 minutes of varying quality.

Even though web breaks are a rather frequent occurrence in paper making, paper machines are not built to handle web breaks very well. Web breaks are written of as a nuisance and not considered a normal part of daily production. Even in [Pappersordlista, 1992] it is difficult, not to say impossible, to find the expression for a web break. In the field of research, web breaks are not well investigated either.

1.3 The project

This project is a collaboration between three partners, NPI (Network for Process Intelligence), M-real, and Lund Institute of Technology.

To ensure that the project should be of interest to the industrial partner, M-real, they were asked to propose interesting areas of investigation. It was discovered, that one of the most difficult problems in the paper mill was web breaks.

Therefore, it was decided to form a project with the goal of improving the steam pressure control of the drying cylinders during web breaks. The purpose being to restart the production of paper, that meets the quality constraints, as quickly as possible after a web break.

1.4 Outline

The next chapter gives a short introdution to the paper machine. Chapter 2 also gives an introduction on how to dry paper and how the dryer section works. Chapter 3 is about how to improve drying and what a web break is. This chapter also introduces the PM7 paper machine in the M-real Husum Mill.

In Chapter 4 a dynamic model of a drying cylinder is presented. In Chapter 5 the model is validated on a drying cylinder in the M-real Husum Mill. Validation is done both during normal operation and during web breaks.

In Chapter 6 the model acquired in chapter 4 is used for developing a new feed-forward strategy for the steam pressure control during web breaks. The chapter also contains an example of the new strategy. The feed-forward strategy has been implemented in the M-real

Husum PM7 paper machine and an industrial validation is given in Chapter 7. This thesis is then completed in Chapter 8 with conclusions and suggestions for future work.

Parts of the results presented in this thesis have been presented previously, [Ekvall, 2004] and [Ekvall and Hägglund, 2004].

2

Introduction to paper drying

This chapter gives a short introduction to the paper machine. The different parts of the paper machine are mentioned, but focus is on the dryer section and how to dry paper. For further studies of the paper machine and paper making, [Smook, 2002] and [Fellers and Norman, 1998] are exhaustive handbooks. More about the dryer section and how to dry paper can be found in [Karlsson, 2000] and a detailed introduction to the steam and condensate system can be found in [Krumenacker and Deutsch, 1999]. Principles for analyzing dryer section steam and condensate systems is treated in [Hill, 1993].

2.1 The paper machine

The main purpose of a paper machine is to produce paper quickly while also keeping a constant quality. Today, paper machines run at speeds up to 2000 m/min and with 10 m wide cylinders.

Producing paper is basically to remove the redundant water from the original pulp and consolidate the fiber structure. At the headbox, the share of dry substance is only around one percent. At the upwind most of the water in the paper web is removed and the dry substance is around 90-95 %. The paper web goes through a number of steps on its way through the paper machine. The steps are (see Figure 2.1):

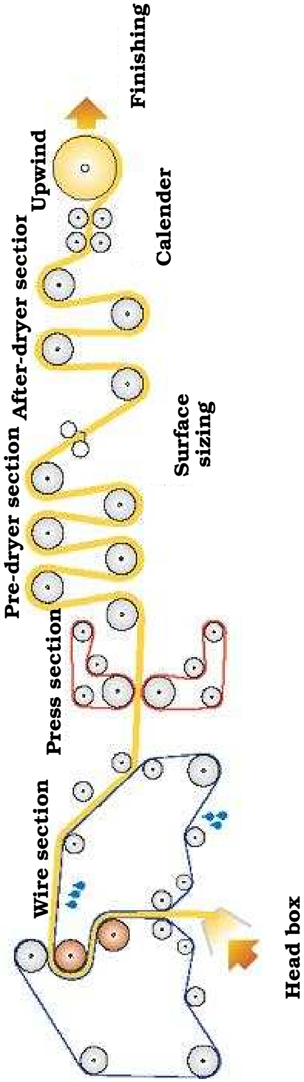

Figure 2.1 A general outline of a multicylinder paper machine. This is the PM7 in Husum, Sweden (courtesy of M-real).

Head box Pulp is distributed evenly on a screen, both across the width of the paper machine and lengthwise. The fibre content in the pulp is only a few percent.

Wire section The sheet is formed on a wire. The wire is permeable, and lets the fibres stay and the water flow away. After the wire section, the fibre content is about 20 %.

Press section More of the water in the web is removed by presses. The pressing also consolidates the web structure. After the press section, the fibre content in the paper web is about 40 %.

Dryer section The remaining water in the web is removed by evaporation on steam heated cylinders. The web now consists of 90-95 % fibres.

Surface sizing The surface is treated with a sizing solution to improve certain physical properties of the web, such as surface strength and printing properties.

Calender The sheet is calendered through roll nips to smooth the surface.

Upwind The paper web is reeled up on a tambour. The final paper contains only 5-10 % water.

The dominant configuration of a drying section in a paper machine is contact drying on steam heated cylinders. The most common methods are *multicylinder drying* (used for printing papers and board) and *Yankee cylinder drying* (mainly used for drying tissue). Other drying methods are *condebelt drying, infrared drying,* and *impingement drying*. This thesis focus only on multicylinder drying.

2.2 The dryer section

From the press section, the paper web enters the dryer section with 50-68% moisture content. After the dryer section the desired moisture content is 2-10%. This implies that 1.2-1.8 kg water/ kg paper must be removed by evaporation in the dryer section. This is less then 1% of the total water amount in the original stock. Evaporation of water is energy consuming, and the dryer section is responsible for almost 2/3 of the paper machine's total energy consumption. Not only must the water be evaporated, it also must be removed from the drying hood to prevent dripping on the paper web. The ventilation of the dryer section is therefore of imperative importance.

In the dryer section, many properties of the final product are determined. If the drying is performed poorly, the paper produced may be too moist. The opposite, too dry paper, is a lesser problem, but can also lead to production difficulties. If the paper is dried unevenelly, the result can be curl (i.e. a change in shape over the whole surface such that the sheet strives to roll itself into a cylindrical form) or moist passages in the web. The strengt of the sheet is also set in the dryer section.

The steam and condensate system

When the paper web enters the dryer section, the moisture content is high and the steam pressure has to be low on the first cylinders to prevent the web from sticking on the cylinders. The lower the moisture content is in the web, the higher the steam pressure is. The highest steam pressure is held in the last drying cylinders in the dryer section.

The drying cylinders are not controlled one by one, but are organized into drying groups. The steam pressure into the drying cylinders is controlled, but there is also a control of the differential pressure. Most of the steam condenses when it comes in contact with the cooler cylinder surface. The outer side of the cylinder surface is cooled by the wet paper web. The condensate is removed by so called siphons. Some of the steam does not condense, but is used to help remove the condensate. This steam is called blow-through steam. Both the blow-through steam and the differential pressure over the steam group ensure condensate removal and help drain each cylinder. The condensate otherwise stays in the cylinder as an energy barrier, preventing an effective heat transfer to the outer side of the drying cylinder.

To reduce the energy costs of producing steam, the drop in steam pressure between the drying groups can be used. The condensate and blow-through steam from one group is collected in a condensate tank and cascaded to the next group. If the reused steam has too low pressure,

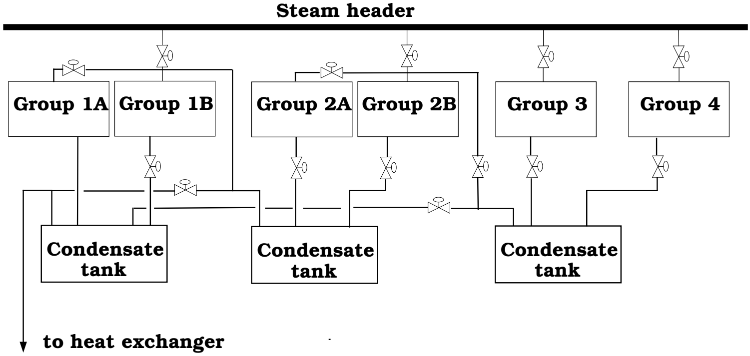

Figure 2.2 An outline of a cascade condensate system. This is the cascade system for PM7, Husum.

steam from the header is added. An example of how a cascade system can work is shown in Figure 2.2, there are also other ways to build a cascade system for a dryer section.

If condensate removal works poorly, the drying cylinders may become flooded. A flooded cylinder will eventually lead to a moisture problem. The energy consumption will also increase since a higher force to drive the cylinder is needed.

Design of the dryer section

The purpose of the dryer fabrics is to make sure that the paper is pressed against the cylinder surface. The most common configuration is the two tier design (see figure 2.3). With the two tier design two different fabrics are used, one for the upper cylinders and one for the lower cylinders. In this configuration the paper web is unsupported between the cylinders, in the free draw.

When the machine speed increases, flutter of the web in the free draw may become a problem. When the web is moist the flutter may even cause web breaks. This can be prevented by inserting a single felt dryer section in the beginning of the dryer section where the moisture content is high (see figure 2.3). In this configuration the felt follows the

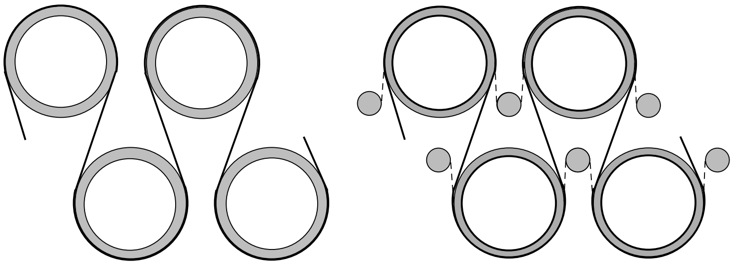

Figure 2.3 Different felt design in the drying section. Single felt configuration (to the left) and two tier configuration (to the right).

paper web and gives support both on the upper and the lower cylinders. The drawback with the single felt is that it keeps the paper web from touching the lower cylinders and therefore reducing the drying capacity. The solution is often to replace the lower drying cylinders with vacuum cylinders.

For a two-tier configuration there are four phases of the drying, first described by [Nissan and Hansen, 1960], see figure 2.4.

1. The paper web is brought into contact with the drying cylinder surface. The side facing the cylinder surface is heated due to heat transfer from the hot cylinder. At the outer side, water is being evaporated.
2. The paper is pressed against the cylinder surface by the felt, and the most heat is transferred from the dryer cylinder to the paper web. The felt covers the web and reduces the mass transfer from the outer paper surface. In spite of this, the increased paper temperature increases the drying rate.
3. The felt looses contact with the paper web and the mass transfer resistance lessens. On the cylinder side, the temperature continues to increase, but on the outer side it starts to decrease.
4. In the free draw evaporation takes place from both sides of the paper web. The drying rate is high, and the paper temperature

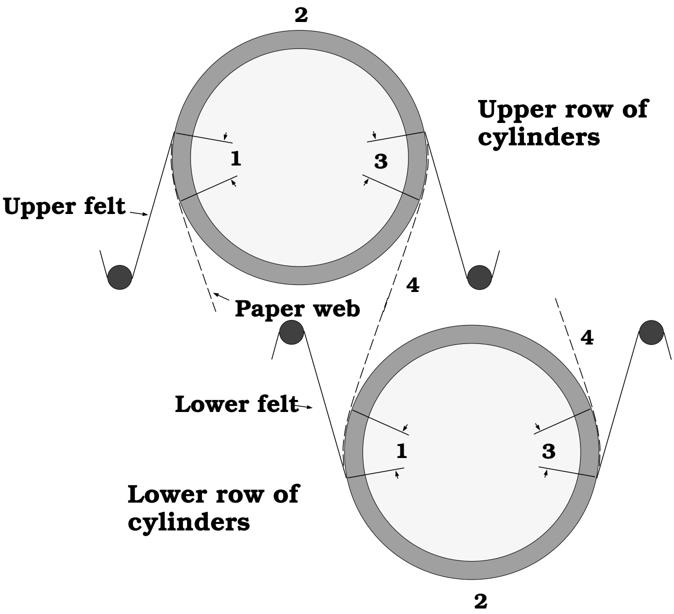

Figure 2.4 The four phases of the drying cycle.

decreases. The temperature difference between the cylinder side and the outer side of the paper web is almost levelled out at the end of the free draw.

