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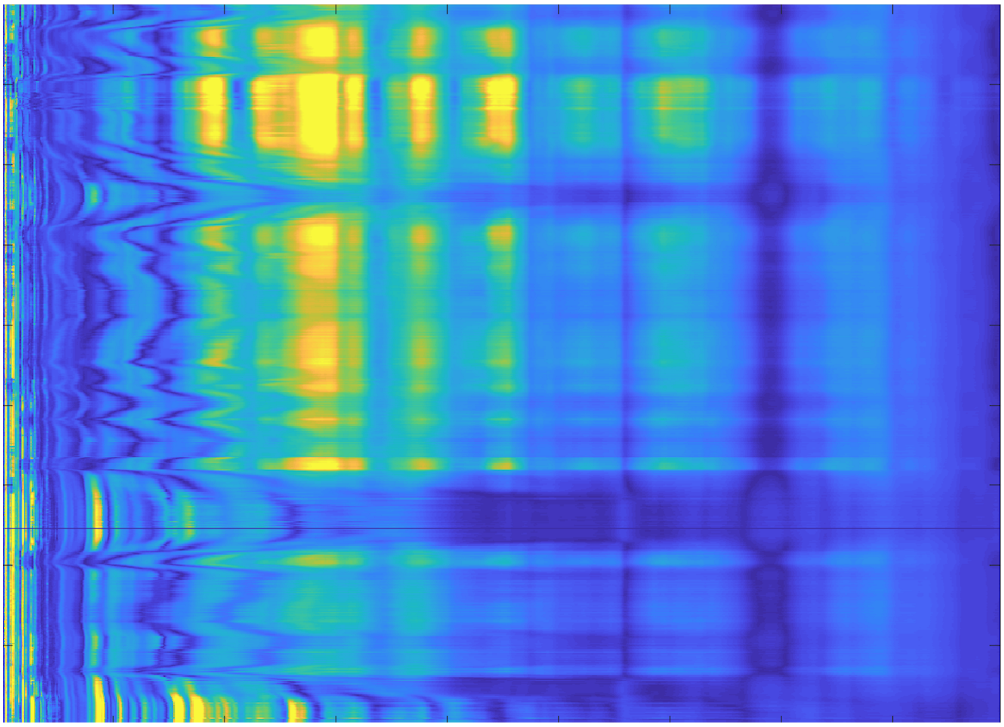

Analysing flashing in black liquor with active acoustic spectroscopy

A study of a recovery boiler in a kraft pulp and paper process

Master's thesis in Innovative and Sustainable Chemical Engineering and Sustainable Energy Systems

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CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2021
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Master's thesis 2021

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Master's Thesis 2021
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Cover: A waterfall plot generated using data from Acospectors placed at Nordic Paper Bäckhammar.

Printed by Chalmers Reproservice
Gothenburg, Sweden 2021

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Abstract

This report covers the research that aimed at identifying flashing in the recovery boiler at Nordic Paper Bäckhammar and determine whether it can be detected by applying active acoustic spectroscopy to the black liquor. An intensity and frequency plot can be used to track the behaviour and properties of black liquor. Photographs of a sootblowing lance can confirm carryover by ocular examination. Carryover on sootblowing lances is believed to indicate that flashing has occurred. By the means of the intensity and frequency plot and the photographs, identification of time periods of possible flashing could be found. Operational data was also studied to determine if any specific parameter was the reason for flashing. The studies found that some patterns in the intensity and frequency plots matched well with the time periods when carryover was detected on the sootblowing lance. However more studies are required to fully confirm the relation between the two. No specific operational parameter was found to be the cause of flashing. From this thesis work, it can be concluded that it might be possible to use the intensity and frequency plots to discover flashing in an early stage, even though it cannot be fully confirmed from this study.

Keywords: recovery boiler, active acoustic spectroscopy, flashing, black liquor, sootblowing lances, carryover, kraft process

Acknowledgements

During this thesis work, several people have had a great importance in helping us in different ways. First of all, we would like to thank Aconsense for giving us the opportunity to do this master thesis work. We are very grateful that they trusted us with this task. We also want to thank Nordic Paper Bäckhammar for giving us an extensive insight in their process.

Moreover, we specifically want to thank the people we have gotten in touch with at Acosense. Ann Winzell helped us in getting in contact with the right people whenever we had a problem and overall managed this project in a clear way so that progress could be made. We also want to thank Pia Holmberg and Astrid Lundgren for the useful input in discussions regarding both active acoustic spectroscopy, the operation of the recovery boiler and the data analysis. Further, we want to thank Astrid Lundgren and Andreas Henriksson for helping us whenever there were problems with the uploaded data to the server. Frederik Rietdijk aided us in understanding the acoustics better through online discussions. Lastly, we want to thank Acosense CEO Karl Nilsson, who gave us a warm welcome and an useful introduction of Acosense at the beginning of this project.

We also want to express our gratitude to Erik Dahlén. He has helped us very much in improving our understanding of the recovery boiler and its tremendous complexity through several workshops and also through valuable input in the weekly meeting discussions. We also want to thank Erik for giving us an educating tour of the Nordic Paper Bäckhammar mill.

When it comes to the contact with Nordic Paper Bäckhammar, we would like to thank process engineer Viktor Schützer for giving valuable input in the discussions regarding the operation of the recovery boiler, but also for providing us with operational data whenever we needed it. Further, we are very glad that a study visit to Nordic Paper Bäckhammar could be arranged, despite the Covid-19 pandemic. This was valuable for our understanding of the recovery boiler and its operation.

Our examiner, Derek Creaser helped us with the academic parts of this project, we are very grateful for this. He also provided us with several suggestions on who to contact regarding certain reflections. Lastly, we want to thank Krister Ström for the valuable discussion we had considering flashing as a phenomenon and the possible reasons behind it.

Emma Arvidsson and Emma Lövström, Gothenburg, March 2021

Contents

List of Figures

List of Tables

List of Concepts

Acospector Online instrument for the process industry that uses active acoustic spectroscopy to analyse fluids in pipes continuously and in real time.

black liquor Black chemical residue mixture from digestion of wood chips with high viscosity. Contains lignin, cellulose, hemicellulose and extractives from the wood. It also contains the cooking chemicals.

BPR Boiling point rise. Describes the difference between the boiling point of the solution compared to the solvent.

carryover Phenomenon occurring in the recovery boiler when small black liquor droplets follow the flue gas flow upwards. Can occur as deposits of black or red spots.

dry content Fraction of organic and inorganic solid material in the black liquor. Sometimes referred to as dry solids.

flashing Phenomenon occurring when the temperature rises above boiling point and the liquid starts to evaporate.

fluid A substance that can be influenced by shear stress and deforms. Gases and liquids are fluids.

hardwood Classification of trees generally containing trees with leaves and more advanced molecular wood design than softwood.

kraft process Also named as a sulfate process. Common when using soft wood as a raw material and uses white liquor, containing NaOH and Na_2S, as cooking liquors.

plugging Phenomena that occurs when there is fouling in the heat exchanging area to the extent that the flue gas flow is restrained.

recovery boiler Unit in a pulp and paper mill that combust organic material and recovers inorganic material.

sootblowing lance Unit in a recovery boiler that utilises steam to remove fouling on the heat exchangers.

Voodoo camera Camera that photographs a sootblowing lance by the recovery boiler.

waterfall plot Three dimensional plot showing intensity at different frequencies over time.

white liquor The chemicals added to an digester together with woodchips prior cooking. Containing NaOH and Na_2S.

1 Introduction

In a kraft pulp and paper mill, there is no doubt that a recovery boiler is an important part of the process. This unit both recovers valuable chemicals from the black liquor and it provides large parts of the process with energy in terms of electricity and heat. In a sustainability aspect, as well as an economic aspect, it is of course preferable to be able to recover as much chemicals and energy from the available raw material as possible.

The operation of the recovery boiler does not always run smoothly. There are some unfavourable operational conditions, flashing is one of them and it is preferable to be able to identify and avoid it. Flashing is a phenomenon in which the black liquor starts to evaporate at the inlet nozzle to the recovery boiler. This phenomenon can reduce efficiency of the recovery boiler, both in terms of recovered chemicals and how the unit can deliver heat to the site.

The breakthrough of using the recovery boiler happened in the 1930s and 1940s [1]. Since then it has been introduced in many pulp and paper industries and is today a central unit in a pulp and paper mill. Despite the long time the recovery boiler has been around, due to the large amount of different chemical reactions, phenomena and mechanisms occurring at the same time, the complexity of it is still not fully understood. Hence, there is a lot more knowledge to be acquired in this subject area.

This thesis is conducted in collaboration with Acosense and Nordic Paper Bäckhammar. Acospectors from Acosense uses active acoustic spectroscopy at the pulp and paper mill of Nordic Paper Bäckhammar with the aim of being able to identify flashing. Data from the Acospectors together with pictures from a Voodoo camera is used to detect carryover, a potential outcome of flashing. The purpose of this thesis is to increase the knowledge on if and when flashing is occurring, i.e. how it can be identified, and also to provide potential measures to avoid flashing.

1.1 Paper process in Bäckhammar

Nordic Paper Bäckhammar is a continuous kraft pulping mill producing both pulp and paper. More specifically they can annually produce 160 000 ton paper and have a capacity to produce 230 000 ton kraft pulp [2]. Figure 1.1 shows a photograph over the mill in Bäckhammar.

Figure 1.1: An overview of Nordic Paper Bäckhammar [3].

The overview of Nordic Paper Bäckhammar gives a sense of the size of the mill. The 13-story-building in the middle left part of the figure contains the recovery boiler and is the highest building on site. The main feedstock in the paper mill is softwood, which is trees with needles, like spruce and pine. The mix between spruce and pine may vary over the year according to Viktor Schützer, process engineer at Nordic Paper Bäckhammar(2021-02-22).

The pulp and paper process starts with pre-processing trees and once they are washed, debarked and chipped, the chemicals, white liquor, are introduced together with wood chips in a digester. After a heat and chemical treatment in the digester, the created cellulose pulp will be washed and further processed while the residue chemicals will be recovered. The residue chemicals have a black colour and is referred to as black liquor. A general description of a pulp process can be seen in Figure 1.2.

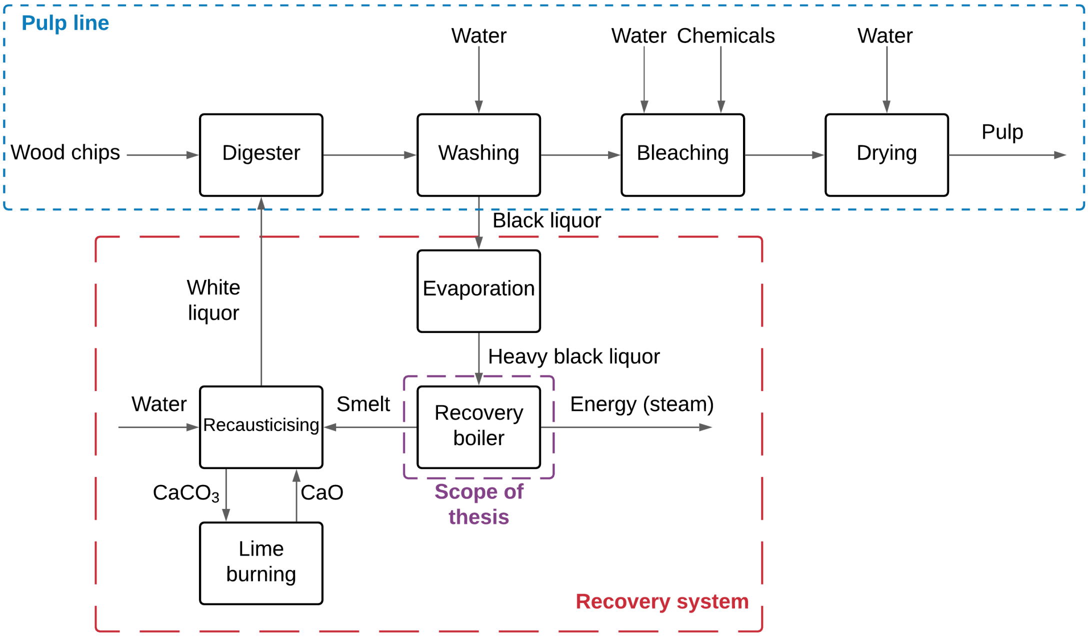


Figure 1.2: A simplified overview of a kraft pulp and paper process, where the blue dashed line illustrates the pulp line and the red dashed line illustrates the recovery system. The purple dashed line illustrates the scope of this thesis.

In Figure 1.2 a simplified pulp line is illustrated within a blue dashed line and with some of the material streams included. The boxes beneath the pulp line, inside the red dashed box, are part of a chemical recovery system. In the simplified example, the chemical recovery consists of evaporation, recovery boiler, recausticising and lime burning. The purple dashed line encloses the scope of this thesis.

1.2 Scope and limitations

The main focus of this thesis is to determine whether flashing and carryover occurs in the recovery boiler and if it is possible to detect this from the data collected using active acoustic spectroscopy. The scope of this thesis is limited to include only the recovery boiler, and its surrounding equipment, and no other unit in the kraft pulp and paper process. This is illustrated in Figure 1.2. As mentioned, the recovery boiler considered is located at Nordic Paper Bäckhammar, from where all the pictures and data used in this thesis were collected. Further, the area of interest will be limited to the inlet of black liquor into the recovery boiler, the char bed at the bottom and the soot blowing lances at the top of the boiler.

The parameters studied in this thesis are limited to air flow rate, and also black liquor flow rate, nozzle pressure, temperature and dry content. The frequency of some operations at Nordic Paper Bäckhammar are limitations for this thesis work. Two examples are laboratory tests of sulfidity and degree of reduction. In order to get a more precise analysis a higher frequency of the mentioned tests would have been desired.

Lastly, one severe limitation of this thesis is the Covid-19 pandemic. Originally, several visits to Nordic Paper Bäckhammar were planned, in order to perform targeted experiments and also some laboratory work. Due to the pandemic, only a short study visit could be arranged. This restricted a larger understanding of the process and also the study performed was not as extensive as originally planned.

2
Theory

This chapter will provide more detailed knowledge on the subjects needed to understand the operation of a recovery boiler. The phenomena and equipment described are not comprehensive to all details occurring in a recovery boiler, but it is some of the most important ones to get an idea of the complexity of a recovery boiler. Most of the information provided is a general description of the operations and phenomena occurring in a recovery boiler and not specific for the recovery boiler at Nordic Paper Bäckhammar. Further, information regarding active acoustic spectroscopy will be supplied, to get a sense of how it can be used in reality.

2.1 Recovery boiler

The recovery process can be considered as one of the main processes in the pulp and paper industry, since it creates value in many ways. It acts both as a chemical recovery unit to recover valuable inorganic chemicals and as a combustion unit to utilise useful energy from the organic content [1]. The energy gained in a recovery boiler often fulfils the whole energy demand of a pulp and paper mill. At Nordic Paper Bäckhammar, the recovery boiler together with a bark boiler recovers enough energy to cover the heat demand on site. Recovery boilers in general also produce high pressure steam, which enables the possibility to generate electricity on site using a turbine [4].

A recovery boiler in a continuous pulp and paper industry is often a huge unit with a lot of equipment within and around the vessel. The main zones in the recovery boiler can be described as the following: the char bed at the bottom, the furnace area in the middle and the heat convection area in the top. See Figure 2.1 for a more detailed description.

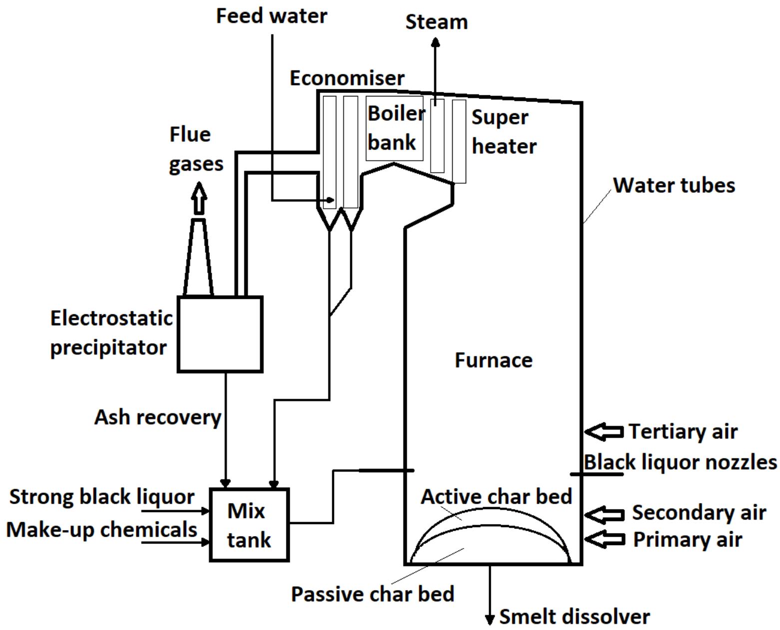


Figure 2.1: A simplified illustration of a recovery boiler and its equipment.

The recovery boiler contains a lot of equipment and systems. Some of these are air systems, black liquor spray nozzles, heat exchanging equipment, sootblowing lances and electric precipitation filters. All equipment in the process has its own possibilities to be optimised. Different flow rates, angles and other operational settings can be adjusted and often they will affect each other. This creates a lot of possibilities to optimise and maintain a stable operation of the recovery boiler, but it also indicates a high complexity of the operation of the recovery boiler.

The resource of the recovery boiler is strong black liquor, sometimes referred to as heavy black liquor. The strong black liquor is black liquor with a high dry content, often between 70-80% [5]. Weak black liquor is concentrated in evaporators to create strong black liquor before entering the recovery boiler. However, the dry content fraction may vary depending on disturbances in the process and the composition of the resources. It may also vary with organic and inorganic variation within the dry content. The black liquor will generally consist of residues from the tree chips that is left from the digester together with the cooking chemicals. Thus, both some cellulose, hemicellulose, lignin and extractives (other smaller amount of substances originating from the wood) from the tree will be present and the cooking chemicals. From the cooking chemicals, it is especially Na and S that is of importance to recover [6].

The organic material in black liquor is to be combusted and the inorganic chemicals are to be recovered. As can be seen in Figure 2.1, the strong black liquor enters the recovery boiler between the secondary and tertiary air levels by pressurised nozzles and droplets are formed [5, 7]. It is preferable that the droplets are of an equal size, often between 1-4 mm [5]. This since a too small droplet will follow the gas flow upwards which will result in less recovered material but also, it can cause problems in terms of fouling in the heat exchanging area as will be described later in this report [5]. Too heavy and large droplets will hit the char bed before drying has been completed, which is not preferable since it can drain the char bed of energy and extinguish it [5]. After the drop enters the recovery boiler it will swell and increase its diameter. The diameter due to swelling will be differently affected during the four stages that a droplet will undergo during the time in the recovery boiler. These steps are drying, pyrolysis, char combustion and smelt reactions and they are all described more detailed in Section 2.2.4.

When considering the heat exchanging equipment, the economiser, boiler bank and superheater seen in Figure 2.1 are all part of the convection area. These, together with the water tubes in the recovery boiler walls are heat exchangers. The water tubes in the walls, also called water riser tubes, will cool the smelt to create a protective solid layer against strongly corrosive substances as well as gain heat [5]. Heat will also be recovered from the flue gases in the upper level of the recovery boiler by water riser tubes and heat exchangers, in the convection area.

Since there are a lot of different processes occurring at the same time in a recovery boiler, it can be helpful to simplify them in order to keep track of the different material and energy streams. An illustration of a simplified flow sheet is presented in Figure 2.2.

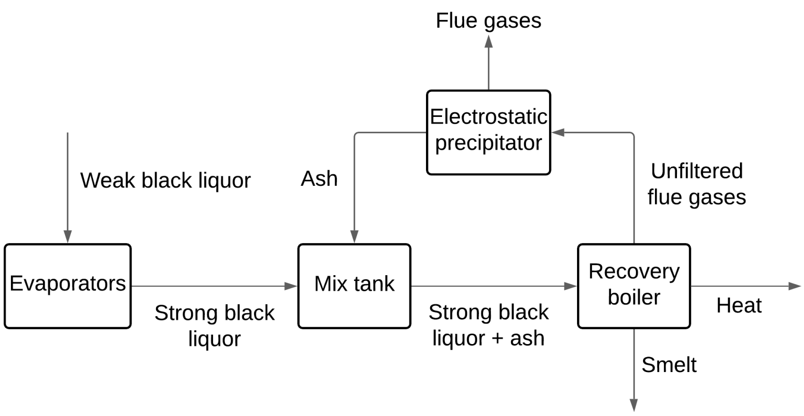


Figure 2.2: Flow sheet of a recovery boiler, considering both material and energy streams.

In Figure 2.2 it can be seen that the ashes from the boiler can be recovered and mixed with the incoming flow of black liquor. The reason for this is to recover even more of the inorganic chemicals rather than simply disposing them. The inorganic chemicals will be recovered in the smelt at the bottom.

Since there is a lot of equipment related to a recovery boiler that operate at the same time, it is a complex system. There are a lot of phenomena occurring and a slightly different condition in one parameter may affect the outcome of another. Thus, it is important to have knowledge of some of the most important phenomena in a recovery boiler and the operating equipment in, or closely connected to the recovery boiler. These are described in the next sections.

2.1.1 Phenomena in a recovery boiler

In the recovery boiler, several different phenomena take place, which all affect the operation of the boiler to some extent. The most relevant phenomena for this thesis are presented in this section.

Heat exchanging

One of the main purposes with a recovery boiler is the extraction of energy as electricity and heat. To do the latter, there must be heat exchangers in the boiler. The heat exchangers in a recovery boiler are recuperative, meaning that two fluids, one hot and one cold, are flowing on each side of the heat exchanger wall [4]. Heat is transferred from the hot fluid, through the wall, to the cold fluid [4]. The amount of heat transferred can be written as a function of the heat exchanging area and the temperature difference between the flue gas and the steam according to Equation (2.1) [8].

$$Q = UA\Delta T_{lm} \tag{2.1}$$

Where Q is the amount of heat transferred in W, U is the overall heat transfer coefficient in W/(m^2°C), A is the mean heat exchanging area of the tubes in m^2 and ΔT_{lm} is the logarithmic mean temperature difference in °C [8].

The heat exchanging area in the recovery boiler is constant. Hence, what mainly affects the amount of heat transferred to the steam is the flue gas temperature and the overall heat transfer coefficient. The latter coefficient depends on both the inside and the outside fluids, as well as the material used in the tubes [8]. Another thing that affects the heat transfer is fouling on the heat exchanging surfaces. If there are deposits, i.e. fouling, on the surfaces, these tend to have a relatively low thermal conductivity. Thus, the U-value will be lower and less heat transfer to the cold fluid is possible [8].

Droplet formation

The size of the black liquor droplets can have a big impact on different phenomena in the recovery boiler. Droplet formation can influence carryover, drying and fouling among other mechanisms. In turn, the droplet formation can be influenced by flashing. Generally, if the droplets are too small they will follow the gas flow upwards in the recovery boiler and create fouling. If they are too heavy they will end up in the char bed before they have dried properly which will drain the char bed of energy [5].

The size of the droplet can be affected by a number of things. For example dry content, temperature, surface tension, and viscosity, can influence the shape and size of the droplets [5]. Several functions and models can be used in an attempt to explain the droplet diameter [5]. Though it is concluded that the main influence on the droplet size is the velocity of the liquor and the nozzle size. Less important is the viscosity, density and surface tension if they remain within reasonable variations [5].

Velocity in the nozzles can be affected by temperature and also boiling point rise, BPR. The BPR is in turn affected by the dry content [9]. Since increased temperature and BPR may affect the pressure and viscosity, then the velocity and flow rate may change [7]. As a conclusion, higher velocity and lower viscosity will decrease the resulting droplet diameter [7].

Swelling

During the four stages of the droplet, its size will change. The swelling characteristics is of great interest. Varying swelling will impact the char combustion rates [10]. Low swelling degree will result in a slow burning rate of the char [10].

The droplet will swell in both the drying stage and the pyrolysis stage, but most of the swelling will occur in the latter [5]. Sometimes the droplet can swell as much as eight times its initial size during the stages, but it is more common with around three times its size [5]. Why and how much the droplet will swell is not fully determined. Though, the diameter will decrease with a higher fraction of inorganic material and it will increase by larger pH in the black liquor [5]. Further, an equal ratio of lignin and carbohydrates will increase the swelling the most [5]. In addition to this, results have shown that black liquor droplets from softwood (kraft processes with higher pH) will increase its diameter more than droplets from hardwood (sulfite processes) [7, 10]. Further, during the last two stages of the droplet, the droplet will decrease in size [5].

Boiling point rise

Boiling point rise, BPR, sometimes referred to as boiling point elevation, BPE, is a way to describe how the boiling point will change during variations in the content of a liquid. BPR is the difference in boiling point between a solution and its solvent [9]. For black liquor this solvent is water. It is important to know the BPR for black liquor, especially during the preceding evaporation to the recovery boiler. The evaporation decreases the water content to obtain a higher dry content of the black liquor [9]. With higher dry content it will be a more effective combustion in the recovery boiler.

At a dry content below 50%, the BPR increases linearly with an increased dry content [9]. On the contrary, above 50% dry content, the BPR increases exponentially instead [9]. When measuring the BPR, it is important to know that different measuring techniques might give varying results [9]. One example of the deviating BPR for black liquor from a kraft process is that it can be between 16-19°C with a dry content of 70% and 24-29°C when the dry content is 80%[9]. Some argue that at 100% of black liquor, the boiling point is 55°C [9].

Not only the amount of dry content is affecting the boiling point, but also the diversity of content and the pressure [11]. Different concentration of salts can for example create surprising behaviours such as deviation from the previously mentioned uprising trend of boiling point [9].

Flashing

When spraying the black liquor into the recovery boiler, the droplet size is of great importance [5]. One phenomenon that can affect this is flashing, which is when parts of the black liquor evaporates [12]. This is due to a shift in the boiling point in black liquor and the temperature of the liquor can then be above the boiling point [12]. As described in the previous section, the boiling point is affected by the pressure and the dry content. Thus, flashing can occur suddenly if either temperature, pressure and dry content change.

When the water in the black liquor evaporates, it expands. Due to this, the volume of the black liquor that needs to pass through the nozzle increases [13]. Since the flow rate of black liquor is constant, the flow velocity is then increased. This creates smaller droplets, which generally results in more carryover and hence, less recovered chemicals [13]. Subsequently, flashing is a disadvantageous state. The more superheated the liquid is, the more vapour is generated and hence, more flashing occurs [12].

Carryover

Carryover is a phenomenon where small combusted and uncombusted particles will continue with the gas flow up towards the top of the recovery boiler [7]. There is a risk that these particles might attach to the heat exchanging units [7]. The carryover particles can either be smelt that have been partly oxidised or black liquor droplets that have not been completely combusted [14]. The sudden increase in size, previously described as swelling, and thus the decrease in density due to the different stages that the droplet undergoes, may ease the possibility for the droplets to be carried away [15].

The rate of carryover in a recovery boiler mainly depends on the entering black liquor droplet size [7]. That is, the smaller the droplets are, the easier they will follow the gas stream upwards creating carryover. However, the gas velocity in the boiler also contributes to the carryover rate. The faster gas velocity, the higher carryover rate [7]. Further, the configuration of the air inlets can also have impact on the amount of carryover. The flow pattern of the secondary air can affect the carryover rate and the primary air flow may lift some of the droplets that already hit the char bed up to the heat convection area [7, 15].

The carryover particles can range from 20 μm to about 100 mm [15] and as previously stated, there are two types of carryover. The carryover due to the material that has not been completely combusted when it attaches to the superheater surface can be noted as dark spots [7]. The other type of carryover particles, detected as pink or red spots, that have been completely combusted, consists mainly of Na_2S [7]. Today it is most common in modern recovery boilers that the carryover particles are of the red/pink type [7]. Three pictures of a sootblowing lance with different amount of carryover can be seen in Figure 2.3.

(a) No carryover. **(b)** Black carryover. **(c)** Red carryover.

Figure 2.3: Three examples of different outcomes of carryover on a sootblowing lance, captured using a Voodoo camera.

Figure 2.3a presents a sootblowing lance with no carryover, only ash deposits. This is a preferable outcome since no unburned black liquor will cause plugging in such a case and the material will be recovered in the smelt instead. Figure 2.3b presents a lot of black spots in different sizes. This is unburned material that has followed the gas flow upwards. Figure 2.3c shows red carryover that can also occur as more pink. The pattern can sometimes turn up as pale pink large areas, and sometimes as smaller distinctive red dots. According to Erik Dahlén (2020-11-19), at some mills, the red carryover can cover the whole lance, thus, no white soot can be seen.

The composition of the carryover depends on the conditions used in the cooking process, the washing processes, the origin of the trees, the conditions in the lower part of the recovery boiler. Variation in composition can also depend on where in the recovery boiler it is [15].

Fouling

Fouling has historically been and is still one of the big operational issues in recovery boilers today [7]. One of the main problems descending from fouling is reduced heat transfer. The more fouling present at the heat exchanging surface, the less heat is transferred [7]. This can be explained by the previous reasoning regarding Equation (2.1), where heat exchanging was concluded to be strongly affected by the overall heat transfer coefficient. Further problems descending from fouling is plugging in the heat exchanging area of the boiler [7]. The plugging occurs when large amounts of carryover and ash have deposited in the top of the boiler [7]. This constrains the flue gas flow and eventually an operational stop for maintenance to remove the deposits might be necessary [7].

While the combustion and reduction of the organic and inorganic material, respectively, is happening, some of the alkali compounds evaporate [7]. These compounds follow the flue gas stream upwards and can eventually accumulate on the heat exchanging surfaces in the top of the boiler [7]. Some small black liquor droplets and char particles can also become entrained in the flue gases, previously described as carryover, and deposit on the heat exchanging surfaces. Further, ash from the combustion of the black liquor droplets can also deposit on the surfaces. All these deposits on the heat exchanging surfaces in the boiler are called fouling [7].

The cause of fouling is not always clear [7]. In many cases it is a combination of events that can lead to fouling [7]. However, there are methods for sootblowing, which cleans the heat exchanging surfaces in the boiler during operation [5].

Channeling, bypassing and dead zones

Channeling, bypassing and dead zones are all unwanted phenomena that may occur and that decreases the efficiency of a reactor. Channeling is when, for example, a gas is not evenly spread through a bed of solid material and thus, creating channels where the gas flows at a higher velocity than the surrounding [5, 16]. This can lead to bypassing and a reduced residence time [5]. If bypassing occurs then chemicals are merely passing by without reacting [16]. On the other side of the spectra is the concept of dead zones. A dead zone is an area where the material is seldom exchanged since they are inaccessible to the regular flow [16]. In these zones, impurities are often accumulated [16].

2.1.2 Equipment inside and around the recovery boiler

The recovery boiler consists of several different types of equipment fulfilling various purposes in the boiler. The most important types of equipment within the scope of this thesis are presented in the following section.

Air System

An air system in a recovery boiler has several functions. Perhaps the most obvious one is to supply the combustion with air, hence oxygen [7]. To do this, the mixing of the oxygen has to be sufficient. Poor mixing can be detected through high concentrations of both CO and O_2 simultaneously in the flue gas [7]. Higher dry content of strong black liquor will increase the demand for air since there is more organic matter that needs to be combusted [7]. Another function of the air supplement is to shape the bed at the bottom of the vessel [5].

An air system consists of different levels of air inlets. Often they are referred to as primary, secondary, and tertiary air. In some cases, even a quandary air level is in place [5]. See Figure 2.1 in Section 2.1 for an overview of the placing of the air system. The air is preheated before entering the chamber to ensure an even temperature over time in the inlet and thus, more efficient combustion [7].

The primary air can, by varying the velocity, be used to shape and size the char bed at the bottom [5]. Low velocity might cause a steep and pointy char bed, and high velocity might cause channelling [5]. Higher velocity might also increase the risk of carryover without utilising its energy from the combustion [5]. Consequently, the combustion efficiency is reduced and the risk of fouling on the heat exchangers will increase [5]. In addition, since the residence time of air is reduced when channelling occurs, more excess air needs to be added to increase the combustion of the material. Maximised residence time is preferred for complete combustion [17].

The secondary air has a large impact of the flow pattern in the chamber, i.e. recirculation or plug flow. The configuration of the air nozzles and the amount of flow in each of them can be used to influence both the flow pattern but also to decrease the risk of channelling [5]. The flow pattern will also have an impact on the risk of carryover [7]. The air ports can be designed to decrease the fouling and also to control the temperature [7].

The tertiary air level has unheated air at high velocity [7]. Right above the third level, the oxidation (combustion) of the remaining combustible gases occurs [5]. An introduction of a fourth level of air stream will reduce the NO_x in the flue gases [7]. This is done by changing the location of the combustion and thus impact the temperature profile to decrease the possibility for NO_x to be created [7].

Altogether, different settings for the different levels of air and also different air patterns at the same level will affect the function of the recovery boiler. Some adjustments will create either more or less carryover, and some will change the temperature profile throughout the boiler [7].

Black liquor nozzles

The black liquor is transported in pipes from previous parts of the mill and is then distributed in the recovery boiler using liquor guns [7]. To get an even distribution and a suitable size of the black liquor droplets in the recovery boiler, nozzles are used [7]. As previously described, the droplet size is of great importance to the operation of the recovery boiler and hence, they have an important role to play in order to keep the boiler operating as efficiently as possible [5].

There are a few different types of nozzles. A few examples are the splashplate, swirlcone, V- and U-type, fan and willow flute nozzle [5, 7]. Typically, the nozzle type is selected to obtain both an effective boiler and an optimal droplet size and usually this is based on previous experience locally [7]. The nozzle type used at Nordic Paper Bäckhammar is the "beer can" nozzle. This type of nozzle is shown in Figure 2.4 and the size of this nozzle is non-adjustable. Regardless of which nozzle type is used, the basic mechanism of droplet formation from the black liquor feed stream is the same [5].

Figure 2.4: A "beer can" nozzle at Nordic Paper Bäckhammar.

Heat exchanging units

As previously described, one of the main purposes of a recovery boiler is to extract energy from the black liquor in terms of heat and electricity. To recover heat, there must be heat exchanging surfaces in the boiler. To begin with, the boiler walls consist of riser tubes, in which feed water will evaporate [4]. The hot flue gases first pass these water riser tubes, and then pass the superheater, evaporator and lastly the economiser [4]. In some cases, there is also an air preheater in the end [4]. This is schematically described in Figure 2.5.