2.3 The drying cylinder

The cylinders in the dryer sections are usually made of grey cast iron and heated with saturated steam. The driving force when drying paper is the temperature difference between the condensing temperature of the steam inside the cylinder and the cool paper web on the outside of the cylinder. The relation between the temperature of saturated steam and the steam pressure is non-linear (see Figure 2.5). The relationship is given by equation (2.1)

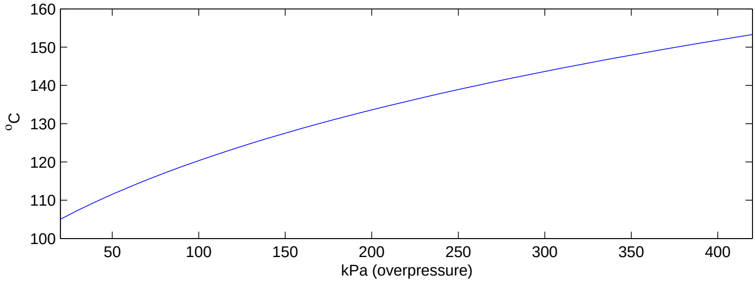

Figure 2.5 The relation between the condensing temperature of steam and the steam pressure.

$$T_{steam} = \frac{1668.21}{7.092 - \log P} - 228 \tag{2.1}$$

where the temperature (T_{steam}) is in degrees centigrade and the absolute pressure (P) is in kPa. This means that a small increase in the steam pressure at low pressures will give a large increase in the temperature of the steam. At high steam pressures, the pressure has to be changed considerably to affect the temperature.

When the steam touches the cooler cylinder surface it condenses. If the condensate remains in the cylinder it will act as an energy barrier. At low paper machine speeds, the condensate will form a puddle at the bottom of the cylinder. At higher speeds the centrifugal force increases and the condensate starts cascading inside the cylinder. At speeds over 400 m/min, there will be a rim of condensate inside the cylinder. To prevent rimming, spoiler bars are installed on the inside of the cylinders. The rim thickness increases slowly if the condensate removal is malfunctioning. This slow increase can lead to runnability problems long after the onset.

The condensate inside the cylinders cannot be removed entirely in spite of spoiler bars and siphons. There will always be a small drying resistance inside the cylinder. A temperature diagram over the cylinder and the paper web is shown in Figure 2.6.

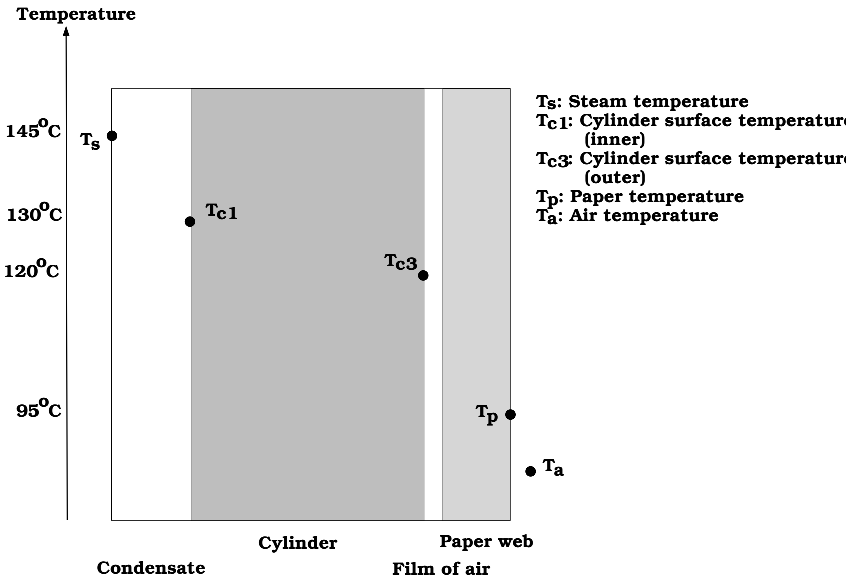

Figure 2.6 The moisture evaporates from the paper surface, and the driving force is the temperature difference between the steam and the paper.

The temperature of the paper web is affected both by the cylinder surface temperature and the temperature of the ambient air in the drying hood. Even if it is the cylinder surface temperature that influences the drying rate, the steam pressure is (almost) always used to control the drying. The reasons are that practical and reliable measurments are needed, and these are much easier to obtain from the steam pressure than from the cylinder surface temperature.

2.4 Control of the drying section

The main goal of the dryer section is to produce a desired content of moisture in the paper. The moisture content is either measured only after the dryer section, at the reel-up, or both at the reel-up and in the middle of the dryer section. The moisture content is normally measured

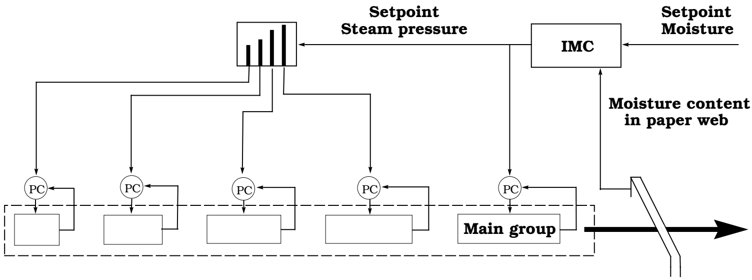

Figure 2.7 Outline of how the steam pressure controll works in the dryer section. The setpoint of the steam pressure controllers are set by the measured moisture content.

with infrared light, which at certain wavelengths is sensitive to water. The moisture content is then controlled by an IMC (Internal Model Controller).

The IMC is the primary controller in a cascade control structure, where the secondary controllers are PID controllers that control the steam pressure in the drying groups (see Figure 2.7). It would have been desirable to control the cylinder temperatures, but the cylinder temperatures are not measured continuously and can therefore not be used for control. There have been attempts using sensors monitoring the temperature of the drying cylinders [Shotton Paper, 1999]. The sensors are mainly used for preventing cylinder flooding, simplifying tail threading, and during warm-up.

The different steam groups consist of various numbers of drying cylinders, depending on where in the dryer section the group is located. The first groups may consist of only one or a few cylinders, whereas the last drying group may consist of 20 drying cylinders or more.

The steam pressure setpoint for the main group is controlled by the IMC. The main group is often the last steam group in the dryer section. The main group has in most cases the highest steam pressure, but not always. The steam pressure setpoints to the preceding steam groups are distributed according to drying performance (precentage of steam pressure setpoint for the main steam group). The first group has the

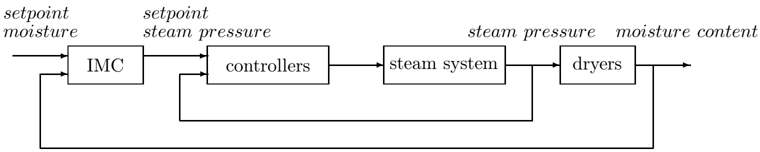

Figure 2.8 Outline of the cascade control structure in the drying section.

lowest steam pressure and then the steam pressure increases towards the last main group. An outline of the cascade control structure of the dryer section is shown in Figure 2.8.

3

Improved drying

This chapter describes what web breaks are and why they occur. What actually happens in the dryer section during a web break is described, as well as ways to prevent web breaks. An overview of the PM7 paper machine in the M-real Husum Mill is also given.

3.1 What a web break is

A web break is when, during operation, the sheet suddenly tears apart and production has to be restarted. The operating point in the drying cylinders changes drastically during a web break. Rethreading the machine and returning to normal operation takes at least 5 minutes and often a lot longer. A return to producing paper within quality limits can take even longer.

After web breaks, the heating capacity of the drying cylinders must be reduced to avoid overheating of the cylinders. This reduction is often performed in an ad-hoc fashion. In some paper machines the steam pressure is reduced to a fixed level and in others the reduction is accomplished as a percentage of the steam pressure before the break. How much the steam pressure is lowered varies from machine to machine. For example, in the M-real Paper Mill in Husum they have three paper machines, all with their own strategy for handling web breaks.

Figure 3.1 The dryer section just after a web break. The paper is on the floor instead of on the cylinders.

Why web breaks occur

The pulp used to produce paper has a lot of properties. The quality of the pulp is important when drying paper. For example, what kind of wood is used, how finely the wood is beaten and what other ingredients that are used all matter when drying the paper. The moisture content in the sheet is a good indicator if the dryer section is working well or not. If the moisture content increases too much, there is a large risk for web breaks.

Grade changes can cause web breaks because many parameters in the paper machine change at the same time. If the dry grammage weight or the machine speed change, the steam pressure also has to be changed. If this is not done properly, the risk is that the web gets too wet or too dry and a web break may occur. During a grade change, the pulp quality can change as well.

Another problem is when the wood fibres in the pulp form lumps. The lumps are thicker than the rest of the web and therefore harder to dry. Sometimes these lumps fall off and leave holes in the web. The holes make the web vulnerable to stress and strain in the dryer section. Large holes often lead to web breaks. It is the same case if the ventilation in the dryer section is poor and water starts dripping on the web. The risk for web breaks increases when the web is weakened in some way.

If the dryer section is performing poorly, the final product will not meet quality limits. A large variation in the pulp can result in moisture content variations. This in turn can lead to even further moisture problems since the moisture cascade system is slow. A high water content in the web can, as stated before, lead to a web break.

3.2 Improved drying

To increase the capacity in the dryer section, the moisture content from the press section can be lowered or the web can be pre-heated before entering the drying section, for example with a steam box. In the drying section the dew point in the drying section can be lowered or the steam pressures in the drying cylinders can be increased.

Moisture profile unevenness can be caused by dirt on the cylinders, poor ventilation in the dryer section, flooded cylinders and dirty felts. The dry grammage profile will all the same have a large effect on the resulting moisture content in the paper web. To improve the drying of paper it is important to continually check the equipment in the dryer section, and identify problems as early as possible. There are a few examples of how prediction of web break can be done, [Li *et al.*, 1998], and [Takiyama, 2004]. [Li and Kwok, 2000] not only tried to predict when a web break is about to occur, but also used a method of trying to prevent the web break from happening.

3.3 Improve web breaks

Minimizing the number of web breaks is a good way to improve the perfomance of a paper machine. Down time means a loss of revenue for the paper producer, but it is also necessary to assure the quality of the paper after web breaks. A malfunctioning dryer section can not only lead to a web break, but a web break can in itself cause the dryer section to perform poorly.

One outcome of a web break can be condensate build-up in the cylinders. This can lead to unevenness in cylinder temperatures. If the cylinder temperatures are uneven in the cross direction, the risk is great that the curl on the final paper will be large. If the middle of the paper web is too dry, the siphons are presumably oversized. Malfunctioning siphons can also lead to moist or dry passages in the web.

The web break is not entirely over until the production is running as it did before the break, within stated quality limits. The web break disturbs the dynamics of the drying section. When the web is back on the cylinders a lot has to be rearranged before the performance is back to normal.