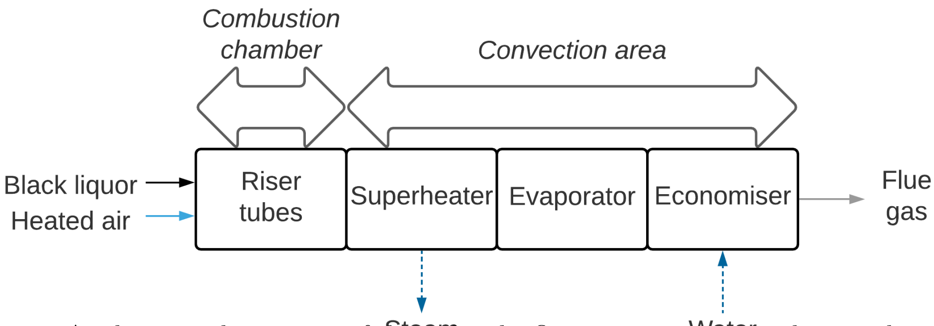


Figure 2.5: A schematic description of the order the flue gases pass certain heat exchanging units in the recovery boiler.

As the flue gases pass through the heat exchanging units, the temperature of the water/steam inside the heat exchanger tubes is increased and the temperature of the flue gases is decreased [4].

As mentioned, fouling is a severe problem in recovery boilers, as it both decreases the heat transfer in the heat exchangers, but it also causes plugging in the convection area. The chemistry and mechanism of deposit and also the flue gas flow characteristics in the heat exchanging area will vary a lot depending on where in the heat convection area they occur [15]. Also, the plugging will be severe at different locations both due to the growth of deposit but also due to the difference in sootblowing frequency at different locations [15]. Additionally, since each process is different from each other, the variation in carryover and deposit will also be specific for each mill [15].

It is crucial to avoid plugging as much as possible [7]. This due to the fact that when severe plugging occurs, there is a need for an operational stop to perform cleaning [7]. This stop will last a few days, since the char bed needs to cool down before it is possible to clean, which takes a long time [7]. Since the whole process site is somehow related to the recovery boiler, a stop for cleaning means that a stop of the whole production at the mill can be necessary. Such a disruption in production causes major economic profit losses and is therefore to be avoided as much as possible. Further reasons to avoid the necessity of cleaning is the fact that the cleaning requires water due to the water soluble sulphate deposits [18]. If the smelt in the bed comes in contact with water, an explosion might occur, which of course is a huge safety risk [7].

There are also other methods for cleaning the heat exchanging surfaces in the recovery boiler. One method is to do a short stop of the boiler, a so called "chill-and-blow", to cool it down [7]. The cooling down might result in the ash deposits cracking up and falling down in the combustion chamber. Further, according to Erik Dahlén (2020-11-19), some small gas explosions can be made in the heat exchanging area during operation, which removes some of the deposits without harming the heat exchanging equipment. There are also methods for continuously sootblowing using lances [7], this is described in more detail in the next section.

Sootblowing lances

One way of removing deposits in the heat exchanging area is by using sootblowing lances. A sootblowing system consists of several rotating lances that can move in and out of the boiler one at a time [5]. At the tip of a lance, there is one or several holes where steam at high velocity can strike the heat exchanging area at a perpendicular angle to the lance [7]. See Figure 2.6 for an illustration of a sootblowing lance.

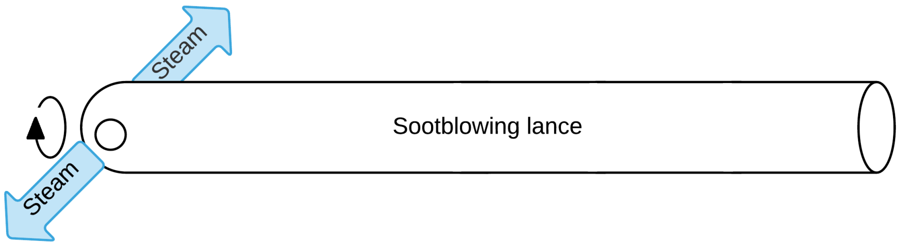


Figure 2.6: An illustration of a rotating sootblowing lance, where steam exits the lance perpendicular to the lance from two openings in the top.

The most important parameters when it comes to determining the efficiency of sootblowing lances, i.e. the removing of fouling, is timing and position [7]. Concerning the timing, the lances will have higher efficiency if they have a schedule that can make sure that in areas where fouling is severe, the frequency of the sootblowing will be increased there, while in areas with less problems, they will not be operating as often [19]. The placement of the sootblowing lances at Nordic Paper Bäckhammar is presented in Figure 2.7.

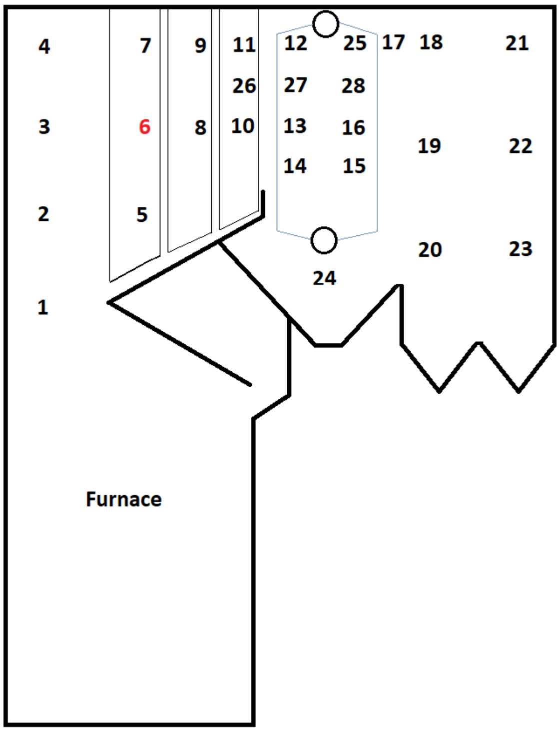


Figure 2.7: An illustration of where the sootblowers in the furnace are located at Nordic Paper Bäckhammar. Sootblower number 6, marked in red, is the sootblower of interest for this thesis work.

In Figure 2.7, the placement of the sootblowing lances can be seen. The sootblowers positioned closer to the furnace, such as sootblower 1-9, will operate with a higher frequency than the others, since plugging occurs more often in these areas. In Figure 2.7, sootblower number 6 is marked in red. In this thesis work, this is the lance that is studied with respect to carryover and fouling. Sootblower lance number 6 is performing the sootblowing every third to fourth hour.

Electrostatic precipitator

In order to make full use of the material in the recovery boiler, the ash from the combustion is often recycled since it contains valuable chemicals. It is also important to recover the chemicals to avoid emitting them. To be able to do this, the ashes must be separated from the flue gases. This is conducted by an electrostatic precipitator, an *ESP*.

A simplified illustration of how an ESP works is presented in Figure 2.8. As can be seen, the ESP consists of several plates, shown as red, they are called collector plates [7]. The plates are connected by strings of wire and high voltage electric current is applied between the electrodes (negative), shown as dark blue in Figure 2.8, and the collector plates (positive) [7]. The green dots in the figure represent the ash particles in the flue gases. Once they pass the electrodes, they will get a negative charge and then be illustrated as light blue dots [7]. This eventually makes them deposit on the positively charged collector plate, this is illustrated by the purple dots [7]. These collected particles can be mixed with the black liquor flow in a mix tank and hence, be recycled back to the recovery boiler.

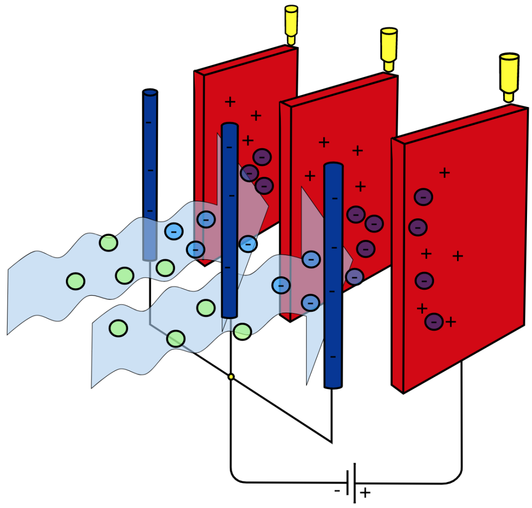


Figure 2.8: A simplified illustration of how an electrostatic precipitator works [20].

2.2 Chemistry in the recovery boiler

Since black liquor contains numerous inorganic and organic components, there are a number of chemical reactions occurring simultaneously in the recovery boiler. The organic compounds are combusted in the furnace and parts of the inorganic compounds are recovered in a smelt in the bottom of the boiler [7].

Some of the reactions occurring in the recovery boiler are described more detailed in the following sections. Sections 2.2.1 to 2.2.3 describe the general principle of the chemistry while Section 2.2.4 describe them more specific for the recovery boiler and the conditions that prevail there.

2.2.1 Pyrolysis, devolatilisation and gasification

The final result from the three processes pyrolysis, devolatilisation and gasification is the same, which is the generation of gaseous fuels from a solid fuel [21]. This takes place through decomposition of the solid fuel [21]. Another thing the three processes have in common is the fact that they are all endothermic, which means that they require heat to be able to occur [21]. Though, the principle of the three processes are different.

The pyrolysis involves the process of thermally converting solid fuel to gaseous fuel when oxygen is not present [21]. The devolatilisation, on the other hand, means that the solid fuel is thermally converted to gaseous fuel when oxygen is present [21]. The gasification is described as conversion of the remaining char in the solid fuel to gaseous fuels through reactions with mainly CO_2 and H_2O [21]. Whichever of the three processes is occurring, in the recovery boiler, the generated gaseous fuel is combusted when released from the solid particle [21].

2.2.2 Combustion

The combustion process is oxidation of a carbon containing fuel, resulting in the products CO_2 and H_2O, if the fuel contains hydrogen [21]. Combustion is an overall exothermic reaction, thus heat is being released as a result of the reaction [21].

The heating value of the combusted fuel determines how much heat that can be recovered in the boiler [21]. As for black liquor the heating value is quite low due to the high content of inorganic material [7]. Further, the lower dry content and higher ash content in the black liquor reduce the heating value, since this affects the amount of water that needs to be evaporated and the amount of inert material [7].

In a combustion process a common risk is generation of NO_x emissions, which can cause environmental issues [21]. Generally, the reaction rate of creating NO_x is low at low temperatures, while at higher temperatures there is an increased risk of higher amount of NO_x [21]. Another emission to consider is SO_x, which is the product from the combustion of the sulphur in the fuel [21].

2.2.3 Reduction and oxidation

Reduction is a chemical reaction in which a substance reduces its oxidation number by adding one or several electrons [22]. The opposite of reduction is oxidation where the oxidation number for a substance increases, hence electrons are removed [23]. Reduction and oxidation reactions can not occur by themselves, they always happen together since electrons can not move freely without an atom [24]. When reduction and oxidation reactions occur, they are often referred to as redox-reactions [25].

2.2.4 Chemical reactions in the recovery boiler

As previously described in Section 2.1, the black liquor droplet from the nozzles undergo several stages in the recovery boiler: drying, pyrolysis, char combustion and smelt reactions. Figure 2.9 shows an illustration of these four stages in the recovery boiler.

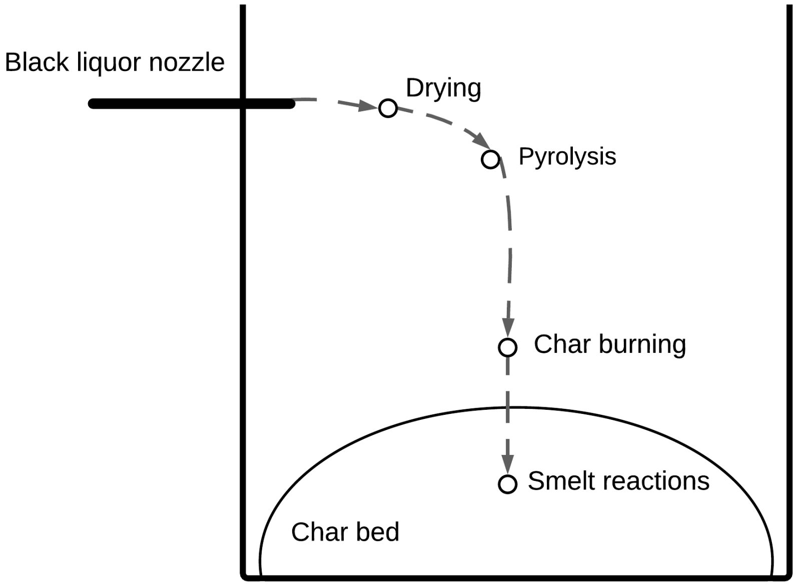


Figure 2.9: An illustration of the four stages that the black liquor droplet will experience on its way from the nozzle to the char bed and the exit.

The four stages are illustrated in correct order in Figure 2.9 for one droplet. Though, since droplets appear in different sizes, the time it takes for them to go through all four stages can vary. All stages are described in more detail in the following sections.

Drying stage

First, drying occurs and the remaining water in the droplet is evaporated. This is possible due to the heat supply coming from the combustion in the recovery boiler [7]. The rate of this stage is determined by the heat transfer to the droplet [7]. The time of drying also depends on the dry content in the inlet black liquor, i.e. how much water that needs to be evaporated.

Pyrolysis stage

The second stage is commonly called the pyrolysis stage, even though devolatilisation is occurring as well [7]. This means that volatiles are released regardless of if there is any oxygen present or not [7]. As mentioned, pyrolysis is an endothermic process, hence it has to take advantage of the energy released from the surrounding combustion to be able to occur. As for the case in the recovery boiler, the main compounds released during the pyrolysis as volatiles are H_2, CO, CO_2, hydrocarbons with low molecular weight, tar and light, sulphur containing gases [7].

As the release of volatiles occur, the volatiles usually surround the black liquor droplet [7]. This restrains the oxygen from getting in contact with the droplet surface [7]. The volatiles are combusted around the droplet, which is surrounded by a visible flame [7]. However, the combustion of these volatiles also occur further up in the furnace, above the tertiary air inlet [5]. Further, characteristic for the devolatilisation step of the combustion of the black liquor droplet is that the droplet swells when volatiles are being released from it [7].

Char combustion stage

After the pyrolysis stage, the remaining carbon, together with most of the inorganic matter are fixed in a solid char and it burns without a visible flame [10]. Thus, the char combustion is considered to begin when the flame is extinguished [7]. However, while some droplets will have completed the pyrolysis stage before it hits the bed, others will continue this stage in the bed. It is mainly on the char bed at the bottom of the recovery boiler where droplets, now turned into char particles, are combusted [7]. Thus generally, the char combustion stage overlaps in time with the pyrolysis stage to some extent [7].

In the recovery boiler, the char burning is a more time consuming stage than the drying and pyrolysis stage, even though it is catalysed by inorganic salts in the black liquor [5, 10]. The overall process for the char combustion stage is exothermic [5]. Moreover, for the reactions in this stage, the mass transport is the rate limiting step since reaction rates are much faster than the transport of gases to and into the char [10].

Smelt reaction stage

At the same time as the char burning occurs, inside the char, the reduction reactions take place [7]. The inorganic, endothermic reduction reactions inside the char, can be described by Reaction 2.2 and 2.3 [5]. Reaction 2.4 is another reduction reaction included in the char burning [7].

$$4\,\mathrm{C}(s) + \mathrm{Na_2SO_4}(l{,}s) \longrightarrow \mathrm{Na_2S}(l{,}s) + 4\,\mathrm{CO}(g) \tag{2.2}$$

$$2\,\mathrm{C}(s) + \mathrm{Na_2CO_3}(l{,}s) \longrightarrow 2\,\mathrm{Na}(g) + 3\,\mathrm{CO}\,(g) \tag{2.3}$$

$$2\,\mathrm{C}(s) + \mathrm{Na_2SO_4}(l{,}s) \longrightarrow \mathrm{Na_2S}(l{,}s) + 2\,\mathrm{CO_2}(g) \tag{2.4}$$

Since these reactions will occur in a reducing environment with restricted access to oxygen, inside the char, these reactions will also occur in deeper layers of the bed where there is poor oxygen supply. The opposite reaction, the oxidation of Na_2S will occur according to Reaction 2.5 if there is excess of oxygen to create Na_2SO_4.

$$\mathrm{Na_2S}(l) + 2\,\mathrm{O_2}(g) \longrightarrow \mathrm{Na_2SO_4}(l) \tag{2.5}$$

Reaction 2.5 is more likely to occur in the shallow layer at the top of the bed, since the oxygen is more accessible and there is less oxygen left in the deeper layers to be consumed [5].

The sulphate and sulphide redox reactions, Reaction 2.2 and 2.5, are often referred to as the sulphide-sulphate cycle [26]. Reaction 2.2 is a rather slow reaction, which implies that if reduction is to be successful, then the access to air has to be restricted [7]. This is why the reduction reactions often occur deeper down in the layers of the smelt where less air will be present.

The aim is to get as much Na_2S as possible to exit at the bottom of the recovery boiler, and this can be measured by the degree of reduction [7]. Higher temperature in the char bed often implies higher degree of reduction [7].

2.3 Effects of operational conditions

As previously described, the recovery boiler with its processes, phenomena and different chemical reactions is very complex. Furthermore, operational conditions of the recovery boiler, such as flue gas temperature and combustion rate of black liquor, can affect the outcome to a large extent. In this section, several different parameters and conditions will be described to examine their impact on the operation of the recovery boiler and the outcomes. This section will not comprehensively cover all different phenomena that may occur, but will give some understanding about the complexity of the operations. Table 2.1 presents an overview of some operational conditions and their potential consequences as well as how these can be prevented.

Table 2.1: Different operational conditions in a recovery boiler, the possible consequences from it and how these can be prevented.

Operational condition	Consequence	Prevention
Lignin removal from black liquor.	Less organic material available to be combusted, decreased viscosity and sulfur release [7, 9].	-
Low level of dry content in black liquor.	High fraction of water that will increase the amount of flue gases.	Increase dry content in black liquor through better evaporation prior to the recovery boiler [7].
High level of dry content in black liquor.	Requires less preheating and increases furnace temperature[7].	-
Boiling point changes in black liquor inlet.	Possible flashing.	Adjust the temperature to be below the boiling point or adjust the pressure [13].
Flashing in black liquor nozzles.	Increased black liquor velocity and nozzle pressure.	Increase nozzle diameter [13].
Volume based liquor distribution.	Air flow rate predicts demand on black liquor volume, and not on combustible dry content.	Base the calculations of required air flow rate on dry solids [27]. Another option is to base the calculations on the amount of O_2 in the flue gases.
Poor bed control and poor flue gas mixing.	Carryover.	Improved air system and liquor distribution system [15].
Increasing gas velocity upwards in recovery boiler.	Carryover increases exponentially [27].	-
High content of SO_2 and SO_3 in the fumes.	Sticky plugging.	Decrease sulfidity in black liquor, decrease the burning of elemental sulfur, sustain a high temperature in the char bed [15].

Continued on next page

Continued from previous page		
Operational condition	**Consequence**	**Prevention**
High fouling rate.	Decreased heat convection and plugging.	Increasing dry solids, decrease content of Cl, and lower sulfidity [7].
Plugging.	Decreases the heat convection and plugs the recovery boiler.	Increase/improve sootblowing and frequency [15].
Increased temperature in combustion.	Increased amount of Na in fume and soot.	Decrease temperature in combustion [7].
Incomplete combustion of material and emissions.	High amount of CO in the flue gas outlet.	Either increase air flow to increase the combustion or increase the residence time of air in the recovery boiler by changing the flow patterns [17].

Every recovery boiler and every process at a pulp and paper mill is unique. This implies that the mentioned conditions in Table 2.1 will not be valid for all recovery boilers and some mills may have more or less problems with those conditions stated.

2.4 Detecting equipment

The most relevant equipment of a recovery boiler has been previously described in Section 2.1.2. To identify different operational conditions at Nordic Paper Bäckhammar, additional equipment are a Voodoo camera and Acospectors. They are both described more detailed in the next sections.

2.4.1 Voodoo camera

A Voodoo camera is a camera that continuously takes pictures of, in this case, one of the sootblowing lances at the recovery boiler at Nordic Paper Bäckhammar. The camera is placed outside the recovery boiler and captures the lances when they are outside the recovery boiler. Pictures are taken approximately every ten minutes. The placement of the Voodoo camera is illustrated in Figure 2.10.

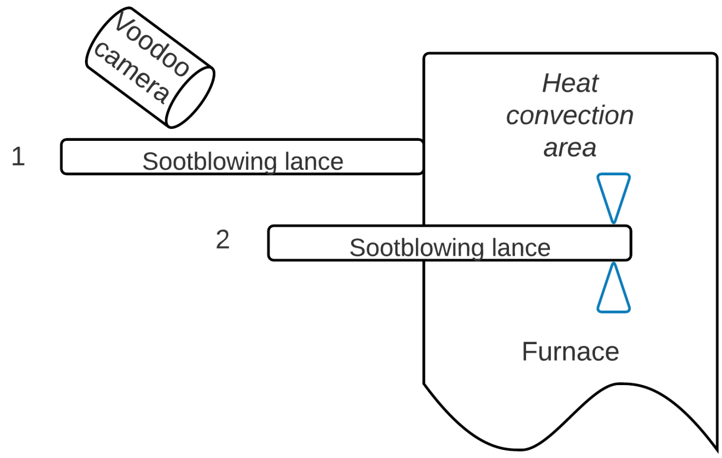


Figure 2.10: An illustration of the placement of the Voodoo camera outside the recovery boiler. 1 and 2 illustrates two different states of the sootblowing lances, where state 1 illustrates a lance outside the recovery boiler and state 2 illustrates a lance inside it, performing sootblowing.

Other than the placement of the Voodoo camera, Figure 2.10 illustrates two different states of the sootblowing lances, where state 1 is outside the recovery boiler and state 2 is inside, performing sootblowing.

The photographs shot with the Voodoo camera show the soot and carryover depositing on the lance. While the sootblowing lances performs sootblowing inside the recovery boiler, the lances are exposed to soot and carryover entrained in the flue gases. Thus, the Voodoo camera will monitor patterns and textures of the soot on the lance. The soot will fall off every time the lance penetrates the recovery boiler and hence, the Voodoo pictures will not present any deposits from a previous operation of the lance. This can give an insight in different operational conditions in the recovery boiler. Further, the pictures taken with the Voodoo camera can be analysed in terms of degree of redness. That is, the amount of red pixels in the picture are counted, and a value of the degree of redness is obtained in percentage.

2.4.2 Acospector - an Acoustic Chemometer

The Acospector is an online instrument developed by Acosense to be sold to their customers. These instruments use active acoustic spectroscopy to analyse fluids in pipes continuously and in real time [28]. One benefit of using Acospectors in a process is that they do not require any contact with the fluid or modification of the process pipe, since the sensors are mounted onto the outside of the pipe [28].

The instruments installed in the industry are sensors for generation and recording of sound and also an amplification and process electronic circuit [28]. Active acoustic spectroscopy works as follows. The sensors send a known sound signal (20-20 000 Hz) which is transmitted through the pipe and the fluid inside [28]. An illustration of the installed sensors on a pipe can be seen in Figure 2.11.

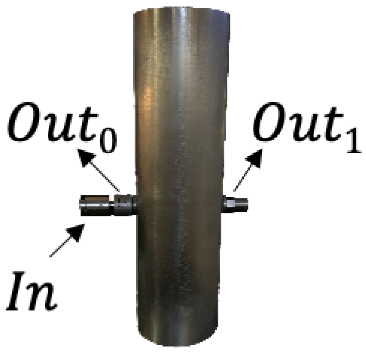


Figure 2.11: An example of sensors for active acoustic spectroscopy, installed onto a process stream pipe.

In Figure 2.11, *In* is the set input sound signal, an actuator creating vibrations applied to the pipe, according to acoustician Frederik Rietdijk (2021-04-08). Out_0 is a signal from a sensor measuring the input force created by the actuator and thus measures the intensity of the force from the input signal. The Out_1 signal is the measurement of the resulting acceleration for the forces. This signal also includes some background noise, since it measures the acceleration of the wall due to all vibrations present, both those caused by our input force, but also from other sources in the surrounding. Out_1 is influenced by the fluid properties of the stream content [28]. Therefore, depending on the content and properties of the fluid, the outgoing signal, Out_1, will be different from the previously mentioned known input sound signal, Out_0 [28]. The signals are processed by using the difference between the signals Out_0 and Out_1. The data can then be presented to the user as for example a certain spectra called a "waterfall plot", described further on in this section [28].

Since each process is unique, the Acospectors are calibrated for a specific process. To calibrate the instrument a reference is needed. The reference can consist of lab samples or other process data or observations. Once the instrument is calibrated, a so called "fingerprint" for the considered process is determined.

At Nordic Paper Bäckhammar, several Acospectors are placed at the site. The placement of some Acospectors at the strong black liquor line can be seen in Figure 2.12.

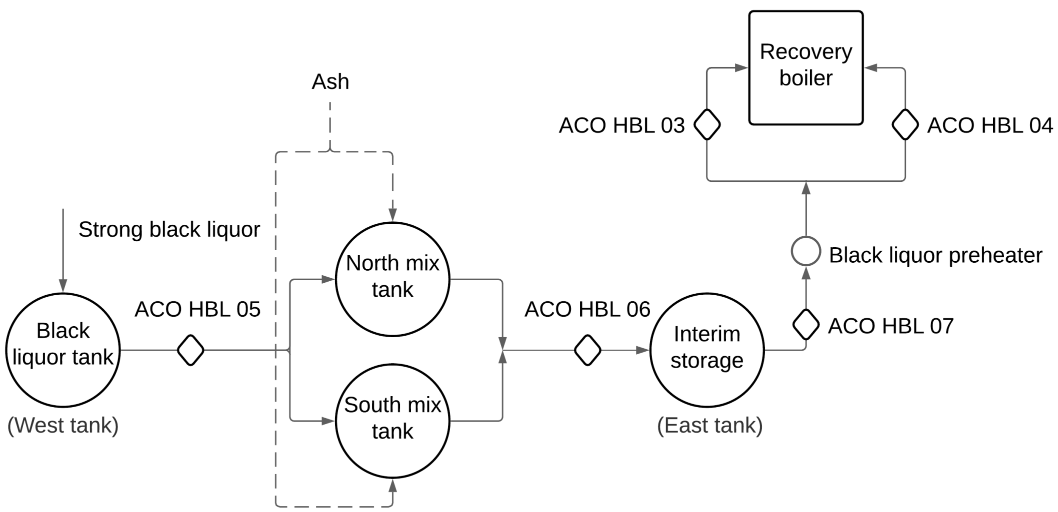


Figure 2.12: An overview from above on the positioning of the Acospectors at Nordic Paper Bäckhammar. HBL indicates that the Acospectors are placed on pipes containing heavy (strong) black liquor.

As can be seen in Figure 2.12, ACO HBL 03 and ACO HBL 04 are placed on each side of the recovery boiler shortly before the black liquor enters the liquor nozzles. ACO HBL 07 is placed prior to the stream split. The remaining two Acospectors, ACO HBL 05 and ACO HBL 06, are placed before and after the mixing tanks. Figure 2.12 presents the black liquor line and ash recirculation, thus, all other material flows such as flue gases and smelt are not shown.

Waterfall plots

The outgoing signal from the sensor is processed, amplified, filtered and transformed, and a graph similar to the one presented in Figure 2.13 is obtained. It shows the intensity of the outgoing signal at different frequencies at a specific point in time.

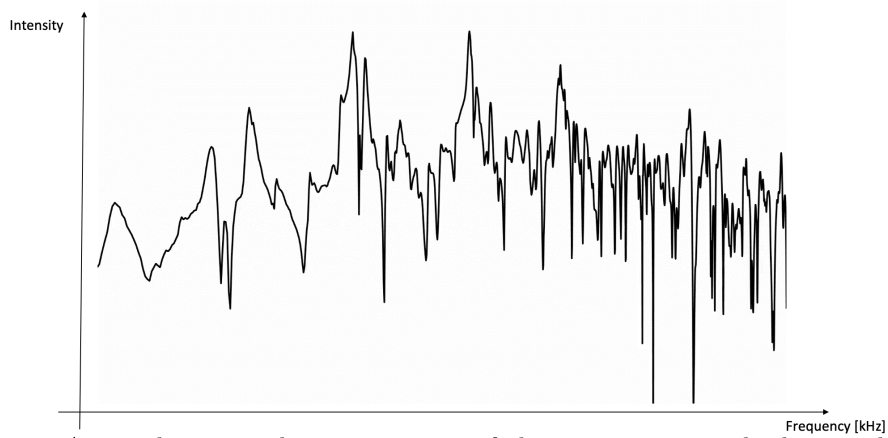


Figure 2.13: A two dimensional representation of the spectra acquired when applying active acoustic spectroscopy on a process stream at a specific point in time. The intensity is plotted against the frequency.

The axes in Figure 2.13 are intensity and frequency of the outgoing signal at a specific point in time. If time is also added as a third axis, a three dimensional plot is obtained, which then shows the acoustic spectra over time. An example of such a plot is presented in Figure 2.14.

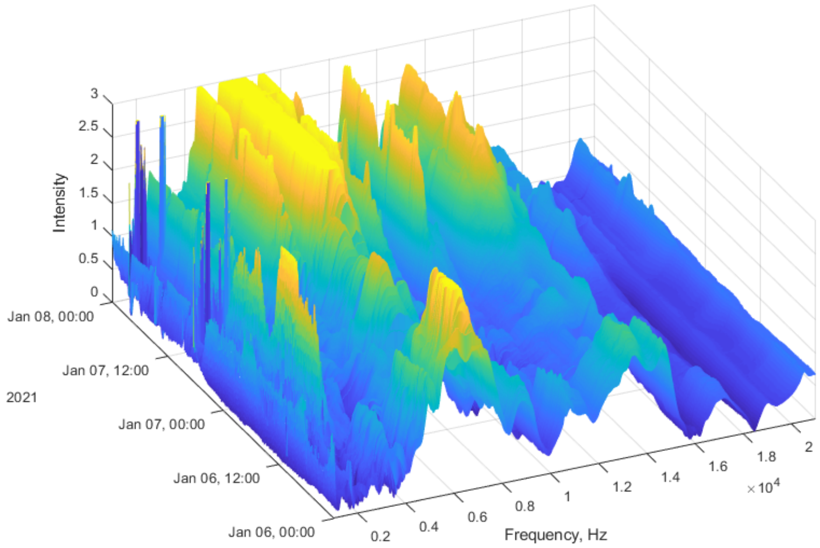


Figure 2.14: An example of a three dimensional representation of the spectra acquired when active acoustic spectroscopy is applied onto a process stream. It shows the intensity of the outgoing signal at different frequencies. A strong yellow colour indicates higher intensity on the outgoing signal and a deep blue colour indicates a lower intensity at that frequency.

In Figure 2.14 it can be seen that the intensity of the outgoing signal varies with time. The colours that indicate the intensity in the plots are relative and not absolute. This means that a specific colour in one plot does not necessarily mean the same intensity as the same colour in another plot from a week earlier. This makes it important to always certify the intensity in one plot with one or several plots of longer duration. The reason the values are relative and not absolute is that each process have a specific intensity span. Since the liquid properties, thus, the intensity can vary with time, there is a risk that smaller changes in intensity can be more difficult to see.

Further, it is important to point out that in a plot such as the one presented in Figure 2.14, the top 1% of the maximum measured value of the intensity is cut off. This, since the plot is relative and not absolute and the 1% often has such a high value that it makes it difficult to distinguish the patterns in the rest of the plot.

The waterfall plots have a resolution of collecting data once each five minutes where 25 seconds is being recorded. The spectra acquired is an average of these 25 seconds recorded. Hence, if any noise would travel the pipes or in the surrounding of the Acospectors with a duration shorter than five minutes, this can affect the appearance of the waterfall plot to some extent. For example if something hits the pipe once during those 25 seconds, near where a Acospector is placed, this sound can be visible in the waterfall plot, however it should not have a huge impact.

To easier study the plot of frequency, intensity and time, a 2D-plot, also called waterfall plot, is presented to the user from the Acospectors. The axes in such a plot are the same as the ones in Figure 2.14, but it is shown from above. The variations in the colour of the plot then represents variations in intensity at certain frequencies over time. An example of a waterfall plot from the same spectra as in Figure 2.14 is presented in Figure 2.15.

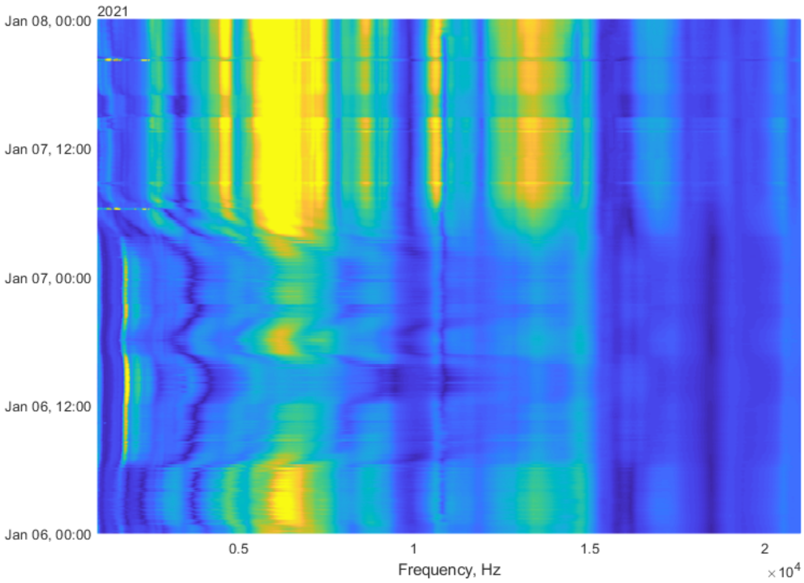


Figure 2.15: An example of a so called "waterfall plot", showing an acoustic spectra. A strong yellow colour indicates higher intensity on the outgoing signal and a deep blue colour indicates a lower intensity at that frequency, relative the ingoing signal.

As can be seen in Figure 2.15, the colours in the spectra varies from deep blue to green to a strong yellow colour. The strong yellow colour indicates a high intensity on the outgoing signal relative the ingoing signal. A deep blue colour on the other hand indicates a lower intensity of the outgoing signal, relative the ingoing signal, in the spectra. Variations in colour in the waterfall plots over time, as can be seen in Figure 2.15, indicates that something has changed in the properties or the content of the fluid studied.

The main criteria considered in the waterfall plots is continuity. The time axis in the waterfall plot is the vertical axis. If the colour distribution is even over time, this indicates that there has been none or minor changes in the black liquor properties. A vertically uneven distribution on the other hand indicates changes in the black liquor properties or in the surrounding. It can be possible to see differences in the waterfall plots connected to changes in the structural surrounding the fluid. For example, if a pipe is loosely attached, its vibrations will likely affect the waterfall plot.