One way to shorten down time and return to the quality limits after a web break is to make sure the cylinder temperatures are not too low. The cylinder temperatures should not be too high either, because this will complicate tail threading and the risk for napping will be great. The aim of this thesis is to find the optimal cylinder surface temperature at which to restart paper production after web breaks.

3.4 The Husum paper machine

The paper machine (PM7) in the M-real Husum Paper Mill produces copy paper, 70-100 g/m^2. The web break strategy, at the time this project started, was causing problems with the moisture content after web breaks. To ascertain the problem, the dryer section and web breaks in the dryer section were studied in detail.

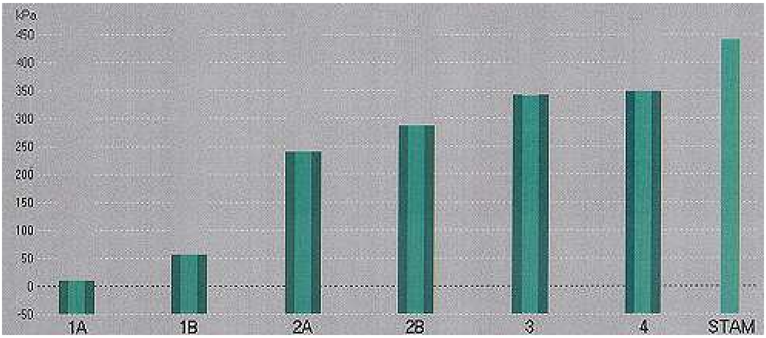

Figure 3.2 The steam pressure setpoints and the current pressure of the different steam groups in the pre-dryer (PM7), and the steam pressure in the steam header (STAM).

PM7

At PM7, the dryer section is divided into a pre-dryer section, surface sizing and an after-dryer section. This thesis concentrates on the cylinders in the pre-dryer section. If the moisture content in the paper is faulty after the pre-dryer section, it is almost impossible to correct the moisture content in the after-dryer section. The main purpose of the after-dryer section is to dry the surface sizing. In case of a web break, the strategy is to concentrate on the pre-dryer section before trying to return to full production in the rest of the dryer section.

The different steam groups in the pre-dryer in PM7 have different setpoints to the steam pressure (see Figure 3.2). The first group ($1A$) has the lowest steam pressure and the last group (4) has the highest steam pressure. The operators can change the setpoints to the first and the last group, and the groups between have setpoints calculated as a percentage of the setpoint to the fourth group. The percentage can also be changed by the operators, and the manufacturer supplies recommended values.

In the first four groups of the dryer section ($1A \rightarrow 2B$), single felt configuration is used. This is to improve runability of the machine and the lower row of cylinders consists of vacuum cylinders only.

During a web break, the setpoints to the steam pressures have to be changed. The setpoint to the last drying group is lowered to a fixed value, and the steam pressure setpoints for the groups $1B \rightarrow 3$ are percentages of the setpoint to the last group. The level for group $1A$ (which consists of only one steam heated cylinder) can be kept constant or be lowered.

The cylinders in the last drying group in the pre-dryer all have a diameter of 1.8 m, and are made of 2.5 cm thick cast iron. Each cylinder has two siphons removing the condensate, and the whole drying group is fed with the same steam pressure.

Online measurement of quality parameters

Most paper quality properties are measured in the laboratory after the paper has been produced. Grammage and moisture content in the paper web are two parameters that are measured online, during production. In the PM7 paper machine, the moisture content is measured both after the pre-dryer section and at the reel-up.

A single-sided infrared moisture sensor is located after the pre-dryer section. The sensor uses the principle of selective infrared absorbtion of the moisture content in the moving paper web. The moisture sensor traverse over the web. An infrared light source transmitts pulsed energy onto the paper sheet, and the light is reflected into a beam splitter. The two beams are subsequently directed to two photodetectors, sensitive to different wavelengths (1.8 μm, which is a reference wavelength, and 1.9 μm, which is water-sensitive). The ratio between the reference and the water-sensitive wavelengths are converted into percent moisture content in the paper web.

After the after-dryer section, a two-sided infrared moisture sensor is located. Instead of having the photodetectors on the same side as the light sourse, the light is transmitted through the web. The percentage of water in the web is calculated by division between the water content and the grammage. The grammage is measured in the same way as the water content, but with a radioactive source instead of an infrared light.

Web breaks at PM7

After a web break a 10-20 cm wide paper sheet is threaded through the pre-dryer section before the sheet is broadened to cover the whole cylinder width. When the pre-dryer section is running as desired, the threading continues through the surface sizing and the after-dryer section. When threading the dryer section, the cylinder surface temperature is very important. If the cylinders are too hot, the thin paper web will tend to stick to the cylinders. On the other hand, if the cylinders are too cold, the paper web will be more fragile due to the higher water content and new web breaks may occur.

The strategy on the PM7 paper machine in Husum is to lower the steam pressure during web breaks to a fixed level. When the measuring of the cylinder surface temperature took place, the level was set to 80 kPa, but was later raised to 100 kPa. It is also possible for the operators to change the level during operation.

4

A dynamic model of a drying cylinder

This chapter describes a dynamic model of a drying cylinder in a paper machine. The goal of the model is to simulate the dynamic behavior of a drying cylinder at a web break in order to improve steam pressure control. The aim is ***not*** to model the entire drying section or to model the moisture content of the paper web. After a web break, a non-optimal cylinder temperature is the most prevalent contributor to faulty moisture content of the paper. The cylinder surface temperature is highly correlated with the moisture content in the paper web.

4.1 Previous work

Many projects have modeled the drying section of a paper machine. Some use static models, others dynamical models, and still others use state models for the drying section. The aim with modelling the dryer section also varies much. The main purposes are to predict how the dryer section can be improved before reconstruction or to improve dryer section control. Naturally it is also interesting to model to get a better understanding for the dynamics in the paper during drying.

[Berrada *et al.*, 1997] have constructed a state model, [Gaillemard, 2004] has created a static model, and [Gardner, 2000] also modeled the drying section statically. Modeling for process control have [Nelson and Gardner, 1996] and [Chen, 1995] done. The department of Chemical Engineering, Lund University is well known for physical modeling of the dryer section. Among recent publications are [Karlsson and Stenström, 2003], [Karlsson and Stenström, 2004] and [Baggerud, 2004].

The starting point for this model was the dynamical modeling of the dryer section of a paperboard machine, made by Håkan Persson at the Department of Chemical Engineering, Lund University ([Persson, 1998]). In his licentiate thesis he conducted capacity studies and modeled the dryer section. Previous work at the same department included mathematical modeling of a multi-cylinder dryer, [Wilhelmsson, 1995]. A good introduction to system modeling and simulation can be found in [Schwarzenbach and Gill, 1992] or in [Thomas, 1999].

4.2 Assumptions

The angle of approach for the dynamical modeling put together by [Persson, 1998] was to look at continuous operation and grade changes in the dryer section (modeling drying cylinders and paper web). To simplify the calculations the cylinder surface was approximated as a flat surface in order to avoid using cylindrical coordinates. All the heat transfer was assumed to be either conductive or convective, and there are no moisture gradients within the web. Instead all evaporation is assumed to take place on the web surface. The evaporation has been investigated by [Wilhelmsson, 1995], who also looked into the properties of the drying air, which is assumed to be constant and independent of the circumstances.

To simplify this model further, additional assumptions have been made in this project. In the present model only one cylinder is considered. The cylinder is assumed to be fully covered with the paper web, neglecting the free draw (see Figure 2.4). This is an assumption that can be made since it is the cylinder surface temperature that is in focus. If the aim of the model was to simulate the moisture content in the paper web or other paper properties, the free draw is important since most of the evaporation takes place there.

The modeled cylinder is also assumed to be located in the dryer section so that the cylinder is fed by steam only from the main line. The situation with flash steam is not considered and the heat transfer from the paper to the air is assumed to be negligible. The steam pressures are expressed in kPa, and are excess pressures (atmospheric pressure not included), if not stated otherwise.

The pocket ventilation is assumed to be knocked out during a web break (the doors to the dryer section opens automatically). As a result, the temperature of the surrounding air is kept constant. The influence of the drying felt is not considered either.

The simulated cylinder is assumed to be in the *constant drying rate zone*. In Figure 4.1 it can be seen that the cylinder temperature increases after the $35th$ cylinder even if the steam pressure is the same in all cylinders in the fourth group (cylinders $27-38$). The paper temperature increases markedly at the $36th$ cylinder, indicating that the paper surface is completely dry, and that the water left in the paper web can be found inside the wood fibres. The sheet now enters the *falling drying rate zone*.

The moisture content in the paper web is included in the model, but not all components that affect the moisture are considered. The main influence is the steam pressure in the cylinder, but also the ventilation, the stock flow, velocity of the paper machine, rate of recirculated paper, and rate of filler effect the final moisture. Since the aim of this work is to investigate the cylinder surface temperature, the moisture has not been considered further.

4.3 The basic equations

The dynamic model of the dryer section is based on mass and energy balances. The model can be summarized in the following four basic equations [Persson, 1998]. A cross-section of the drying cylinder and the paper web is shown in Figure 4.2. The first basic equation is the unsteady heat conductivity equation for the cylinder

$$\frac{\partial T_c}{\partial t} = \frac{k_c}{\rho_c c_{p,c}} \frac{\partial^2 T_c}{\partial z_c^2} - v_x \frac{\partial T_c}{\partial x} \tag{4.1}$$

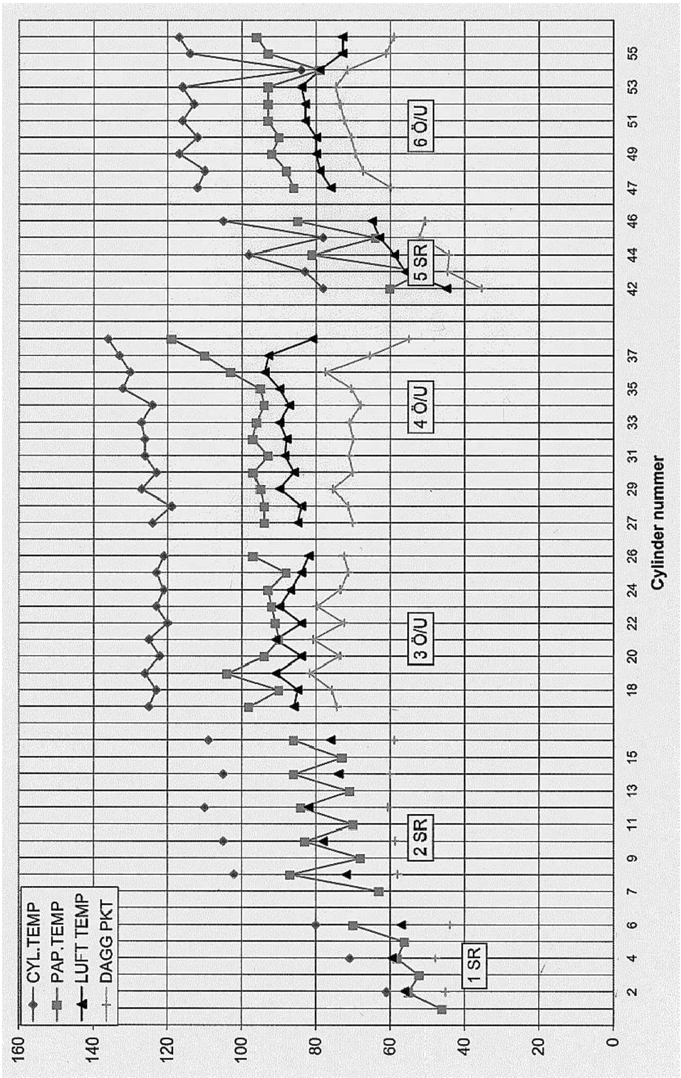

Figure 4.1 A temperature profile from the Husum, PM7 paper machine. The profile shows the cylinder temperature (CYL.TEMP), the paper temperature (PAP.TEMP), the air temperature (LUFTTEMP), and the dew point (DAGG-PKT). (Courtesy to M-real)

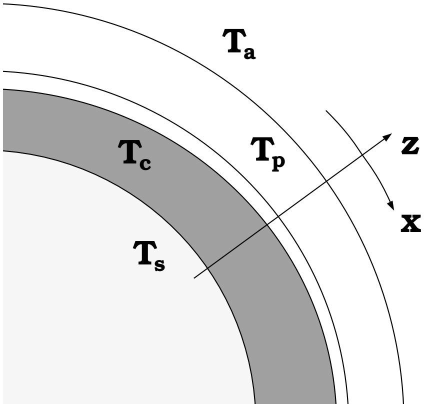

Figure 4.2 The cross-section of cylinder and paper web. The temperatures are the steam temperature (T_s), the cylinder temperature (T_c), the temperature of the paper web (T_p) and the temperature of the ambient air (T_a). The z-direction is the thickness direction and x is the machine direction.

where T_c is the cylinder temperature, t is time, k_c is the thermal conductivity for the cylinder, ρ_c is the cylinder density, $c_{p,c}$ is the specific heat capacity for the cylinder, z_c is a coordinate in the thickness direction of the cylinder shell, and v_x is the machine speed. The first term on the right hand side is the conductive heat transfer and the second term is the convective heat transfer. Since the cylinder normally is regarded as only one node, the convective term is negligible.

The second equation is the unsteady state heat conductivity equation for the paper web

$$\frac{\partial T_p}{\partial t} = \frac{k_p}{\rho_p c_{p,p}} \frac{\partial^2 T_p}{\partial z_p^2} - v_x \frac{\partial T_p}{\partial x} \tag{4.2}$$

where T_p is the temperature of the paper web, ρ_p is the paper density, $c_{p,p}$ is the specific heat capacity for the paper, and z_p is a coordinate in the thickness direction of the paper. The first term on the right hand side is the conductive heat transfer in the z-direction and k_p is a lumped parameter for all types of heat transfer in the web (i.e.

conduction and evaporation/condensation within the web). The second term on the right hand side is the convective term.

The equation for the mass balance of water is given by the third equation

$$\frac{\partial \mu}{\partial t} = -v_x \frac{\partial \mu}{\partial x} - \frac{1}{G_{p,dry}}(\dot{m}_i + \dot{m}_o) \qquad (4.3)$$

where μ is the moisture ratio, $G_{p,dry}$ is the basis weight (dry fibres), and $\dot{m}$ is the evaporation rate. The first term on the right hand side is convection transport of water in the machine direction. The second term on the right hand side represents the evaporation from both sides of the web.

The last equation is the equation for mass balance of dry material in the paper

$$\frac{\partial G_{p,dry}}{\partial t} = -v_x \frac{\partial G_{p,dry}}{\partial x} \qquad (4.4)$$

The right hand side term is the transport of solid dry material in the machine direction and $\partial G_{p,dry}/\partial t$ is accumulation of solid dry material.

These partial differential equations must be discretized in order to obtain a solvable system of equations. [Persson, 1998] used centre differentiation and backwards differentiation [Davis, 1984].

$$\frac{\partial^2 T}{\partial z^2} = \frac{1}{(\Delta z)^2}(T_{i-1} - 2T_i + T_{i+1}) \qquad (4.5)$$

$$\frac{\partial T}{\partial x} = \frac{1}{\Delta x}(T_i - T_{i-1}) \qquad (4.6)$$

4.4 Boundary conditions and physical properties

The boundary conditions and physical properties have been thoroughly investigated by [Wilhelmsson, 1995].

Boundary conditions in the z-direction

The boundaries between the steam and the cylinder, and between cylinder and the paper are represented by heat transfer coefficients. Equation (4.7) describes the heat transfer from the steam inside the cylinder to the inner cylinder surface ($z_c = 0$).

$$-k_c \left.\frac{\partial T}{\partial z}\right|_{z_c=0} = h_{sc}(T_s - T_{c,0}) \tag{4.7}$$

The steam temperature inside the cylinder is T_s and $T_{c,0}$ is the temperature on the inner side of the cylinder, and k_c is the thermal conductivity. The heat transfer coefficient between the steam and the cylinder (h_{sc}) is a fitting parameter. The value of h_{sc} mostly depends on the thickness of the condensate layer inside the cylinder. [Wilhelmsson, 1995] assumes the value to be in the range $800 - 5000$ W/m$^{2\circ}$C.

The expression for heat transfer between the cylinder and the paper is given by equation (4.8). The calculations are made in the boundary on the outer side of the cylinder ($z_c = d_c$).

$$-k_c \left.\frac{\partial T}{\partial z}\right|_{z_c=d_c} = h_{cp}(\mu)(T_{c,d_c} - T_{p,0}) = k_p(\mu) \left.\frac{\partial T}{\partial z}\right|_{z_p=0} \tag{4.8}$$

The heat transfer is dependent on the moisture content in the paper web

$$h_{cp}(\mu) = h_{cp}(0) + 955 \cdot \mu \tag{4.9}$$

where $h_{cp}(0)$ is a fitting parameter. [Wilhelmsson, 1995] varies $h_{cp}(0)$ between $200 - 500$ W/m$^{2\circ}$C.

At the interface between the cylinder and the surrounding air only convective heat transfer is considered, heat transfer by radiation is neglected. The boundary condition is given by equation (4.10).

$$-k_c \left.\frac{\partial T}{\partial z}\right|_{z_c=d_c} = h_{ca}(T_{c,d_c} - T_a) \tag{4.10}$$

In the original model [Wilhelmsson, 1995] it is assumed that all the evaporation takes place on the surface of the paper web. The heat for evaporating the water is either conducted to the web surface or convected from the surrounding air.

$$\dot{m}_{pa}\lambda = -k_c \left.\frac{\partial T}{\partial z}\right|_{z_p=d_p} + h^*_{pa}(T_a - T_{p,d_p}) \tag{4.11}$$

where h^*_{pa} is a corrected heat transfer coefficient for simultaneous heat and mass transfer. But, in this model, the assumption is made that the convection from the ambient air can be neglected ($h^*_{pa} = 0$). The evaporation rate, $\dot{m}_{pa}$, is calculated with the Stefan equation

$$\frac{\dot{m}_{pa}}{A} = \frac{K_{G,pa} M_W P_{tot}}{\Re T} \ln\left(\frac{P_{tot} - P_a}{P_{tot} - P_p}\right) \tag{4.12}$$

where A is the area of the cylinder, $K_{G,pa}$ is the mass transfer coefficient between paper and air, M_W is the molecular weight for water, P_{tot} is the total pressure, $\Re$ is the gas constant. The vapor pressure of water, P_p, is given in equation (4.13), and is a function of the temperature (given in Kelvin).

$$P_p = 133.332 \cdot e^{\left(18.3036 - \frac{3816.44}{T-46.12}\right)} \tag{4.13}$$

Boundary conditions in the x-direction

Boundary conditions in the x-direction are only applicable for the paper web. All boundary conditions are given by a set of initial conditions. These are the paper web temperature and moisture content from the preceding (imaginary) cylinder as well as the stock flow.

Physical properties of the cylinder

The drying cylinders are made of cast iron, and the composition of carbon and other metals in the cast iron determine the physical properties. The following values are used for the thermal conductivity, the specific heat capacity, and the density: $k_c = 45$ W/m°C, $c_{p,c} = 500$ J/kg°C, and $\rho_c = 7300$ kg/m^3.

The temperature of saturated steam inside the cylinder is given by equation (2.1).

Physical properties of the paper web

For the paper web, most of the physical properties depend on the moisture content in the web. All the following properties and values are from [Persson, 1998].

The paper's thermal conductivity (k_p) is given by

$$k_p = \frac{k_{dry} + \mu \cdot k_w}{1 + \mu} \tag{4.14}$$

where k_w is the thermal conductivity for water. For the thermal conductivity for dry paper k_{dry}, the value 0.08 W/m$^{2\circ}$C is used.

The specific heat capacity for paper, $c_{p,p}$, is given by

$$c_{p,p} = \frac{c_{p,fiber} + \mu \cdot c_{p,w}}{1 + \mu} \tag{4.15}$$

where $c_{p,w}$ is the specific heat for water and the value used for the specific heat for the fibers $c_{p,fiber}$ is 1256 J/kg°C.

Due to the fact that the web shrinks as it dries, the density of the paper web depends on the thickness of the paper web and how moist the web is.

$$\rho_p(\mu) = \frac{(1 + \mu) \cdot G_{dry}}{d_p} \tag{4.16}$$

The basis weight for dry paper is G_{dry} and d_p is given by equation (4.17)

$$d_p(\mu) = G_{dry}\left(\frac{1}{\rho_{dry}} + \frac{\mu}{\rho_w}\right) \tag{4.17}$$

where ρ_w is the density for water and ρ_{dry} is the density for non-calendered paper, which is in the interval $500\ - 700$ kg/m^3.

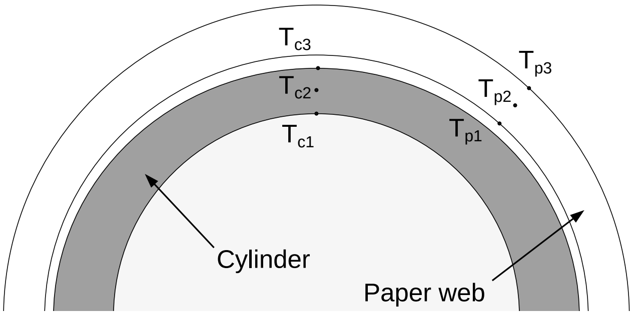

Figure 4.3 The different nodes in the thickness direction of the cylinder and the paper web.

4.5 The model

In the thickness direction (z), both the cylinder and the paper web are divided into three nodes (see Figure 4.3). The first node of the cylinder is on the inside of the cylinder shell, the part of the cylinder in contact with steam and condensate. The second node is inside the cylinder shell and the third node is on the cylinder surface. The three nodes of the paper are the inner side of the paper which is touching the cylinder (first node), the interior of the paper (second node) and the third node is located on the outer side of the paper, which is in contact with the surrounding air.

In the machine direction (x) the model has been reduced to boundary conditions following from the previous (imaginary) cylinder. This includes both paper web temperature (in all three nodes, T_{pi}^{prev}) and the moisture (μ^{prev}).

The derivation of the equations used in the model can be found in [Persson, 1998].

The cylinder

The discretized differential equation for the inner nodal point in the cylinder, following from equation (4.1).

$$\frac{\partial T_{c1}}{\partial t} = \frac{k_c}{\rho_c c_{p,c}(\Delta z_c)^2}\Big(-2\Big(1+\Delta z_c\frac{h_{sc}}{k_c}\Big)T_{c1} + 2T_{c2} + 2\Delta z_c\frac{h_{sc}}{k_c}T_s\Big) \quad (4.18)$$

The heat transfer coefficient between the steam and the cylinder shell is h_{sc}. The temperature of the steam inside the cylinder is T_s.