It may also be possible to find whether the fluid in a pipe is a gas or liquid due to the difference in intensity in the waterfall plot [29]. This since the sound will travel at different speed in various phases, due to variations in compressibility and the variation in density [29, 30]. The sound will travel fastest in the solid material, then slower in liquid and slowest in gas [29]. The compressibility for a material will generally be largest for a gas, lowest for a solid and a liquid will be somewhere in between [30]. Also, since temperature and pressure can change, the properties of both solids, fluids and gases can vary. The changes in the properties might be possible to observe by the waterfall plots of the sounds [29]. According to acoustician Frederik Rietdijk (2021-03-05), the changes can be noticed since they will be changing the energy transfer between the solid material and the fluid. Thus it can be possible to observe if and when liquid changes into gas and vice versa.

3
Methods

To determine if there was flashing and carryover in the recovery boiler, a method of both ocular analysis of the active acoustic spectroscopy data and photographs from the Voodoo camera together with an examination of operational parameters was conducted. The main method was the day-to-day analysis of both the pictures taken with the Voodoo camera as well as the waterfall plots. The main observations of the waterfall plots were made on data from ACO HBL 03 and ACO HBL 04 and by way of exception other Acospectors were analysed. The placement of the Acospectors can be seen in Figure 3.1.

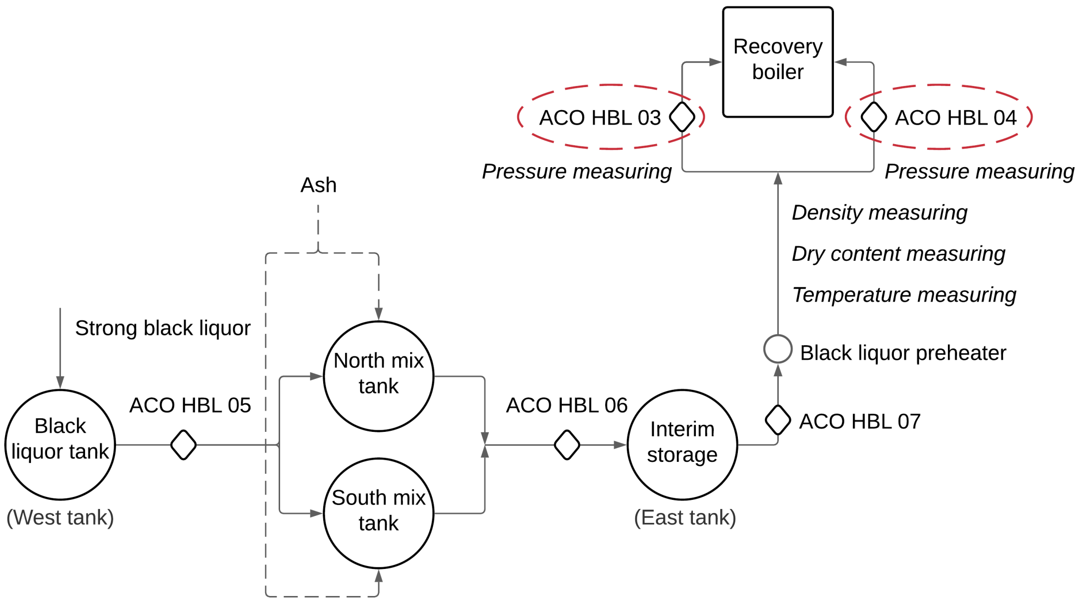
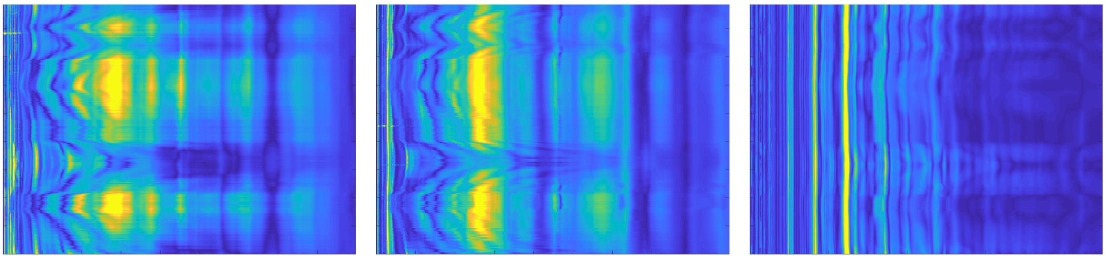


Figure 3.1: An illustration of the placement of the Acospectors at Nordic Paper Bäckhammar, where the two Acospectors mainly considered, ACO HBL 03 and 04, are marked with dashed, red lines.

In Figure 3.1, ACO HBL 03 and 04 are marked with dashed, red lines. As can be seen, they are both placed on separate sides of the recovery boiler, close to the black liquor nozzles.

The reason why specifically the waterfall plots from ACO HBL 03 and 04 were studied, and no other Acospectors, is their placement. They are both placed close to the black liquor inlet of the recovery boiler. ACO HBL 05 and 06 are placed too far from the recovery boiler to provide any valuable information regarding the conditions in the boiler. Further, when comparing the waterfall plots from ACO HBL 03 and 04 to waterfall plots from ACO HBL 07, placed upstream in the process, it can be noted that the waterfall plots from ACO HBL 07 does not indicate the same variation in intensity as the ones from ACO HBL 03 and 04 even though the composition of the fluid has not changed. See Figure 3.2 for an illustrative example of the difference between the mentioned waterfall plots.



(a) ACO HBL 03. **(b)** ACO HBL 04. **(c)** ACO HBL 07.

Figure 3.2: Waterfall plot created using data from three different Acospectors.

As can be seen in Figure 3.2, ACO HBL 07 shows a more evenly distributed pattern than the other two, even though some small variations can be seen. In other words, it is likely that conditions in the recovery boiler will affect ACO HBL 03 and 04 in a way that does not influence ACO HBL 07. Further, as can be seen in Figure 3.1, there is a black liquor preheater between ACO HBL 07 and ACO HBL 03 and 04, which also can be a reason for the different appearances of the spectra.

Once waterfall plots from ACO HBL 03 and 04 and Voodoo pictures were analysed separately, they were compared to each other, in order to confirm similarities and connections between them. These analyses are presented in more detail below. Further, the actions performed if a lot of carryover on the sootblowing lances was noted, are also presented below.

3.1 Waterfall plot and Voodoo picture analysis

The Voodoo camera takes pictures of one specific sootblowing lance, sootblowing lance number 6, approximately every ten minutes. However, the sootblowing lances enter the recovery boiler according to a predetermined sequence. The sootblowing lance that is photographed enters the recovery boiler approximately once every three to four hours. This can cause a delay in noticing possible changes in the amount of carryover.

The pictures of the specific sootblowing lance were analysed ocular in terms of how much black and red carryover that was deposited on the sootbloowing lance. From the pictures, a scale of reference for each carryover type (black and red), was formed based on the variation in amount of carryover. These scales were created in order to keep the results comparable and they are presented in Appendix A. The pictures analysed where assigned a number from the reference scale to get a quantitative and comparable number of each of the two measures. Further, if black or red carryover was detected, the time period in which they appeared were noted.

The waterfall plots primarily considered had a time span of two days. As described in Section 2.4.2, the waterfall plots are relative in intensity and not absolute. Thus, if variations were noted within the two day plot, it was necessary to also consult a plot with a longer time span, in this case, ten days. If the variation in the intensity, the colour distribution, was visible in the ten day plot as well the results were considered as more certain. An example of variation in intensity, i.e. when there can be possible changes in the fluid properties, is presented in Figure 3.3.

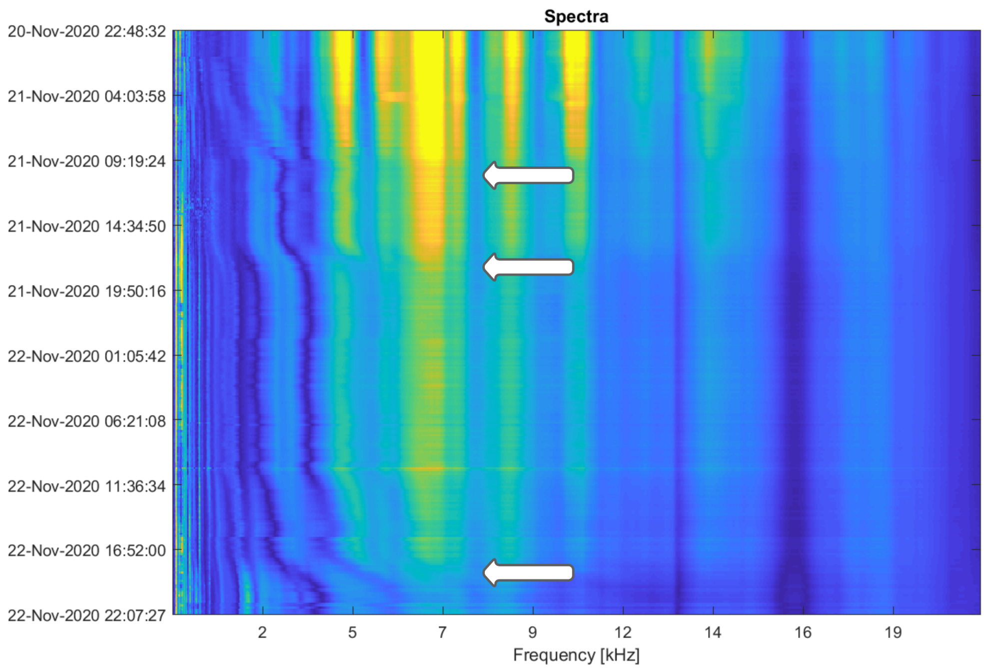


Figure 3.3: An example of a variation in colour distribution in the waterfall plots. The arrows point to around the time when a change in the fluid properties could have occurred.

The arrows in Figure 3.3 indicate where changes in intensity occurs in a waterfall plot. As mentioned, the Voodoo pictures and the waterfall plots were also compared to each other, this was to see if alterations occurred at the same time, i.e. where the arrows point at in Figure 3.3. It should be mentioned that the residence time is short for the black liquor droplets between the Acospectors HBL 03 and 04 and the soot-blowing lance number 6. Thus, this residence time was not taken into consideration.

In the early parts of this thesis work, the Voodoo pictures were analysed first and thereafter the waterfall plots. This was due to the fact that the waterfall plots are more sensitive to when changes occur. The Voodoo pictures can be somewhat more vague due to the lower time resolution. Hence, in order to ensure that there were no preconceptions when analysing the Voodoo pictures, these were analysed first. Once more experience was gained in analysing both the Voodoo pictures and the waterfall plots, the analysis was performed the other way around, i.e. the waterfall plots first and thereafter the Voodoo pictures. This due to that in the end, the user of the Acospectors will mainly look at the waterfall plots in order to see changes. Hence, it is preferable to be able to foreseen what outcome the Voodoo pictures will show, based on the waterfall plots.

3.2 Connections between data and reality

If major changes were noted in either merely the Voodoo pictures or in both the Voodoo pictures and the waterfall plots, that could indicate that the operation of the boiler was run differently from usual. It could also indicate that the mill in Bäckhammar had some known or unknown operational issues, that can cause carryover. In such a case, contact was established with the process engineer Viktor Schützer at Nordic Paper Bäckhammar. This was to discuss if there had been any operational issues regarding the recovery boiler.

3.2.1 Black carryover

Operational data obtained from the mill was analysed at occasions when black carryover was detected through the Vodoo pictures. The parameters of interest include:

- Black liquor flow rate
- Total air flow rate
- Primary, secondary and tertiary air flow rate
- Black liquor nozzle pressure
- Black liquor temperature in nozzles
- Black liquor dry content

These parameters were all plotted with respect to time. When analysing the operational data, the parameters looked upon first were the air and black liquor flow rate. This due to that it was believed that if drastic changes could be noted in these parameters around the time when black carryover started to appear, it could be the reason for the appearance of black carryover.

Further, the pressure and temperature in the black liquor nozzles were analysed. If sudden changes in the pressure and/or temperature were noted during the time period of black carryover, then flashing could be suspected. Variations in the dry content might also be a cause of flashing and therefore this was also investigated.

There were also other samples available, such as degree of reduction, sulfidity, pH of the ash that was to be recycled and dry content of the black liquor. However, some laboratory samples were taken with a frequency of one week and other samples were taken each working day. The low frequency of sample gathering somewhat prevented the possibility to link any result of these samples to the waterfall plots or the Voodoo camera pictures. The fact that several changes in both the waterfall plots and the Voodoo pictures could be noted in one week means that the laboratory samples taken once a week could not be correlated to all of these changes.

3.2.2 Red carryover

When it comes to the red carryover, it was more difficult to find a connection between the waterfall plots and the occurrence of the red carryover in the Voodoo pictures. Due to this, the time periods with red carryover were not investigated as thoroughly as the ones with black carryover. Hence, it was decided to only search for answers for the red carryover in the primary, secondary and tertiary air flow rates and no other parameters. This, since the air flow was thought to be the most likely reason for the red carryover.

3.2.3 Unexpected patterns in the waterfall plots

During the investigation of the waterfall plots, some unexpected, random patterns were occurring between the beginning of December to the start of January. The outdoor temperature was investigated to find any connections, since outdoor temperature might affect the process. From SMHI's weather station in Kristinehamn, which is the closest weather station to the site in Bäckhammar, data was collected and analysed. This to establish or reject any connection to the outdoor temperature.

4
Results

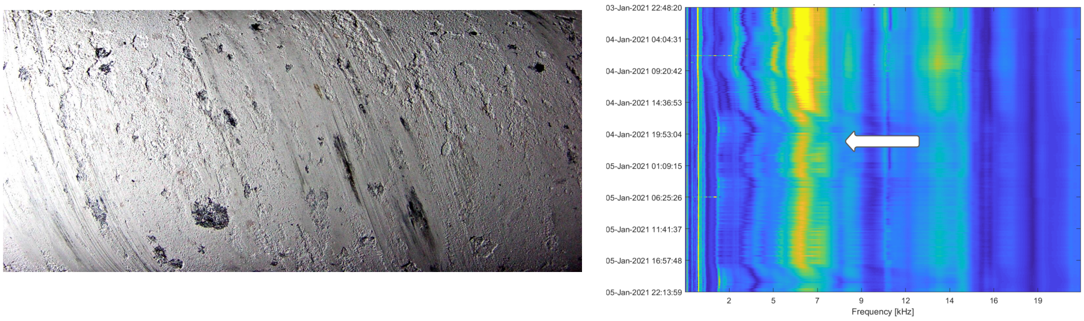
In this thesis work, the results partly come from the ocular investigation of both the Voodoo pictures and waterfall plots. Hence, this chapter will present several figures of these two kinds. Other results will descend from the examination of the operational data and therefore, graphs showing how these parameters change over time will also be presented in the next sections.

It is useful to note that the Voodoo pictures will only show new results every three to four hours, due to that the sootblowing lance only enters the recovery boiler that often. Thus, when carryover on the sootblowing lance will appear, the behaviour causing it might have been ongoing for several hours before it can be seen in the Voodoo pictures. The same thing will be valid for the time when the carryover ceases to appear, the behaviour might continue up to four hours after the last observation of carryover on the sootblowing lance. The noted time periods in this section will only be based on the time of new results in the Voodoo pictures.

First, the results from the investigation of connections between the Voodoo pictures and the waterfall plots will be presented. Then, the results from the investigation of the causes of black carryover can be seen, regarding both air and black liquor flow rate as well as other operational parameters. The latter results will be displayed by four diverse examples. Example 1 and 2 are presented in Section 4.2 and investigates the connection between black carryover and air and black liquor flow rate. Example 3 and 4 in Section 4.3 investigates the pressure, temperature and dry content when black carryover occurs. There are further examples presented in Appendix D to give a deeper understanding of the results. All data from the operational parameters can be seen for each month in Appendix C. Moreover, the results from the investigation of the causes of red carryover is presented in this chapter, and also the causes of the unexpected formations appearing in the waterfall plots.

4.1 Connections between waterfall plots and Voodoo pictures of black carryover

The results of first investigating the Voodoo pictures for carryover and then finding patterns in the waterfall plots showed that there is a connection between the two to some extent. As can be seen in Figure 4.1, the waterfall plot shows a dampened pattern at the specific time period when black carryover can be observed.

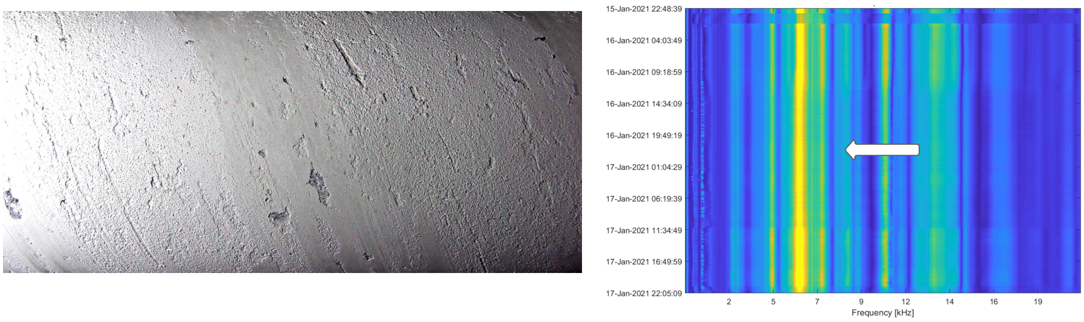


(a) Black carryover at the sootblowing lance 2021-01-04 at 22.23 .

(b) Waterfall plot from 2021-01-03 at 22.48 to 2021-01-05 at 22.13, from ACO HBL 04. The white arrow indicates when the Voodoo picture was taken. A dampened pattern is indicated by the arrow.

Figure 4.1: Black carryover can be seen at the same time as dampened intensity is observed in the waterfall plot.

In Figure 4.1, black carryover on the sootblowing lance seems to overlap in time with the dampened area. Further, in Figure 4.2, it can be seen that a period of non-repressed areas of the waterfall plots seems to match well with a sootblowing lance without any carryover.