For the inner surface of the cylinder the following equation is valid

$$\frac{\partial T_{c2}}{\partial t} = \frac{k_c}{\rho_c c_{p,c}(\Delta z_c)^2}(T_{c1} - 2T_{c2} + T_{c3}) \quad (4.19)$$

For the cylinder surface there are two possibilities. The cylinder is either covered with paper or the cylinder is completely exposed to the surrounding air (i.e. during a web break). In ordinary cases, equation (4.20) is valid. During a web break, equation (4.21) is used instead.

$$\frac{\partial T_{c3}}{\partial t} = \frac{k_c}{\rho_c c_{p,c}(\Delta z_c)^2}\left(2T_{c2} - 2T_{c3} + 2\Delta z_c\frac{h_{cp}}{k_c}(T_{p1} - T_{c3})\right) \quad (4.20)$$

$$\frac{\partial T_{c3}}{\partial t} = \frac{k_c}{\rho_c c_{p,c}(\Delta z_c)^2}\left(2T_{c2} - 2T_{c3} + 2\Delta z_c\frac{h_{ca}}{k_c}(T_a - T_{c3})\right) \quad (4.21)$$

The heat transfer coefficient between the cylinder shell and the paper is h_{cp} and h_{ca} is the heat transfer coefficient between the cylinder shell and the surrounding air. The temperature of the surrounding air is T_a.

The paper

The rewriting of the heat transfer in the paper in equation (4.2) to a discretized equation gives the following expression for the first node in the paper web

$$\frac{\partial T_{p1}}{\partial t} = \frac{k_p}{\rho_p c_{p,p}(\Delta z_p)^2}\Big(2\Delta z_p\frac{h_{cp}}{k_p}T_{c3} - 2\Big(1+\Delta z_p\frac{h_{cp}}{k_p}\Big)T_{p1} + 2T_{p2}\Big) - \frac{v_x}{\Delta x_p}(T_{p1} - T_{p1}^{prev}) \quad (4.22)$$

In the interior of the paper web the equation is

$$\frac{\partial T_{p2}}{\partial t} = \frac{k_p}{\rho_p c_{p,p}(\Delta z_p)^2}(T_{p1} - 2T_{p2} + T_{p3}) - \frac{v_x}{\Delta x_p}(T_{p2} - T_{p2}^{prev}) \quad (4.23)$$

For the paper surface the assumption is made that the heat transfer from the paper to the air can be neglected and therefore the equation for the outer surface of the paper (the transition from the paper to the air) is given by

$$\begin{aligned}\frac{\partial T_{p3}}{\partial t} &= \frac{k_p}{\rho_p c_{p,p}(\Delta z_p)^2}\left(2T_{p2} - 2T_{p3} - \frac{2\Delta z_p}{k_p}\dot{m}_{pa}\lambda\right) \\ &\quad - \frac{v_x}{\Delta x_p}(T_{p3} - T_{p3}^{prev})\end{aligned} \quad (4.24)$$

The moisture

For the phase *cylinder - paper web - air* the discretized and unstable mass balance for the water in the paper is given by equation (4.25). The moisture ratio in the paper is μ.

$$\frac{\partial \mu}{\partial t} = -\frac{v_x}{\triangle x_p}(\mu - \mu^{prev}) - \frac{1}{G_p}\dot{m}_{pa} \quad (4.25)$$

4.6 Implementation

All equations are implemented in Matlab Simulink. The model is divided into two subsystems, the cylinder and the paper web. The simulation is driven by the measured steam pressure. The outlines of the Simulink model can be seen in Figure 4.4.

The cylinder subsystem needs the steam temperature, T_s, which has to be calculated from the measured steam pressure. The other inputs are the temperature of the inside of the paper web, T_{p1}, the heat transfer between cylinder and paper, h_{cp}, the temperature of the ambient air,

T_a, and the web break signal, d, indicating whether there is paper on the cylinder or not. The outputs are the cylinder temperatures in all three nodes, T_{c1}, T_{c2} and T_{c3}.

The paper web subsystem is fed with the cylinder surface temperature, T_{c3}, the partial pressure of water steam in the surrounding air, P_a, the basis weight of the paper web, G_p, and the machine speed, v_x. The outputs from the paper web subsystem are the temperatures of the paper web in all three nodes, T_{p1}, T_{p2} and T_{p3}, and the moisture content in the paper web, μ. The last output from the paper web subsystem is the heat transfer coefficient between cylinder and paper, h_{cp}, which is moisture dependent, see equation (4.9).

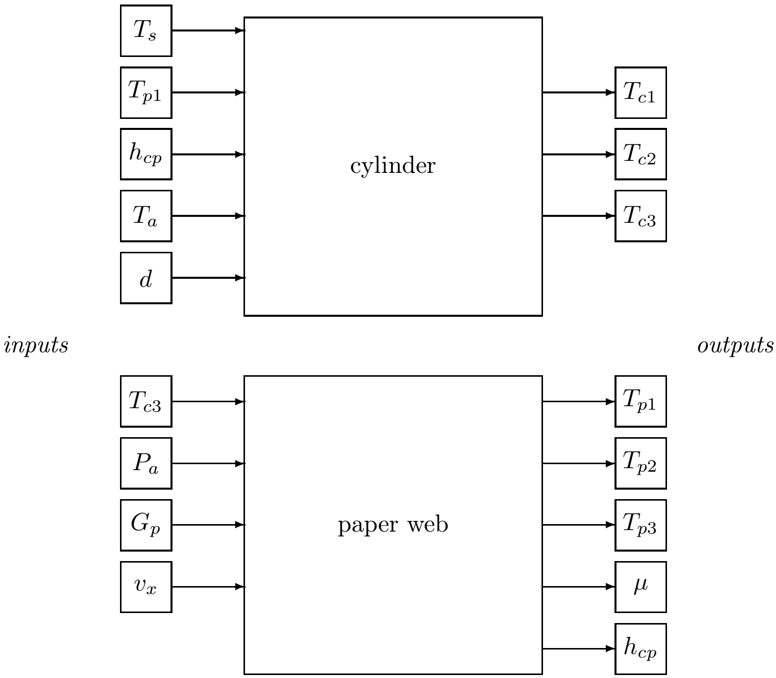

Figure 4.4 The outlines of the simulation.

5

Model validation

The accuracy of the model was verified through experiments conducted at the M-real Paper Mill in Husum, Sweden. Verifications were made both during normal operation and during web breaks.

5.1 Experimental conditions

The validation of the model is made on *one* cylinder in the Husum PM7 paper machine. The chosen cylinder is cylinder number 33 in the pre-dryer section at PM7. Cylinder 33 is one of the cylinders in the last drying group in the pre-dryer section, where the moisture content in the paper web is low. After the pre-dryer section there is a measuring instrument recording the moisture content. The drying group that cylinder 33 belongs to has the advantage of being fed with steam from the header only, and the influence of flash steam can be disregarded.

5.2 Measuring the cylinder surface temperature

The dryer section is a harsh environment with moist air and high temperatures. To be able to measure the cylinder surface temperature continuously, a trestle for the temperature sensor was built. The trestle stabilizes the sensor, which is very sensitive to vibrations. The trestle was also used for preventing the measuring equipment from getting

Figure 5.1 The temperature measuring equipment mounted at cylinder 33.

caught up in the drying felt in case of emergency. The trestle is shown in Figure 5.1.

The temperature sensor has to be a contact sensor due to the fact that the drying cylinders are shiny and therefore reflect radiation from a infrared sensor. Humidity in the air can also absorb infrared radiation of certain wave lengths. If an infrared sensor is used, it is more likely that the temperature of the sourrounding air is measured and not the cylinder's surface temperature.

The temperature sensor is a Swema SWT 315, which was used on top of cylinder 33 (see Figure 5.2). The sensor has a protecting metal wafer and a Ni-100 foil element. The sensor is connected to a converter

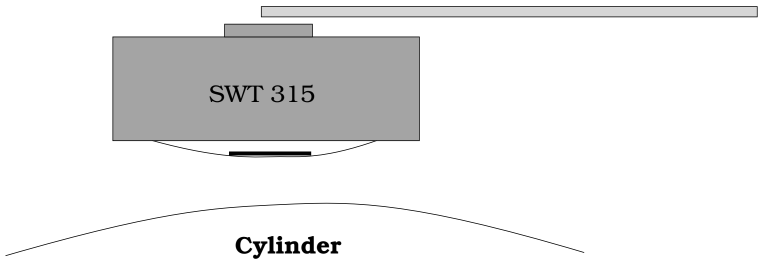

Figure 5.2 A picture of the contact sensor that measures the cylinder surface temperature.

(Swematemp 200), which converts the temperatures ($0 - 200°C$) into a voltage (0-1 V). An additional converter is needed to transform the signal into a current (0-20 mA), which is the unit used in the process control system. A logger is connected to the control system via an OPC-link. The surface temperature, together with steam pressure, moisture content, differential pressure, grammage, and machine speed were logged.

5.3 Experiments

A number of experiments have to be performed to verify the whole model. Both the dynamics of the drying cylinders and the properties of the controller have to be investigated.

In total, four different experiments were performed to get the necessary data about the process. The dynamics of the drying cylinders have to be supervised both during normal operation and during web break. If the cylinder surface temperature is measured, setpoint changes to the steam pressure controller also provide data about the PID-controller. When a web break occurs, the steam valve closes completely, and no information is received about the PID-controller. The case is the same after a break, the valves open up completely to increase the steam pressure as quickly as possible.

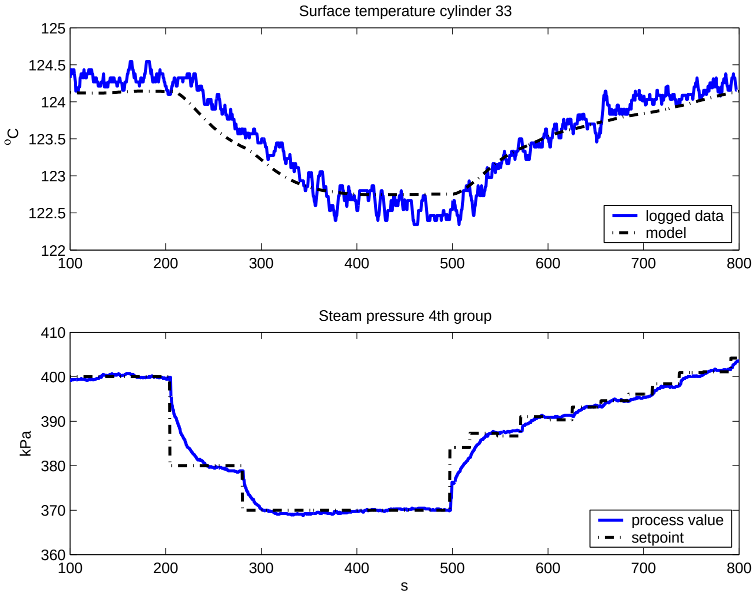

Figure 5.3 The cylinder surface temperature and the steam pressure changes during normal operation for cylinder 33 at PM7, Husum.

5.4 Normal operation

Figure 5.3 shows an evaluation performed at normal operation. A few step-changes of the setpoint to the steam pressure controller were made, and the figure shows that the model captures the dynamics well. The converter connected to the temperature sensor was out of order during the surface temperature measurement, and that is the reason for the discretized temperature signal.