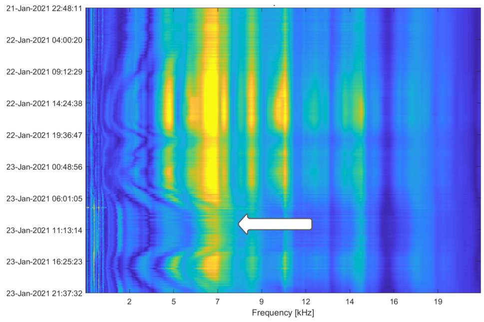
(a) No black carryover at the sootblowing lance 2021-01-16 at 22.07.

(b) Waterfall plot from 2021-01-15 at 22.48 to 2021-01-17 at 22.05, from ACO HBL 04. The white arrow indicates when the Voodoo picture was taken. The waterfall plot shows a clear and undisturbed pattern.

Figure 4.2: No carryover can be seen when the waterfall plot shows non-repressed patterns.

From what is presented in Figure 4.1 and Figure 4.2, the results would be that when black carryover can be observed, the waterfall plot has a dampened pattern, while no carryover can be seen in the non-repressed time slots. However, these results are not comprehensive. At several occasions, no connections could be made between the outcome of black carryover in the Voodoo pictures and the patterns of the waterfall plots. See Figure 4.3 for further insights.

(a) No black carryover at the sootblowing lance 2021-01-23 at 10.24.



(b) Waterfall plot from 2021-01-21 at 22.48 to 2021-01-23 at 21.37, from ACO HBL 04. The white arrow indicates when the Voodoo picture was taken. The waterfall plot indicates dampened pattern at the time of the Voodoo picture.

Figure 4.3: No black carryover can be seen even though the waterfall plot had a dampened pattern at the time.

Figure 4.3a highlights the lack of black carryover even though it could be suspected, due to previous mentioned results regarding the connection between black carryover and the dampened pattern in Figure 4.3b.

All occasions with black carryover have been investigated regarding the connection between the carryover periods and the waterfall plots. Table 4.1 presents how many of the periods with black carryover that occurred at the same time as dampened patterns in the waterfall plots.

Table 4.1: The amount of connections or lack of connections between the time periods with black carryover and the waterfall plots. The number of occasions with unexpected patterns can also be seen.

Description	**Quantity**
Connection found	10
No connection found	2
Poor connection or partly no connection	4
Unexpected patterns	4
Total	20

In Table 4.1 the amount of connections found between the black carryover occasions and the dampened patterns in the waterfall plots was noted together with the occasions with no connection. Also the occasions were noted when the connection would be poor, for example with dampened patterns in only one of the two Acospectors, HBL 03 or 04, or when the connection was found only for a part of the time noted for black carryover. The unexpected patterns sometimes disturbed the investigation of connection between the waterfall plot patterns and carryover periods, thus, these occasions are also accounted for in Table 4.1. These unexpected patterns are further elaborated in Section 4.5.

4.2 Black carryover and air and black liquor flow rate

Operational data from Nordic Paper Bäckhammar was studied around the points in time when black carryover was noted on the sootblowing lances. Among other factors, two of them often seemed to change drastically at the same time as black carryover appeared. These factors were the total air flow rate and the black liquor flow rate. Usually, these two parameters follow a similar trend, i.e. when the black liquor flow rate is increased, so is the air flow rate. At several occasions it was noted that when one or both of these two parameters were drastically increased, it was often followed by a period with more carryover. However, contradicting results were also found, when there was a drastic increase in at least one of these flows, which did not result in carryover.

In Table 4.2, all occasions with black carryover noted during this thesis work is presented, along with an indicator whether the air and/or black liquor flow rate was increased prior to the start of the noted carryover period. Further, a range of the valuation of the amount of black carryover during the time period is presented. These valuations are based on the reference scales that was created for black carryover, presented in Appendix A.

Table 4.2: The time periods when black carryover occurred at the sootblowing lance and an indicator whether the air and/or black liquor flow rate was increased. Further, a range of the valuation of the amount of black carryover during the time period is presented. The time period in **bold** is elaborated further in Example 1

Carryover starting	Carryover stopping	Increased air and/ or black liquor flow	Valuation
2020-11-21 at 10	2020-11-22 at 22	Yes	1-5
2020-11-29 at 00	2020-11-29 at 07	Yes	1-3
2020-12-01 at 03	2020-12-01 at 14	No	1-3
2020-12-02 at 17	2020-12-03 at 10	Small increase	1-5
2020-12-03 at 17	2020-12-06 at 07	Yes	2-6
2020-12-10 at 06	2020-12-11 at 10	No	1-6
2020-12-12 at 09	2020-12-15 at 05	Yes	1-4
2020-12-21 at 18	2020-12-22 at 09	Small increase	2-5
2020-12-31 at 02	2020-12-31 at 19	Yes	3-6
2021-01-01 at 11	2021-01-02 at 15	No	2-4
2021-01-04 at 12	2021-01-07 at 01	No	1-4
2021-01-08 at 15	**2021-01-11 at 16**	Yes	2-6
2021-01-12 at 12	2021-01-13 at 09	Small increase	2-4
2021-01-18 at 04	2021-01-18 at 08	Yes	1-2
2021-01-19 at 11	2021-01-20 at 18	Small increase	1-3
2021-01-21 at 18	2021-01-21 at 22	No	3
2021-01-24 at 06	2021-01-25 at 09	No	1-4
2021-01-25 at 23	2021-01-26 at 04	No	3-6
2021-02-02 at 23	2021-02-04 at 06	Yes	2-4
2021-02-13 at 05	2021-02-13 at 19	No	1-3

In Table 4.2, *Yes* indicates similar trends in the air and black liquor flow rate as the ones that will be presented in Section 4.2.1 and Appendix B.1. The time periods marked with *No* in Table 4.2 indicate that no such similar trend in the air and black liquor flow rate was detected in the operational data studied. The time period marked in **bold** is the time period examined in Example 1.

4.2.1 Example 1

An increased amount of carryover together with a drastically increased amount of total air and/or black liquor flow was detected several times during this thesis work. One example of this occurred between 2021-01-08 at around 15.00 and 2021-01-11 at around 16.00. A picture taken with the Voodoo camera during this period of time is presented in Figure 4.4. The specific picture presented was taken 2021-01-10 at 11.59 and shows an example of how much carryover was present during that period of time. The waterfall plot from this occasion is presented in Figure 4.5.

Figure 4.4: A Voodoo picture (2021-01-10 at 11.59) showing the presence of carryover during the time period 2021-01-08 15.00 to 2021-01-11 16.00.

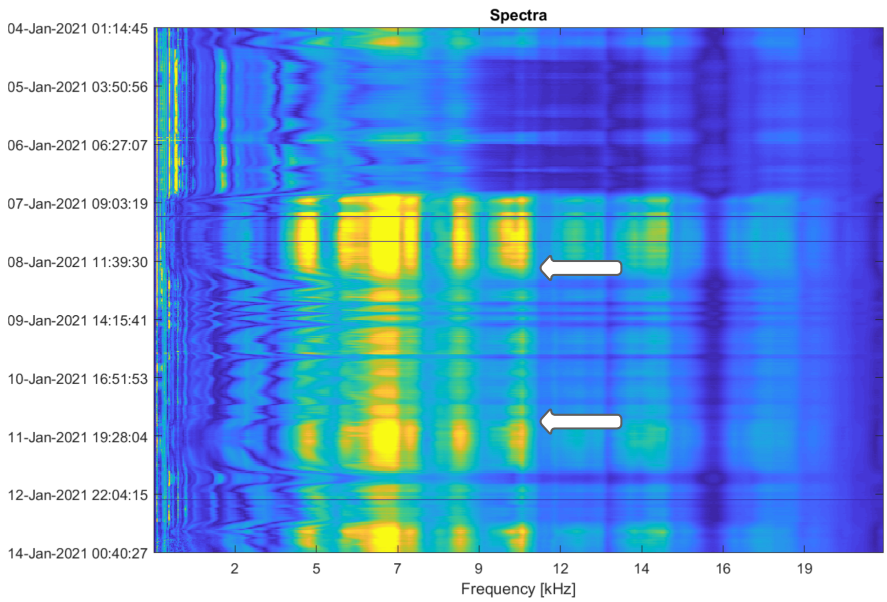


Figure 4.5: A waterfall plot from ACO HBL 03 showing the time period between 2021-01-04 at 01.14 to 2021-01-14 at 00.40, showing when black carryover was detected. The white arrows indicate when the carryover started and stopped according to the Voodoo pictures. The area between the white arrows indicate a somewhat dampened pattern.

The occasion when carryover was detected is marked in Figure 4.5 with white arrows pointing to the start and the end of the mentioned time period. As can be seen, this area is dampened in the spectra. Further, the total air and black liquor flow was plotted with respect to time and the graph is presented in Figure 4.6.

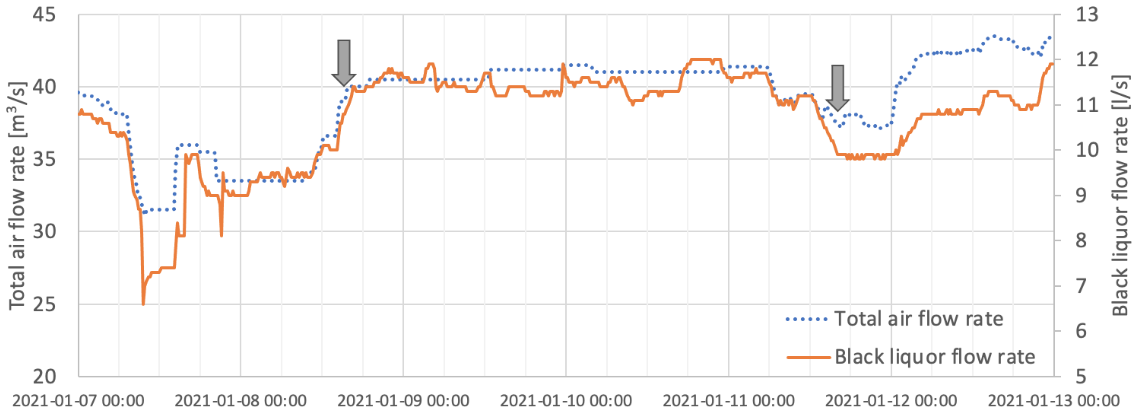


Figure 4.6: Total air and black liquor flow rate plotted with respect to time during the time period 2021-01-07 - 2021-01-12. The grey arrows indicate when time period with carryover starts and stops.

In Figure 4.6 the total air flow rate (m^3/s) is represented by the blue dotted graph and the black liquor flow rate (l/s) is the orange graph. The grey arrows indicate when the first and last Voodoo pictures showing carryover were detected. However, the real starting and stopping time can differ with a few hours, since the sootblowing lance studied only enters the recovery boiler once every three to four hours. More specifically, this means that the carryover might have started up to four hours earlier than stated in Figure 4.6 and it might have continued up to four hours later than stated.

In Figure 4.6 it can be seen that prior to the time when the carryover started to occur, both of the plotted flows had increased a lot. In this case, the time period in which the carryover occurred lasted for several days. However, in this example, the carryover seems to cease to appear once the flow rates are decreased again.

There are further examples similar to the one presented above, where carryover is present at the same time as an increased air and black liquor flow rate. An example of this kind is presented in Appendix B.1.

4.2.2 Example 2

Figure 4.7: A Voodoo picture taken 2021-01-22 at 21.44, showing no black carryover despite the increase of air and black liquor flow rates.

Even though some periods with drastically increased air and/or black liquid flow rates occur, not all of them result in black carryover. As can seen in Figure 4.7, the sootblowing lance has neither any red or black carryover during this time period. Thus, examples that are contradictory to the previously elaborated Example 1 can be found. The Voodoo picture in Figure 4.7 is taken 2021-01-22 at 21.44. The waterfall plot of the same date and time, indicated by a white arrow, is presented in Figure 4.8.

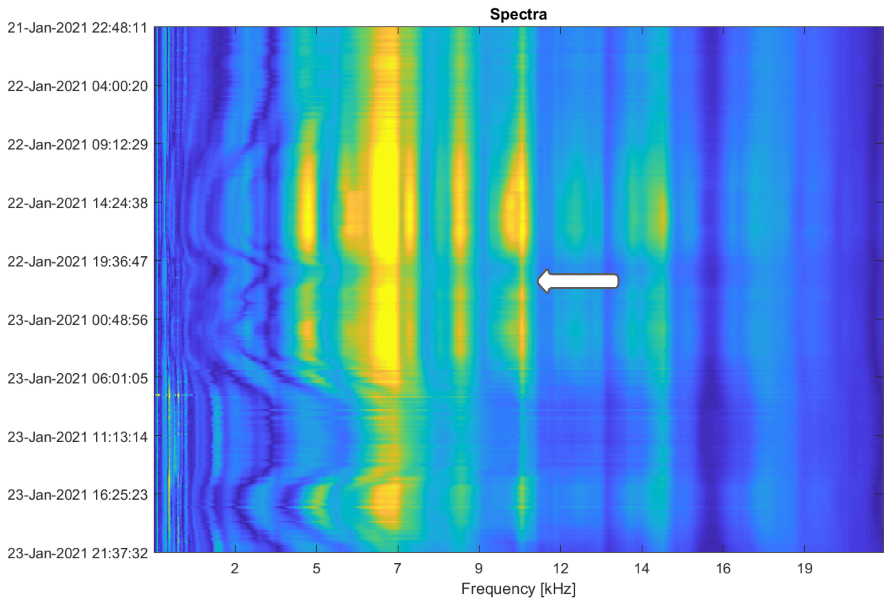


Figure 4.8: A waterfall plot from ACO HBL 03 showing the time period between 2021-01-21 at 22.48 to 2021-01-23 at 21.37, when no black carryover was detected. The white arrow indicates when the Voodoo picture was taken. The area close to the arrow indicate clear intensity with a minor disturbance.

The waterfall plot in Figure 4.8 indicates a pattern of quite small intensity variations, even though some minor changes could be noted close to the arrow. The total air and black liquor flow rates in the time period between 2021-01-20 and 2021-01-25 is presented in Figure 4.9

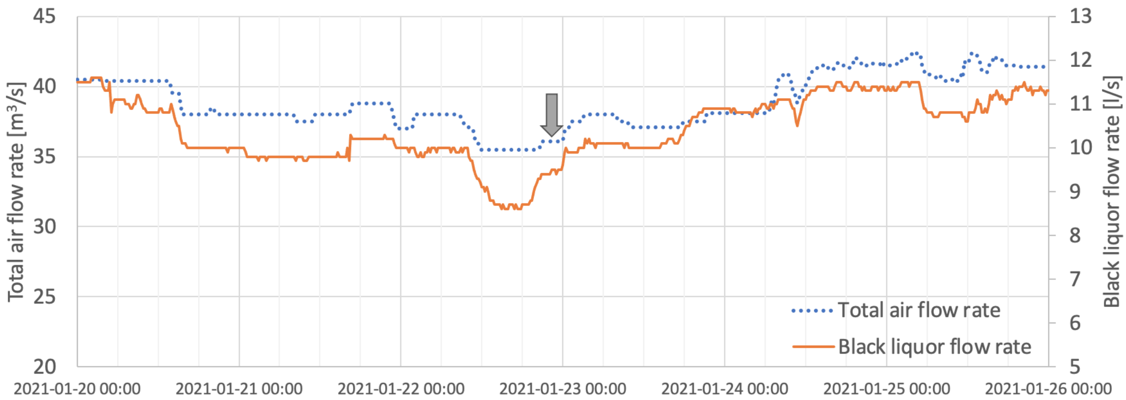


Figure 4.9: Total air and black liquor flow rate plotted with respect to time during the time period between 2021-01-20 and 2021-01-25. The grey arrow indicates when the Voodoo picture was taken.

The grey arrow in Figure 4.9 indicates when the Voodoo picture was taken. It can be seen that this is shortly after an increase in black liquor flow rate. To conclude, the presented example shows that a drastically increased air and/or black liquor flow rate does not necessarily need to result in carryover.

A further result which contradicts the idea that high flow rates of air and black liquor results in carryover is presented in Appendix B.2. The referred example in the appendix shows that even though the air and black liquor flow rates are high, no carryover can be seen in the Voodoo pictures.

4.3 Examination of further operational parameters

As described in the previous section, one behaviour that often occurred at the same time as the black carryover was a drastically increased flow rate of the black liquor and/or total air. However, as could be seen in Table 4.2, there were several occasions when no such increases of the mentioned flow rates could be detected. Hence, a search for other parameters as an explanation was performed. All the occasions mentioned in Table 4.2 were further investigated regarding other operational parameters, but the main focus was the time periods marked with *No* in Table 4.2.

The operational parameters studied were the nozzle pressure and temperature, and the dry content of the black liquor. The evaluation of the mentioned parameters for some of the time periods marked with *No* in Table 4.2 is presented in Table 4.3. Further, a range of the valuation of the amount of black carryover during the time period is presented. This valuation is based on the reference scale that was created for black carryover, presented in Appendix A. An extended version of Table 4.3 including all the time periods with black carryover is presented in Appendix D.

Table 4.3: Occasions when black carryover occurred at the sootblowing lance along with an indicator on how the nozzle pressure, black liquor temperature and the dry content changed around the specific time interval given. Further, a range of the valuation of the amount of black carryover during the time period is presented.

Carryover starting	**Carryover stopping**	**Nozzle pressure**	**Black liquor temperature**	**Dry content**	**Valuation**
2020-12-01 at 00	2020-12-01 at 14	Stable, varies between 1.63-1.65 bar	Increases from 129-130°C	Stable at 72.8-72.9%	1-3
2020-12-10 at 06	2020-12-11 at 10	Quite stable, varies between 1.59-1.74 bar	Increases from 129-132°C	Varies between 71.8-73.5%	1-6

The time periods presented in Table 4.3 are elaborated in the upcoming sections as Example 3 and 4.

4.3.1 Example 3

The first occasion of black carryover without a drastic increase of air and/or black liquor rate that was investigated for other parameters as an explanation for the carryover was 2020-12-01 at the time period between around 00.00-14.00. In Figure 4.10, an example of the amount of carryover during the mentioned time period is presented. The Voodoo picture is taken 2020-12-01 at 06.43.

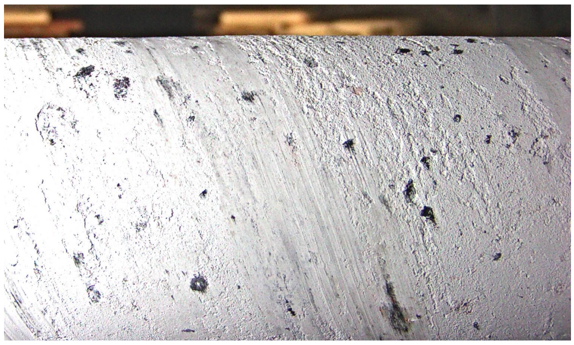


Figure 4.10: A Voodoo picture, taken 2020-12-01 at 06.43, showing an example of the amount of carryover during the time period 2020-12-01 00.00 to 2020-12-01 14.00.

The waterfall plot from ACO HBL 04 corresponding to the same time period is presented in Figure 4.11, where the white arrows indicate the observation of the first and last Voodoo picture showing black carryover.

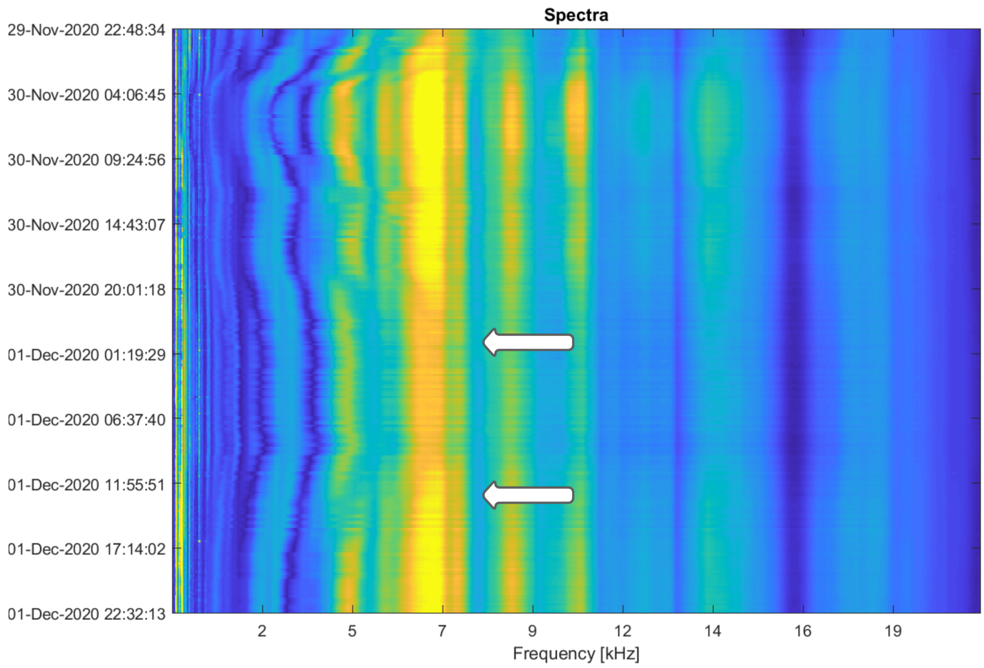


Figure 4.11: Waterfall plot from ACO HBL 04 during the time period between 2020-11-29 22.48 to 2020-12-01 22.32. The white arrows indicate when the first and last Voodoo picture showing black carryover was observed. The area between the arrows has a dampened pattern.

A slight reduction in intensity can be noted in the waterfall plot in Figure 4.11 during the same time as the carryover period. A plot of the pressure in one of the black liquor nozzles during this time period is presented in Figure 4.12.

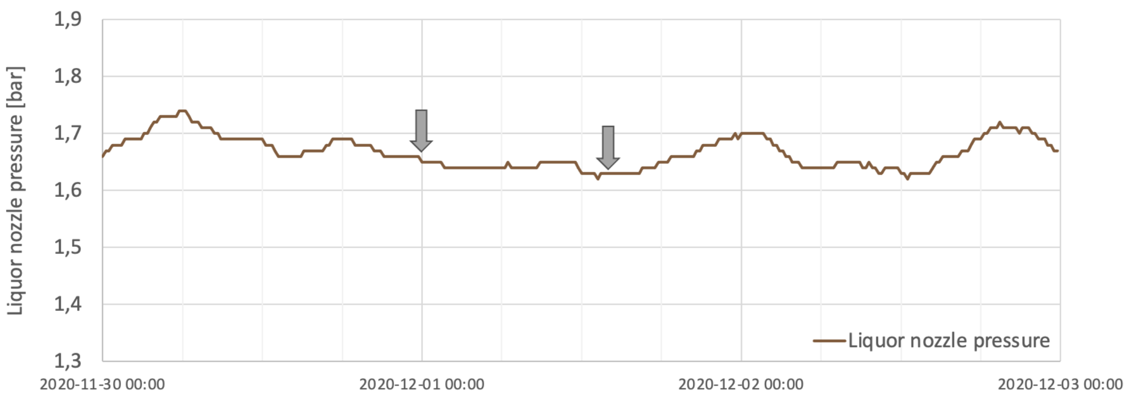


Figure 4.12: A graph showing the variations in pressure in one of the black liquor nozzles in the time period between 2020-11-30 and 2020-12-02. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

In Figure 4.12, the grey arrows indicate when the first and last Voodoo picture showing carryover was observed. It can be seen that the pressure is quite stable during this period in time. The time periods outside the studied time period vary slightly more. Further, a plot of the black liquor temperature in one of the nozzles during this period in time is presented in Figure 4.13

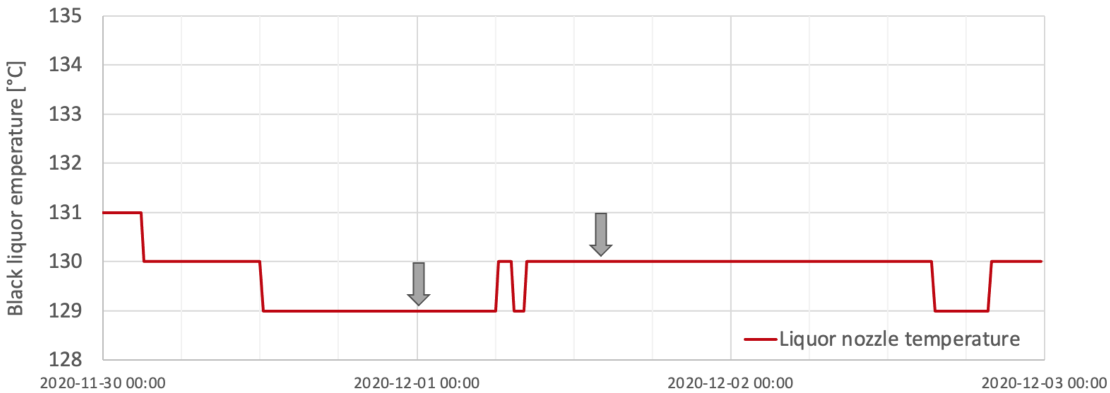


Figure 4.13: A graph showing the variations in temperature of the black liquor in the time period between 2020-11-30 and 2020-12-02. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

As can be seen in Figure 4.13, the temperature increases by 1°C during this time period. However, the change in temperature occurs in the midst of the period. Additionally, the black liquor dry content was also plotted, the graph is presented in Figure 4.14.

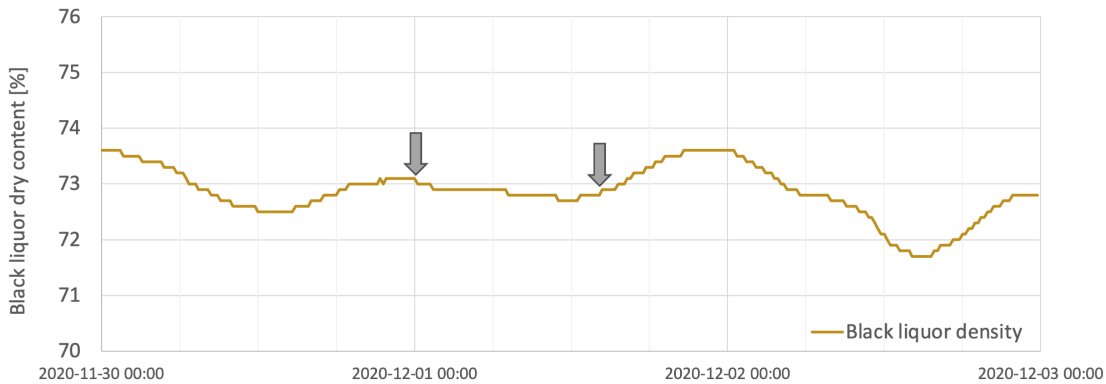


Figure 4.14: A graph showing the variations in dry content of the black liquor in the time period between 2020-11-30 and 2020-12-02. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

Looking at Figure 4.14, it can be concluded that the dry content is quite stable during this time period. However, it can be seen that the dry content increases both before and after the studied time period.

As a result from the presented graphs of the operational parameters in this example, no drastic changes can be seen. Neither do the parameters show any abnormally low or high values.

4.3.2 Example 4

The search for other parameters as an explanation for black carryover than drastically increased air and/or black liquor flow rate can be seen in this example. This is another example of carryover with a dampened pattern in the waterfall plot occurred in the time period between 2020-12-10 at around 06.00 to 2020-12-11 at around 10.00. An example of how much carryover that was present at the sootblowing lances during this period in time is presented in Figure 4.15. This specific Voodoo picture is taken 2020-12-11 at 06.45.

Figure 4.15: A Voodoo picture, taken 2020-12-11 at 06.45, showing the presence of carryover during the time period 2020-12-10 06.00 to 2020-12-11 10.00.

Figure 4.16 presents the waterfall plot from ACO HBL 03 from the mentioned time period. The white arrows indicate when the first and last Voodoo picture where black carryover was present was observed.

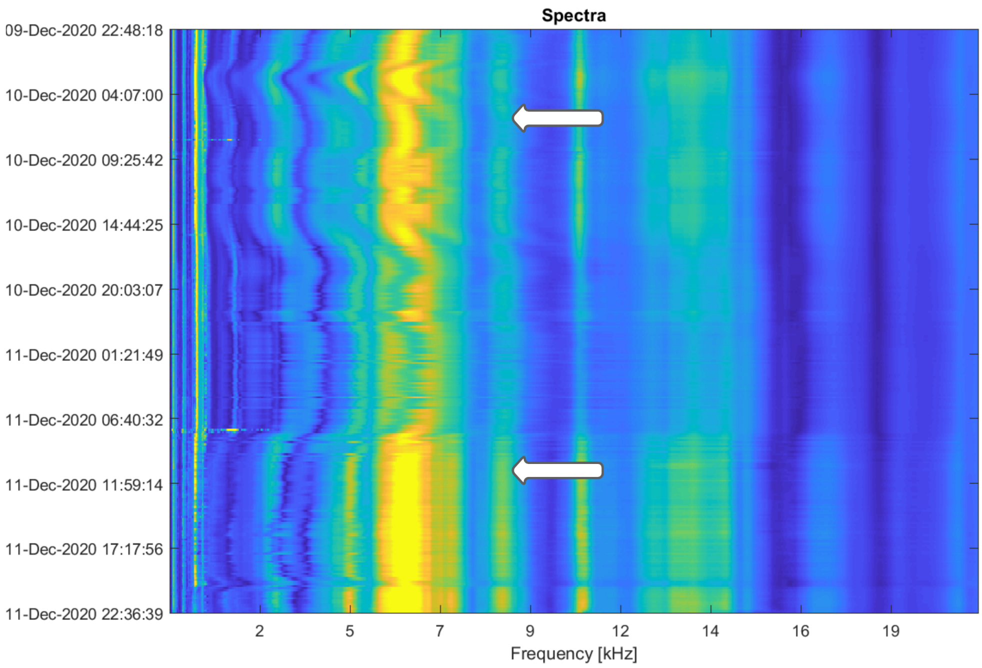


Figure 4.16: Waterfall plot from ACO HBL 04 during the time period between 2020-12-09 22.48 to 2020-12-11 22.36. The white arrows indicate when the first and last Voodoo picture showing black carryover was observed. The pattern in the waterfall plot is neither all non-repressed or dampened, but a mixture of them both.

It can be seen in Figure 4.16 that there are some variations in intensity during this time period. At the end of it, the intensity is more stable and the shift between the period with carryover and without carryover is quite clear in the plot.

A graph of how the pressure in one of the black liquor nozzles varied during the mentioned time period is presented in Figure 4.17. The grey arrows show when the carryover started and stopped occurring on the sootblowing lance.

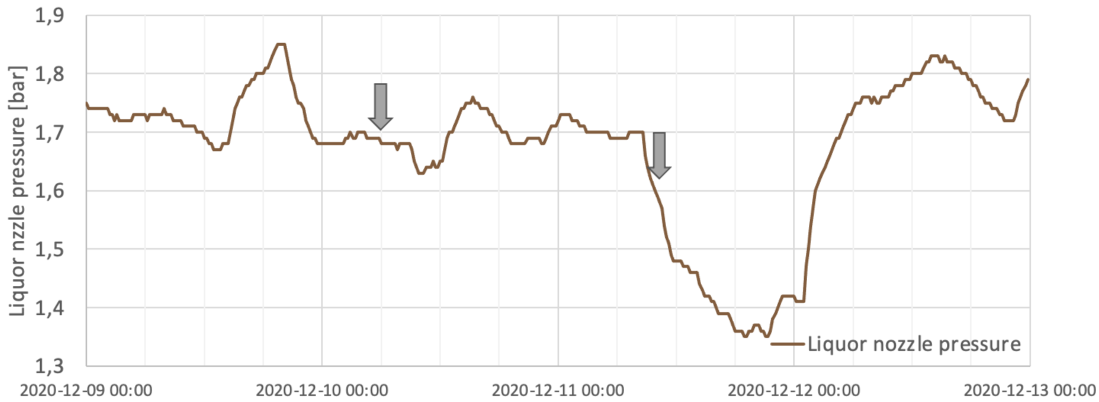


Figure 4.17: A graph showing the variations in pressure in one of the black liquor nozzles in the time period between 2020-12-09 and 2020-12-12. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

It can be seen in Figure 4.17 that the pressure varies during this time period. At the end of this time period, there is a big reduction in pressure. Though, no carryover was seen during this decrease in pressure.

The black liquor temperature in one of the nozzles was also plotted with respect to time for this specific time period, the graph is presented in Figure 4.18, where the grey arrows indicate when the first and last Voodoo picture showing carryover was observed.

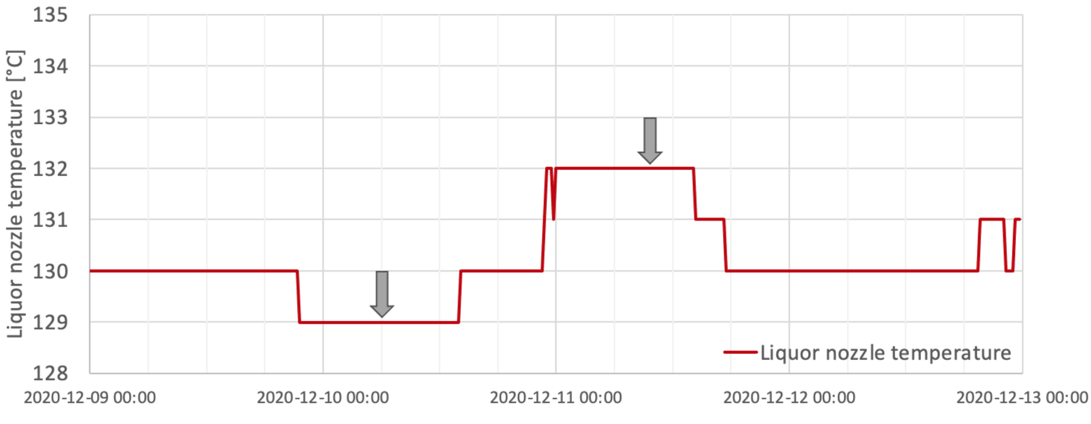


Figure 4.18: A graph showing the variations in temperature of the black liquor in the time period between 2020-12-09 and 2020-12-12. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

As can be seen in Figure 4.18, there is an increase in temperature of 3°C in total during this time period. This increase occurs a few hours after the carryover started to appear. A graph of the dry content variations in this specific time period is shown in Figure 4.19.