5.5 Web break

Figure 5.4 shows the surface temperature and the steam pressure during a web break. The setpoint to the pressure controller is taken from

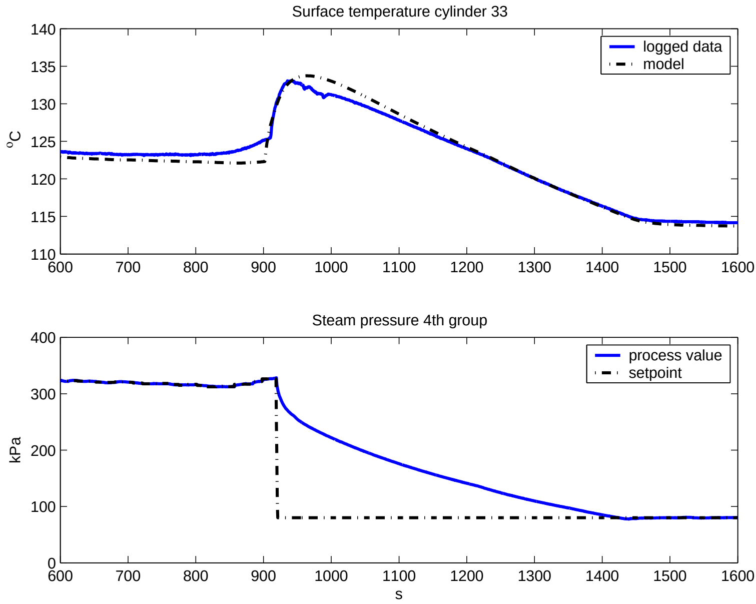

Figure 5.4 The cylinder surface temperature and the steam pressure for drying cylinder 33 at PM7, Husum, during a web break. The web breaks a $t = 920$ s.

the IMC controller before the web break. During web breaks, the setpoint is fixed to 80 kPa. When the web breaks, the surface temperature increases immediately. This is due to the loss of the cooling effect from the paper web. The dynamics of the drying cylinder makes the reduction of the steam pressure a slow process. Since it is difficult to know when the web is about to break, the measurement took place at a planned shutdown. The quality of the pulp was changing just before the break, and the increase in surface temperature before the break is an indication of this.

Before the break, the steam pressure is close to 330 kPa, and the saturated temperature for the steam is 146°C. The temperature on the outer side of the cylinder is 124°C (see Figure 5.4) and the paper web has a cooling effect of around 20 degrees. If the steam pressure is

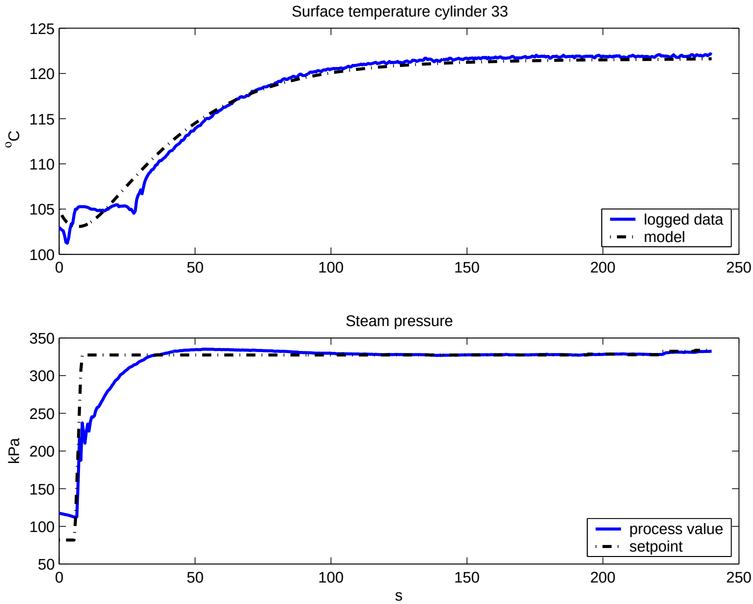

Figure 5.5 The response of the cylinder surface temperature due to a steam pressure increase when the web is back on the cylinder after a web break.

not lowered during the break, the cylinder surface will reach a steady state temperature a few degrees lower than the temperature of the satureated steam inside the cylinder.

5.6 After a web break

Figure 5.5 shows what happens when the paper web is restored to the cylinders. There are sensors that detect when the broadening of the web is completed, and a signal is sent to the steam pressure controller to return to the same pressure as before the break. The setpoint is kept constant and is not taken from the IMC controller until the whole paper machine is working again (paper starting to reel-up again) and the moisture content is measured. For this measurement, the setpoint from the IMC controller is obtained at 220 seconds, see Figure 5.5.

The temperature difference during the break in Figure 5.4, 114°C, and in Figure 5.5, 105°C, is due to fact that the sheet is back on the cylinder in Figure 5.5.

Figure 5.6 shows another example of the cylinder surface temperature after a web break. This data has not been used for validating the model, on the account of the temperature fluctuations at the time 150 seconds and 200 seconds. In spite of the varying surface temperature, it is interesting to see how the cylinder is affected when the paper sheet covers the cylinder. The first 25 seconds in Figure 5.6 is during the break, and after that the web is broadened and the temperature drops immediately due to the cooling effect from the wet web. At the time 60 seconds, the sensor indicates full width on the web, and the steam pressure setpoint is set to the same value as before the break.

5.7 Summary

The model derived in Chapter 4 has been verified through experiments performed on the paper machine PM7 in the M-real Husum Mill. The main goal of the model is to describe the dynamics between the steam pressure in the cylinder and the cylinder temperature. Experiments have been performed both during normal operation and during web breaks. The measured steam pressure has been fed into the model and the resulting cylinder temperature from the model has been compared with the true cylinder temperature.

During normal operation, the dynamics was explored through step changes in the setpoint to the pressure controller. During web breaks, both the steam pressure and the cylinder temperature were measured before, during, and after the breaks. All these experiments show that the output from the model agrees well with the true cylinder temperature. Therefore, the model is suitable for derivation of the control design performed in the next section.

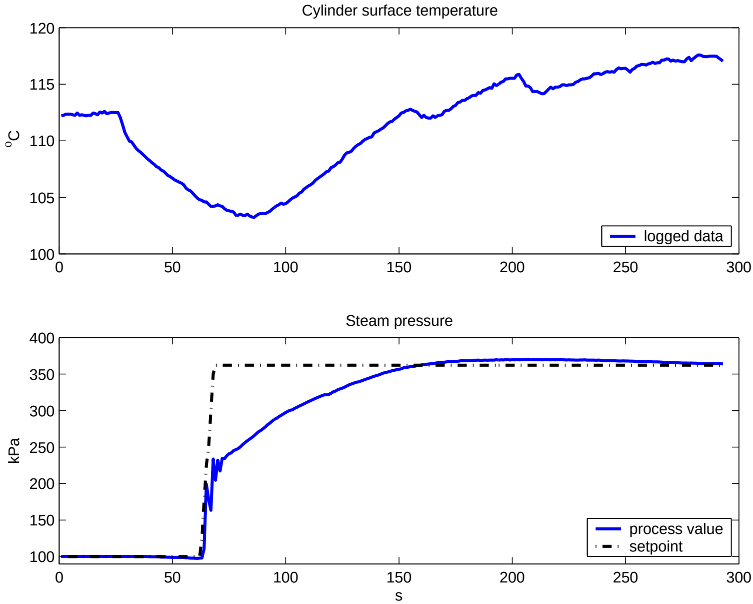

Figure 5.6 The response of the cylinder surface temperature due to return to normal operation after a web break.

6

Steam pressure control

The aim of this project is to control the steam pressure of the drying cylinder in such a way that the same drying properties are obtained after the web break as before. To achieve this, the steam pressure must be reduced during web breaks since the large cooling effect from the paper web is lost. The objective is to have the same cylinder temperature after the web break as before.

6.1 The IPZ model

The only way to alter the steam pressure on the paper machine is to change the setpoint of the steam pressure controllers. The model developed in chapter four describes the dynamics between the steam pressure and the cylinder temperature. This model must be complemented with a model that describes the dynamics between the steam valve position and the steam pressure. Such a model is found in [Slätteke, 2003]. The name of the model, IPZ, emanates from the structure of the model; a transfer function with an integrator, one pole, one zero, and a time delay.

$$G(s) = k_v \frac{1 + sT_1}{s(1 + sT_2)} \, e^{-sL} \tag{6.1}$$

The IPZ-model has been developed for normal operation, and is a simple model of a nonlinear process. This means that one set of model

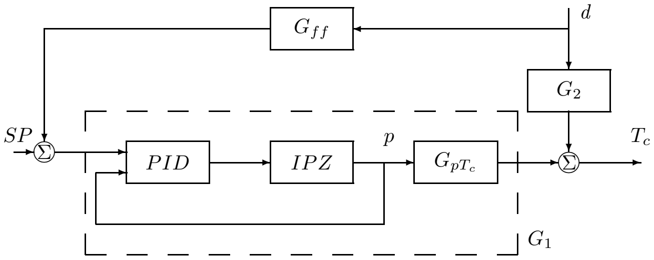

Figure 6.1 A block diagram of the feed-forward control.

parameters, obtained at one operating point, will not be appropriate for other operating conditions. In [Slätteke, 2003], only normal conditions are treated, and there are no examples of web breaks. The IPZ model mainly influences the swiftness in the steam system.

The dynamics of the drying cylinder changes drastically during a web break. During a web break there will be two different operating points. There is one operating point when the cooling effect from the web is lost and another when the paper gets back on the cylinders. The changes in the steam pressure also affect the changed dynamics of the drying cylinders.

6.2 Feed-forward control

The idea is to use a feed forward control to reduce the steam pressure when a web break occurs, see Figure 6.1. The setpoint (SP) in Figure 6.1 is the setpoint from the IMC, see Figure 2.8. The steam pressure setpoint from the IMC controller is constant during web breaks. The measuring frame, measuring the moisture content in the web, is switched off during web breaks. Therefore the IMC setpoint cannot be updated.

Feed-forward is made from the digital signal d which takes the value zero during normal operation and one during web breaks. The transfer function G_1 describes the dynamics between the setpoint of the steam pressure controller and the cylinder surface temperature. To obtain G_1, the setpoint of the steam pressure controller was reduced in steps of 10 kPa without paper on the cylinder. The transfer function is nonlinear due to the nonlinear relationship between steam pressure and steam temperature. The step responses were fitted to a first order model with a time delay:

$$G_1 = \frac{k_1(p)}{1 + 65s} \, e^{-22s} \tag{6.2}$$

where $k_1(p)$ is the nonlinear gain. The numerical values of the time constant and the time delay in (6.2) are mean values from all the step responses made with steam pressures ranging from 210 kPa to 420 kPa. The gain is partially given by the static relation between steam pressure and steam temperature (the Antoine equation)

$$T_{steam}(p) = \frac{a}{b - \log(p + p_{atm})} - c \tag{6.3}$$

where $a = 1668.21$, $b = 7.092$, $c = 228$, p_{atm} is the atmospheric pressure, and the pressures are in kPa. The static relation between steam temperature and cylinder temperature is not linear, but $T_c = 0.97 \cdot T_{steam}$ gives an appropriate approximation. The new parameters of (6.3) become $a = 1618$, $b = 7.092$ and $c = 221$. A comparison between the simulated temperature and the calculated values of the cylinder surface temperature can be found in Figure 6.2.

Equation (6.3) is a well known physical relation, giving the steam temperature if the steam pressure is known. However, between the inside of the cylinder and the cylinder surface there will be a temperature gradient. Due to the resistance in the cast iron cylinder and the surrounding (cooler) air, the surface will be a few degrees cooler than the interior of the cylinder. The relation stated here, $T_c = 0.97 \cdot T_{steam}$, is specific for the M-real, Husum PM7 paper machine.

The transfer function G_2 in Figure 6.1 describes the dynamics between the web break signal d and the cylinder temperature. To obtain G_2, the steam pressure was held constant during a number of web breaks,

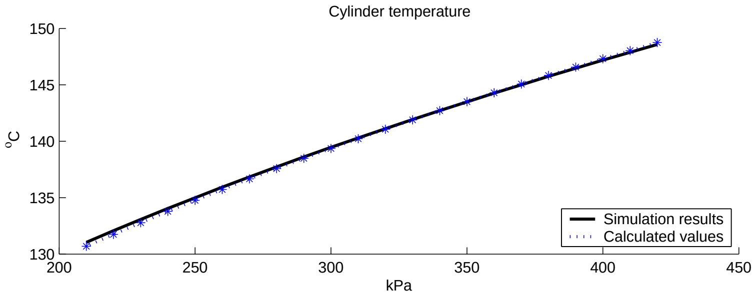

Figure 6.2 Comparison between the simulated temperature (from the Simulink model) and the calculated values of the cylinder surface temperature (from the modified Antoine equation).

and a first order model with delay was determined. The steam pressure was changed in steps of 10 kPa between 300 kPa and 420 kPa. This model was also nonlinear.

$$G_2 = \frac{k_2(p)}{1 + 80s} e^{-4s} \tag{6.4}$$

$k_2(p)$ is the nonlinear gain and the numerical values are mean values from the different breaks. A linear fit gives the following equation for the gain

$$k_2(p) = m_2 + k_2 \cdot p = 10.02 + 0.02295 \cdot p \tag{6.5}$$

A comparison between the gain and the steam pressure can be found in Figure 6.3.

The time delay in G_1 is significantly longer than in G_2. This means that it is impossible to provide an ideal feed-forward compensation for web breaks. The disturbance will influence the cylinder temperature. To obtain a quick compensation, the dynamics in G_1 and G_2 are neglected, and only the static gains $k_1(p)$ and $k_2(p)$ are treated. The realization of the feed-forward compensation is non-trivial because of the nonlinearities that make the gains pressure dependent.

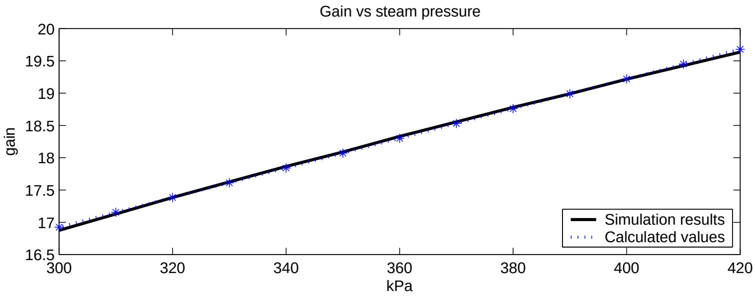

Figure 6.3 Comparison between gain and steam pressure during a web break.

Suppose that the steam pressure before the web break is p_0. From (6.4) and (6.5) the cylinder temperature increase caused by the web break becomes

$$T_{inc} = m_2 + k_2 \cdot p_0 \tag{6.6}$$

To compensate for the temperature increase, the steam pressure must be decreased from p_0 to a lower value p_1. From (6.2) and (6.3) the temperature decrease can be determined

$$T_{dec} = \frac{a}{b - \log(p_0 + p_{atm})} - \frac{a}{b - \log(p_1 + p_{atm})} \tag{6.7}$$

An optimal reduction of the cylinder temperature is *not* obtained by setting $T_{dec} = T_{inc}$, since this would yield a lower cylinder temperature when the web comes back on the cylinder again than before the break. The desired temperature reduction is given by

$$T_{dec} = T_{inc} - \Delta T \tag{6.8}$$

where ΔT is an adjustable offset in the temperature.

The desired steam pressure during web breaks can now be determined from the equations (6.6), (6.7), and (6.8).

$$\log(p_1 + p_{atm}) = b - \frac{a(b - \log(p_0 + p_{atm}))}{a - T_{dec}(b - \log(p_0 + p_{atm}))} \tag{6.9}$$

The aim with modelling the feed-forward controller is to find a controller that optimizes the cylinder surface temperature during a web break. Using $\Delta T = 0$ gives the same temperature before and during the web break, but the temperature will be lower after the break due to the cooling effect from the paper web. To get back to the same drying capacity as fast as possible, ΔT can be chosen so that the cylinder surface temperature is higher during the break ($\Delta T > 0$).

Although, it is not always possible to have the cylinders as warm or warmer as during normal operation. Cylinders that are too warm can cause sticking problems which often lead to new web breaks. In this case, $\Delta T < 0$ would be a wiser choice.

6.3 A simulation example

The control strategy is demonstrated in Figure 6.4. The figure shows three cases with different values of ΔT.

The PID-controller used in the example has the same parameters as the real controller on the paper machine. The PID parameters are $k = 5$, $T_i = 16$, and $T_d = 0$. The parameters for the IPZ-model during normal operation have been taken from a step response experiment. The parameters valid for normal operation are $k_v = 0.033$, $T_1 = 40.38$, $T_2 = 11.38$, and the time delay is ignored ($L = 0$).

Since the dynamics of the drying cylinder changes during a web break, two other sets of parameters have been used for the simulation example. When the web breaks and the steam pressure is lowered, the parameters $k_v = 15$, $T_1 = 50$ and $T_2 = 10$ are used. When production is about to restart, the tail threading begins, and the steam pressure is restored, and another set of parameters is used, $k_v = 30$, $T_1 = 110$ and $T_2 = 10$. These IPZ parameters used during a web break have been obtained by studying the steam pressure behavior during breaks.

Compared to the strategy of reducing the steam pressure to a fixed value, (see Figure 5.4, showing a web break, and what happens after

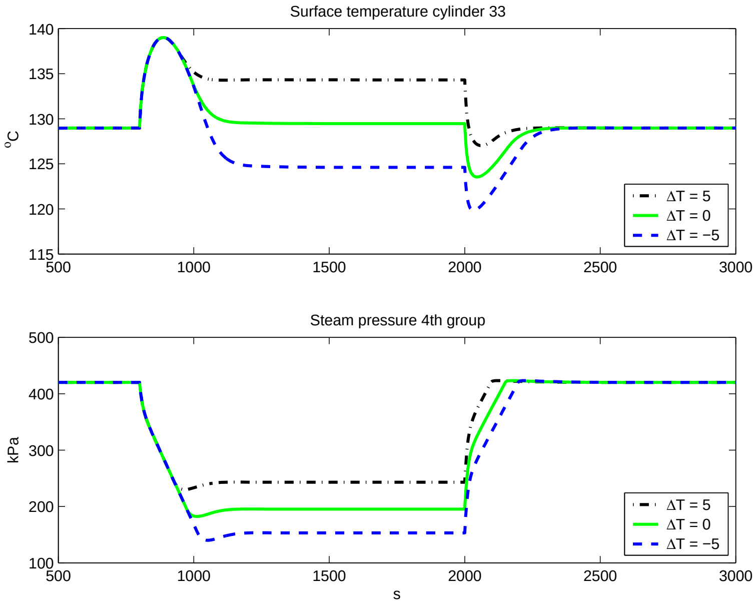

Figure 6.4 The steam control during web breaks. Different values of ΔT have been used.

a web break in Figure 5.5), the feed forward controller with $\Delta T = 5$ (see Figure 6.4) is more expedient in returning to the desired cylinder temperature. There is a dip in the cylinder temperatures for all values of ΔT when the paper web returns to the cylinder. Since the after-dryer section has to be threaded before the paper machine can start producing paper again this is not a problem. However, the temperature dip has to be kept low, otherwise the moisture content in the sheet will be too great and the risk for new web breaks will increase with the moisture content in the paper web.

6.4 Summary

Based on a the models derived in the previous chapters, a new feedforward strategy to improve steam pressure control during web breaks has been derived. Feed forward is made from a digital signal d that is one during web breaks and zero during normal operation. The feedforward signal is fed to the output of the IMC controller, which means that the setpoints of the steam pressure controllers are modified when the web breaks (d goes from zero to one), and when the web is back on the cylinder after the break (d goes from one to zero).

The idea behind the compensator is to obtain an optimal cylinder temperature during the web break, so that the desired moisture content of the paper is obtained as fast as possible after the break. The feedforward compensator is a static nonlinear function of the steam pressure applied before the web break.

7

An industrial validation

The feed-forward strategy presented in the previous chapter has been tested on the PM7 paper machine in Husum. Data from the test is presented in this chapter.

7.1 Earlier strategy

The earlier strategy at the PM7 paper machine was to lower the steam pressure to a fixed level during web breaks. This strategy is a few years old and the running properties of the paper machine have changed. The steam pressure during normal steady-state run has increased, and so has the machine speed. Different operators have different opinions on how to best dry the paper, and the setpoint of the steam pressure controller has changed, preferably between 80 and 120 kPa. Still, this strategy would sometimes present moisture problems.

The simulation in the previous chapter shows that pressures between 80 and 120 kPa cause cylinder temperatures that are too low, resulting in too moist paper. It will take some time to adjust the steam pressure to the right level, causeing the moisture problem to remain as long as the cylinders have the wrong temperature.

In Figure 7.1 is an exampel of a problem with the moisture content in the paper web after a web break. The paper web is very fragile when the moisture content is high, and unsatisfactory moisture levels in the paper can result in new web breaks (which is the case in Figure 1.1).

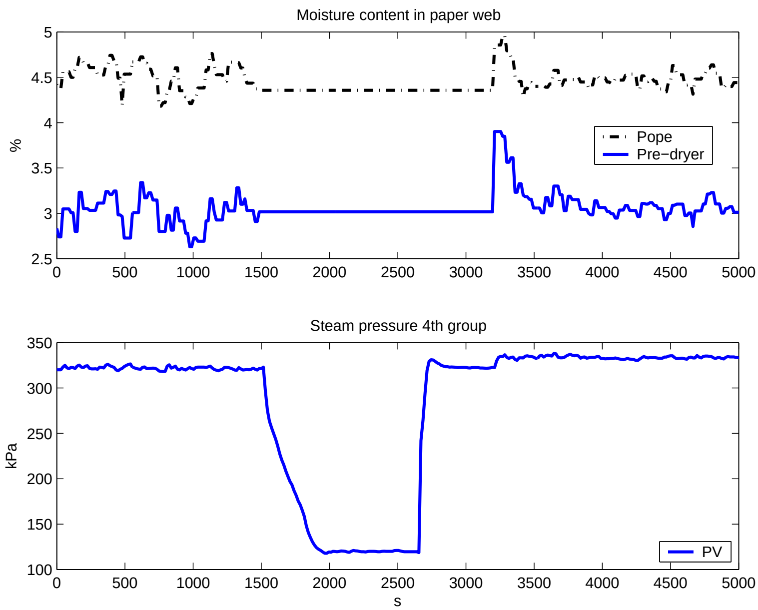

Figure 7.1 Moisture content both at the reel-up (pope) and after the pre-dryer section after a web break. The web break in the pre-dryer lasts between 1500 and 2700 seconds. The whole machine is running again after 3200 seconds.

The steam pressure setpoint is returned to the same value as before the break as soon as sensors indicate full width of the paper web in the pre-drying section. In Figure 7.1, the steam pressure in the pre-dryer is increased after 2600 seconds. When the web breaks, threading the rest of the paper machine takes some time, and the measuring frames start working first 10 minutes later. The frames record a high moisture content, that is, the cylinders are too cool, and the steam pressure has to be increased.

The setpoint of the moisture controller is the desired moisture content in the paper at the reel-up. In this case it was 4.5%. In Figure 7.1 it can be seen that the after-dryer section cannot correct a faulty moisture content that arises in the pre-dryer section. The bump in the moisture

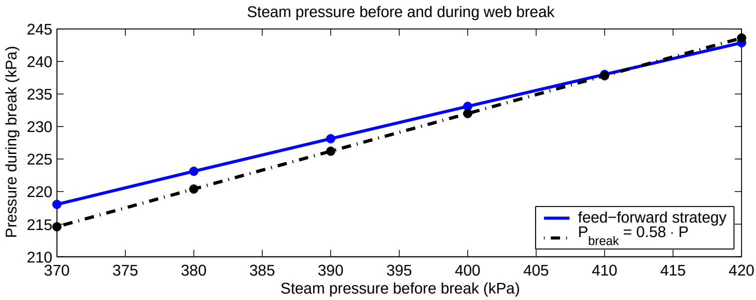

Figure 7.2 The steam pressure during web break given by the feed-forward strategy compared with 58% of steam pressure before the web break.

content for the pre-dryer section right after the break can also be seen in the moisture content for the paper web at the reel-up.

7.2 Feed-forward strategy

The new feed-forward strategy presented in the previous chapter focuses on keeping the cylinder surface temperatures unchanged instead of lowering them. The steam pressure still has to be lowered during web breaks since the loss of the cooling paper web will otherwise overheat the cylinders.

The feed-forward strategy has been implemented at the PM7 paper machine and the strategy has been validated during web breaks. The strategy has been slightly simplified for the PM7 paper machine, instead of using the logarithmic expression in equation (6.9) the new pressure during a break is 58% of the steam pressure used before the break. This gives agrees well with the working range for this paper machine (370-420 kPa), given $\Delta T = 5$ (see Figure 7.2). The first cylinder in the dryer section has a fixed steam pressure setpoint during web breaks (-20 kPa) to prevent napping.

To validate the feed-forward strategy, the cylinder surface temperature during a web break was measured. It is (almost) impossible to predict

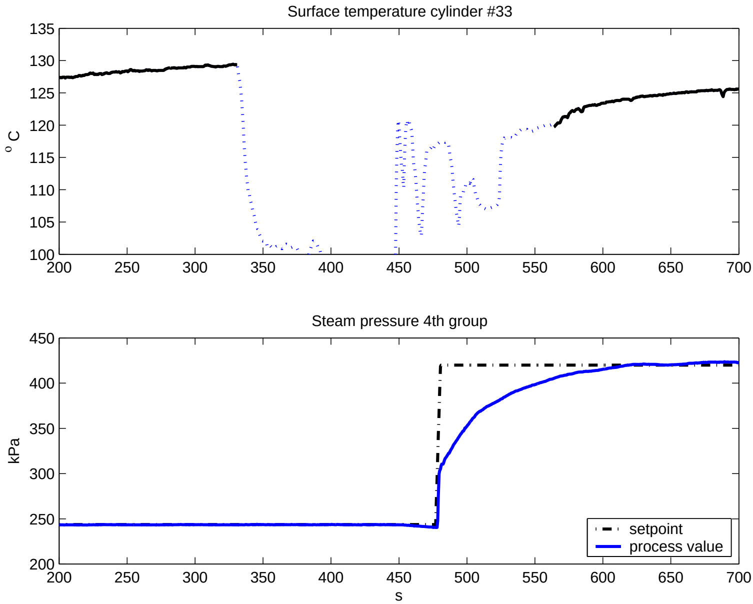

Figure 7.3 The cylinder surface temperature for cylinder 33 with the new feed-forward strategy. The web is broken under 475 seconds, after which the broadening of the web is completed and the steam pressure is restored.

when the web is about to break, therefore only the last part of the web break can be measured. The temperature in Figure 7.3 shows that the cylinder surface temperature is about $120°C$ during the break, which is $3-4$ degrees hotter compared to the temperature after the break. The solid lines show the cylinder surface temperature, the dotted line is measuring errors due to problems with the measuring equipment. During the tail threading the rod with the temperature sensor got caught in the paper web. To prevent the rod from ending up between the felt and the cylinder it had to be removed. Unfortunately that meant that the effect from the wet paper web on the cylinder temperature was not recorded. In any case, the experiment shows that the feed-forward strategy provides the desired cylinder surface temperature during a web break, just a few degrees higher than during normal operation.

The effect on the moisture content in the paper web with the new feed-forward strategy is very satisfactory. The moisture content both at the reel-up and after the pre-dryer is shown in Figure 7.4. The machine speed was lowered at the beginning of the break to simplify the cleaning up of pieces of paper that tend to stick everywhere when the web breaks. After the web break there is a slightly increase in the moisture content after the pre-dryer section. The increase is so small that it does not affect the moisture content in the final product.

Experiences

The new feed-forward strategy is currently running at the PM7 paper machine in Husum. The strategy has still not been in use long enough to evaluate the runability of the paper machine, but the opinion of the operators and the PM7 staff are that the strategy is working well. The time it takes to get the paper web back on line and the time it takes for the moisture content in the web to stabilize have been shortened. One problem was discovered at an early stage. The steam pressure in the dryer group $1B$, consisting of the 4th and the 6th cylinder, increased during web breaks and so did the cylinder surface temperature. This made tail threading more and more difficult the longer the web break was. This has been solved so that the second dryer group ($1B$) also has a fixed value during web breaks.

7.3 Summary

The feed-forward strategy derived in the previous chapter has been tested on the paper machine PM7 in the M-real Husum Mill. Even though few experiments have been recorded, the results so far are excellent. The measured cylinder temperatures are close to the desired temperatures, and the moisture content of the paper is also quickly returned to normal after the web break.

Proof of the effectiveness of the control strategy is that the strategy was kept in place after the first trials, and it is to this date still running on the PM7 machine.

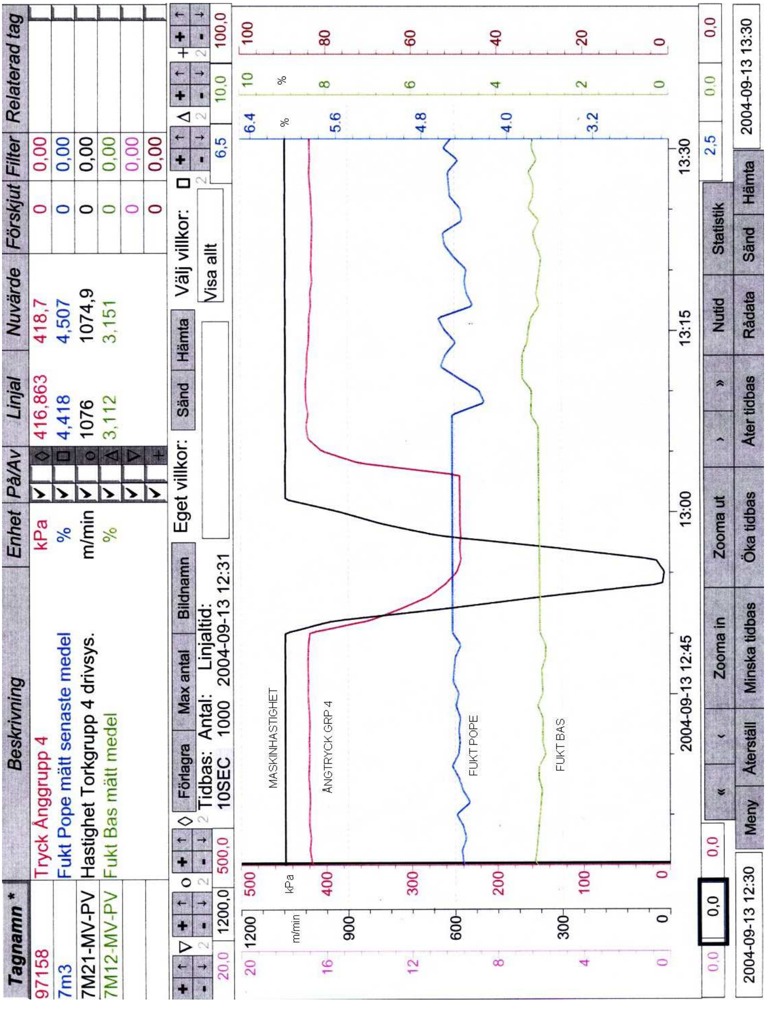

Figure 7.4 The moisture content in the paper web at the reel-up (FUKT POPE) and after the pre-dryer section (FUKT BAS). The picture also show the machine speed (MASKINHASTIGHET) and steam pressure in the 4th group (ÅNGTRYCK GRP 4).

8

Conclusions and future work

The goal of this project was to improve paper quality and increase paper production by improving the steam pressure control during web breaks. This final chapter gives conclusions and suggestions for future research.

8.1 Conclusions

The approach was to first derive a detailed model of the dynamics describing the relation between the steam pressure in the cylinder and the cylinder temperature. The model is presented in Chapter 3. It is a physical model based on four basic partial differential equations and boundary conditions. The model is discretized and implemented in Matlab/Simulink.

The model was verified through experiments performed on the paper machine PM7 in the M-real Husum Mill. This verification is given in Chapter 4. Experiments were performed both during normal operation and during web breaks. The measured steam pressure was fed into the model and the resulting cylinder temperature from the model was compared with the true cylinder temperature. The experiments showed that the output from the model agreed very well with the true cylinder temperature.

Based on the model, a new feed-forward strategy to improve steam pressure control during web breaks was derived in Chapter 5. The idea is to produce a feed-forward compensation from the digital signal that tells whether the paper is on the cylinder or not. The feed-forward signal is fed to the output of the IMC controller, which means that the setpoints of the steam pressure controllers are modified when the web breaks, and when the web is back on the cylinder after the break.

The idea behind the compensator is to obtain an optimal cylinder temperature during the web break, so that the desired moisture content of the paper is obtained as quickly as possible after the break. The feed-forward compensator is a static nonlinear function of the steam pressure applied before the web break.

The new feed-forward strategy was tested on the paper machine PM7 in the M-real Husum Mill. Even though few experiments have been preformed, the results so far are very satisfactory. The measured cylinder temperatures are close to the desired temperatures, and the moisture content of the paper is also quickly back to normal after the web break.

The new control strategy has been well received at the mill, and this strategy has now replaced the earlier one, and is used routinely.

8.2 Future work

The strategy presented in this thesis assumes a constant paper and pulp quality. To prevent the machine chest from filling up during long web breaks, the amount of broke in the pulp is normally increased. Much of the broke has been dried before, and this influenses the drying properties. Also, if the amount of broke is great, the steam pressure might have to be adjusted.

The quality of the pulp can change a significantly between different grades and paper qualities. The beating and different fibre compositions influence the drying properties of the paper, but by how much and what is the relation?

The model of a drying cylinder has so far only been used for evaluation of normal operations and web breaks. During grade changes the steam pressure has to be altered for the new grade. Today is this often done in an ad-hoc manner. The model obtained in Chapter 4 can be used to predict the outcome of a grade change.

The model can be used to get an early warning that something is wrong. Hopefully, the model can also be used for detecting anomalies, and in best case prevent web breaks.

Notations

		Unit
A	cylinder area	m^2
G_p	specific heat capacity	J/kg°C
G	basis weight	kg/m^3
h	heat transfer function	W/m°C
k	thermal conductivity	W/m°C
K_G	mass transfer coefficient	m/s
M	molecular weight	kg/mol
$\dot{m}$	evaporation rate	kg/m^2s
P	pressure	kPa
P_a	partial pressure of water steam in the surrounding air	Pa
P_p	partial pressure of steam in the surrounding air	Pa
$\Re$	the gas constant	J/molK
T	temperature	°C
t	time	s
μ	moisure ratio	kg H_2O/kg fibre
v	paper velocity in dryer section	m/s
x	space coordinate (machine direction)	m
z	space coordinate (thickness direction)	m
λ	heat of evaporation	J/kg
ρ	density	kg/m^3

	Control Variables
SP	setpoint of controller
PV	process value
G	transfer function
T	time constant
k	gain
L	time delay

Subscript

a	air
c	cylinder
p	paper
s	steam
v	vapour
w	water
dry	dry fiber

9

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