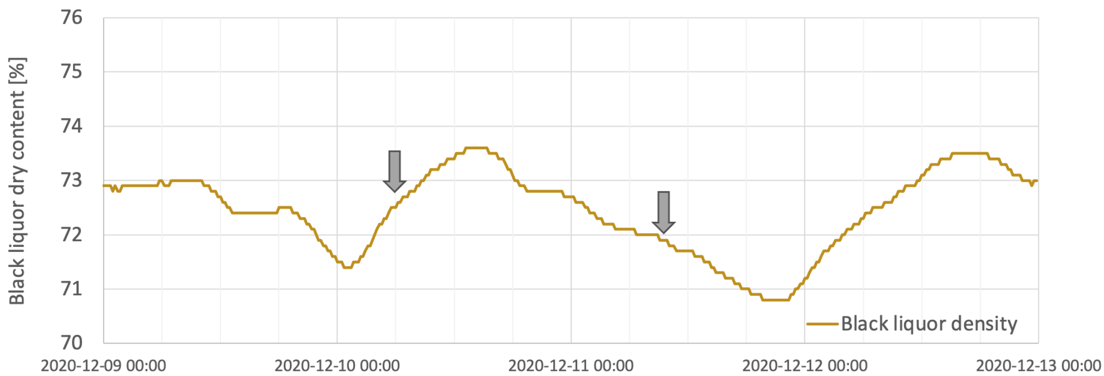


Figure 4.19: A graph showing the variations in dry content of the black liquor in the time period between 2020-12-09 and 2020-12-12. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

In Figure 4.19 it can be seen that there is both an increase and a reduction of dry content during the mentioned time period. The dry content varies between 73.5% to 72.0%.

In this presented example it can be seen that all operational parameters varied a lot within the time period. However, outside the mentioned time period, they are also varying. Be aware that there is another black carryover period that can be seen in these graphs. As noted in Table 4.2, the time period from 2020-12-12 at 09.00 to 2020-12-15 at 05.00 is a black carryover period and this example is further investigated in Appendix B.1.

4.4 Red carryover

The examination of the Voodoo pictures showed that red carryover appeared in two different types, red distinctive smaller dots and larger pink areas. The time periods that had any of these red carryover did not synchronise with any pattern in the waterfall plots. This makes it difficult to predict the red carryover by the use of waterfall plots. However, there was a suspicion that the appearance of red carryover had to do with the primary air flow. This since the primary air flow can drag along material from the bed upwards in the boiler. Hence, this was investigated, along with the other two air flows, since they are closely connected. However, the comparison of red carryover periods with the rate of air flow in the recovery boiler did not synchronise in any pattern. There was red carryover when all flow rates, i.e. the primary, secondary and tertiary were increasing, decreasing or were constant. There was also red carryover when the flow rates did not follow the same trends, i.e. primary increased, secondary was constant and tertiary was decreasing and further combinations. As a result of this, no connection between any air flow rate and the red carryover could be found.

4.5 Unexpected formations in waterfall plots

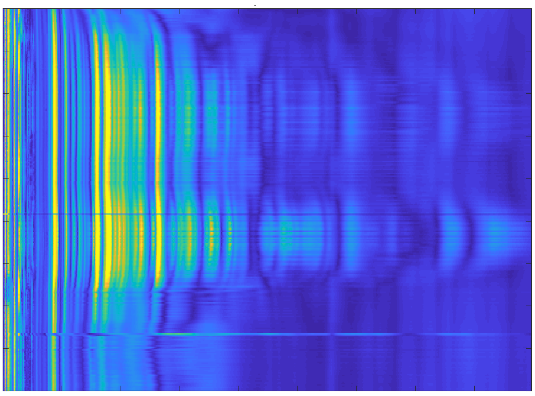


Figure 4.20: An example of the unexpected formation appearing in the waterfall plots during December until the beginning of January. The waterfall plot ranges between 2020-12-12 22.48 to 2020-12-14 21.57.

During several occasions of the data sampling, unexpected formations occurred in the waterfall plots. An example of this pattern is presented in Figure 4.20 and these are the narrow yellow and blue stripes that occurs. These patterns appeared completely random and had no connection to any appearance of the Voodoo pictures. Neither was any connection found to the operational parameters.

One suspicion was that the unexpected patterns had something to do with the weather. This since the strange patterns extended from the beginning of December to the beginning of January, thus during overall colder weather than in November. The time periods of the unexpected formations in the waterfall plots were compared with air temperature collected by weather station of SMHI in Kristinehamn, which is located around 18 km from Nordic paper in Bäckhammar. The weather data for autumn of 2020 can be seen in Appendix E.

No connection could be found between the occasion where unexpected formations in the waterfall plot and the temperature at Kristinehamn's weather station. There were no drastic changes, or unusually low or high temperatures where these formations occurred. Neither was there any unexpected pattern occurring when temperatures in Kristinehamn was deviating severely or were very low or high. Further, throughout January and February, the temperature was even lower than in December and then, no such patterns were observed in the waterfall plots. Hence, the hypothesis that these patterns had anything to do with the weather was discarded.

It could be argued that the inside climate should also have been investigated, since the recovery boiler is placed inside a building. However, since such data was not easily available, this was not considered. Further, the outside temperature should give an indication of if it was reasonable to also look into the inside climate since the walls are thin.

5
Discussion

In this chapter, the previously presented results will be discussed, along with the main sources of error for this thesis work. Suggestions for future work will also be presented.

5.1 Sources of error

Some sources of error have been identified during this thesis work. These include the experimental setup, the method used for the investigation of waterfall plots, Voodoo pictures and the measurements performed at Nordic Paper Bäckhammar, among other things.

An ocular analysis can be a subjective tool when performed by a human, this is a source of error in this thesis. When it comes to the Voodoo pictures, this was partly prevented by creating the scales of the amount of black and red carryover. These scales are presented in Appendix A. Nevertheless, this is still an uncertainty that remains. The waterfall plots were also studied ocular, but these can be confirmed by data analysis. Though, data analysis of that kind is not part of this thesis. Additionally, the waterfall plots have a lot more data points, and makes all reflection upon these more valid.

Regarding the ocular examination of the Voodoo pictures, it could be argued that a picture analysing tool could be used instead of the human eye to estimate how much black and red carryover that was deposited on the sootblowing lance, since this would give more certain results. As a matter of fact, there was a tool of this kind available to calculate the degree of redness in each picture taken of the lance. However, the results from this tool was in the end not very useful due to that it also calculated the degree of redness of the pictures where the lance was inside the boiler, i.e. the picture did not capture the lance at all. This would give deceptive peaks of the degree of redness at some points when the calculated values were plotted over time. Additionally, it was observed that the red carryover had a tendency to fade away over time, probably due to oxidation of the red carryover or other phenomena, which would also make the tool for calculating the degree of redness give deceptive results. Further aspects on the ocular analysis of the red carryover is that it can not be discarded that possible black spots were interfering with detection of red spots in time periods when the waterfall plots indicated that there could be carryover, meaning that there might have been red carryover present, but it was disguised by the black carryover.

When it comes to using a similar tool for calculating the amount of black carryover, this was not something that was available. However, hypothetically, it would be problematic to use such a tool. This due to that in many pictures of the lance, the deposited ash had partly fallen off the lance and left spots where the lance itself was exposed. These spots would look similar to the black carryover and a hypothetical calculating tool would likely mistake these spots for carryover. Hence, in the end, a careful ocular examination of the Voodoo pictures was probably the best way to go together with knowledge of the difference between the dark patterns of the lance beneath the deposits and the actual carryover.

Another aspect on the examination of the Voodoo pictures, already mentioned several times in this report, is that the sootblowing lance only enters the recovery boiler every three to four hours. Hence, there is an uncertainty of up to four hours in when the carryover begins and when it ceases to occur. This is a big source of error when it comes to connecting the carryover periods to the waterfall plots and the operational data. Since the sootblowing lances enter the recovery boiler according to a predetermined schedule, it will become more difficult to overcome the problem of low frequency. Though, there are a few ways to get around this problem to some extent. One option is that the boiler entering frequency of the studied lance could be increased, however, this would result in other parts of the boiler being less frequently cleaned, which is probably not desired. However, it might be possible to make the lance only enter the boiler mechanically, that is that it does not perform sootblowing each time it enters. Another option is installing a second Voodoo camera, capturing a lance nearby the currently studied lance. This way, a doubled insight would be gained in when changes occur in the amount of carryover. However, since it would then not be the exact same lance at the same location that was studied every time, this would also be a source of error, but still give a larger understanding for the phenomena as a whole.

Another aspect to consider is that different people run the recovery boiler. It is possible that the operation can differ slightly, depending on which process operator is working that shift. Even though this should not have a huge impact, it could still be a cause for some variations in the operational data.

When it comes to data sampling, there is always some degree of error in continuous measuring and thus, this is a source of error. One parameter that stands out in this topic is the temperature, which instrument only logs temperature in whole numbers. This makes it more difficult to see small changes in temperature, since the instrument rounds it off to the nearest whole number. Thus, this is a significant source of error in this thesis work since temperature is an important parameter.

5.2 Discussion about results

The first thing to have in mind when reading this section is that the work has mainly covered the periods where black carryover was detected in the Voodoo pictures and further, where it is suspected that flashing occurs.

The reason that flashing is suspected is mainly because of the presence of carryover at some occasions. Flashing changes the phase of the liquid and therefore the black liquor velocity increases. Droplet formation is affected by velocity and carryover originates from smaller droplets entrained in the up-going air supply. Thus, the possible smaller droplets from flashing might be seen as carryover on a sootblowing lance. Hence, the conclusion that it will have an impact that can cause carryover is not far fetched.

The time periods when black carryover can be found are also notable in the waterfall plots. Hence, there are some indications that the black carryover can be detected by merely observing the waterfall plots. However, the areas in the waterfall plots that indicate the same pattern as when the carryover can be seen, does not always result in Voodoo pictures with black carryover, see Section 4.1. Despite the fact that the black carryover cannot be seen every time there is a dampened pattern in the waterfall plot, it can still be suspected that flashing occurs during these time periods. This, since flashing does not necessarily have to result in carryover.

Furthermore, it is also possible that the addition of ash in the black liquor flow will affect the outcome of the waterfall plot since this addition will probably impact several parameters. These parameters can be the density, viscosity, amount of combustible material, swelling and the boiling point due to different combinations of inorganic salts. Although the amount of recovered ash might have an effect on the black liquor and the waterfall plots, it is difficult to measure this since it is unknown how much ash that is added from the ESP-filters at Nordic Paper Bäckhammar. This is because it involves a simple mechanical addition in which no measurements are taken.

Since flashing results in a phase change of the fluid that will greatly change the properties of it, the Acospectors would have the ability to detect it. In other words, this reasoning would confirm that flashing could be possible to see in the waterfall plots and that the phenomena occurs. However, this requires that the unexpected patterns, presented in Section 4.5, are not appearing, since these patterns tend to eliminate all other patterns. Further, regarding the flashing, it would be preferable to get any sort of confirmation of the appearance of flashing in all the suspected areas since the Voodoo pictures are the only verification of carryover in the process. On the other hand, it can be discussed whether flashing without any carryover causes any problems in the heat convection area, since no carryover could be detected, and thus, no fouling occurring.

Some of the areas with black carryover was believed to be the outcome of a rapid increase of both air and black liquor flow rate. This, since it may take some time for the other settings in the recovery boiler to be adjusted to the sudden changes. However, it has later come up to discussion whether this is a correct conclusion or not, since also during some of these this periods, a dampened area can be found in the waterfall plots. It is the same dampened pattern that can be found in the waterfall plot during the suspected flashing periods. Another proposed cause of these periods is that if flashing occurs, the volume flow would increase rapidly and greatly since gas occupies more volume than liquid. Therefore, since the flow rate of black liquor is measured in litre per second, this value could be misleading if, firstly, the measuring unit is calibrated to a liquid, and secondly the flow is supposed to be of pure liquid. If it is believed that the flow rate of black liquor is liquid, when it is not, then other settings in the recovery boiler might be adjusted wrongly.

An additional reason for the varying amount of carryover is the phenomenon of swelling. Since the degree of swelling can vary with the content of black liquor, then it is reasonable to include the swelling as a feature that might impact the amount of carryover. Consequently, the result of swelling will be a reduction in density and then, the black liquor droplets will more easily be entrained in the up-going air flow. Since the origin of softwood trees change both geographically and by species, and the amount of recycled ashes from the ESP-filters is not measured, then the content of the black liquor will be difficult to determine.

Further on, from the operational data it can be seen that pressure, temperature and dry content varies a lot, and if the operating condition is close to the boiling point, a small change in either of them could initiate the flashing. The boiling point is dependent on the dry content of black liquor and the boiling point will rise with increased dry content and will be reduced with an increased water content. The dry content might then be the parameter that drives the black liquor flow into the event of flashing. Furthermore, if either the pressure drops or the temperature rises, this can also cause the state of the fluid to be above the boiling point. Though, no single parameter has been found to be the cause of the suspected flashing. Additionally, since the content of black liquor is unique to every process, it can be difficult to predict the boiling point. Even within the same process the black liquor content can change both due to the preceding process at the mill but also due to seasonal changes in the wood.

Some of the examples from the results presented in Section 4.3 indicate that there are changes in at least one parameter during the period of carryover with suspected flashing. Though, none of the examples shows the same behaviour as another example. Despite that some of the parameters varies a lot outside the mentioned periods with carryover, this does not give an outcome of carryover. However flashing is, as mentioned, a very rapid behaviour and dependent on many different parameters. This can cause some problems when trying to detect it in the boiler by this method. This since the flashing can begin and then end in between when the sootblowing is performed by the studied lance.

The red carryover was not considered in this thesis work to a large extent due to two reasons. Firstly, the red carryover was not of tremendous amounts when it occurred and sometimes it was barely visible. Secondly, it was found that the occurrence of red carryover did not match with any patterns of the waterfall plots in the same way as the black carryover did. Thus, it would be difficult to discover the red carryover from the waterfall plot. However, there might be some possibility that since there was such a small amount of red carryover generally, it could be difficult to detect it. Hence, there might have been patterns connected to red carryover in the waterfall plots that overlap in time with these occasions. If such periods existed, they were, as mentioned, difficult to notice.

5.3 Future work

Several limitations and decisions were made during this thesis work. Therefore, there are a lot of aspects not considered in this thesis that are interesting to investigate further in future studies in this subject area.

When it comes to connecting occasions with carryover to operational data, the selection of parameters that were examined were limited to the ones that were most believed to cause carryover. For a more extensive study, it could be preferable to also investigate other operational parameters, such as concentration of certain species in the flue gases, certain salts in black liquor and the amount of recirculated ash.

Half way through this thesis work, the study was limited to focus mainly on the black carryover, since its occurrence seemed to match better with the patterns in the waterfall plots than the red carryover. Hence, a further study could look deeper into the red carryover to see if it can be connected to any operational parameters. Further aspects regarding the red carryover is that two different types of red carryover was detected during this thesis work, small distinct red dots and larger pink spots. It would be interesting to look deeper into if there is any difference in when these two types of red carryover occurs and if they can be connected to any operational parameter.

Similarly for the black carryover, in the studying of the Voodoo pictures, the black patterns of carryover have consisted of either smaller black dots or larger dark areas. It was also detected that different periods had different amounts of black carryover. No further investigation was done in this to find any reason for the difference in the patterns. However, this could be interesting to investigate, if a cause can be found.

The only occasions considered when examining operational data was the time periods when black carryover was observed on the sootblowing lances. However, it would be beneficial to also perform further studies on more, future occasions when the dampened patterns in the waterfall plots could be matched with a carryover period. This would validate the results even more. Further, flashing can happen without carryover appearing and vice versa. Hence, one aspect in future work in this area is to investigate all time periods with dampened intensity patterns in the waterfall plots and not only the occasions with carryover.

As mentioned, some unexpected patterns appeared in the waterfall plots at several occasions, that could not be connected to any specific operational parameter or anything else. Thus, for future work within this area it would be beneficial to look deeper into this. This is important since, when these patterns appear, it is not possible to use the waterfall plots to discover periods with dampened patterns.

One hypothesis in this thesis was that a reduction of temperature might prevent flashing or stop ongoing flashing. Due to the Covid-19 pandemic, it was not possible to test this in this thesis work. However, this is n important recommendation for future work within this subject. A targeted experiment of this kind would mean that the waterfall plots are to be monitored carefully, to be able to discover dampened patterns in an early stage. Once these patterns appear, the temperature is to be reduced with approximately 2°C. If the dampened patterns then disappear in the waterfall plots, and this temperature reduction does not affect any other parts of the recovery boiler in a non-preferable way, this can be a good way to prevent or stop ongoing flashing. This type of targeted experiment has to be performed several times in order to establish a certain result.

6
Conclusion

Based on the results and discussion, some conclusions could be made and these are presented in a bullet point list below. The conclusions partly concern the hypothesis that flashing can be seen when using active acoustic spectroscopy and also if any operational parameter was the cause of carryover.

- **Dampened patterns:** The dampened patterns in the waterfall plots are suspected to indicate flashing. However, further investigations and experiments has to be made to fully confirm this.
- **Detecting flashing:** If the dampened areas can be confirmed to indicate flashing, then the waterfall plot can be used to detect flashing in an early stage.
- **Cause of flashing:** No specific operational parameter alone was found to be the cause of flashing. Though, temperature, pressure and dry content are strongly believed to be involved.
- **Experiment suggestion:** Possible future work includes reducing the black liquor temperature if the waterfall plots indicate flashing.
- **Extended examination:** For future work, investigate operational data for all periods of dampened pattern in the waterfall plot for further understanding.
- **Ocular analysis:** Carefulness is important when performing an ocular investigation of the Voodoo pictures, since it can be difficult to detect red carryover and sometimes difficult to distinguish the black carryover from the sootblowing lance.
- **Unexpected patterns:** The unexpected patterns in the waterfall plot was not found to correspond to any specific operational parameter that was investigated and other reasons were not found.

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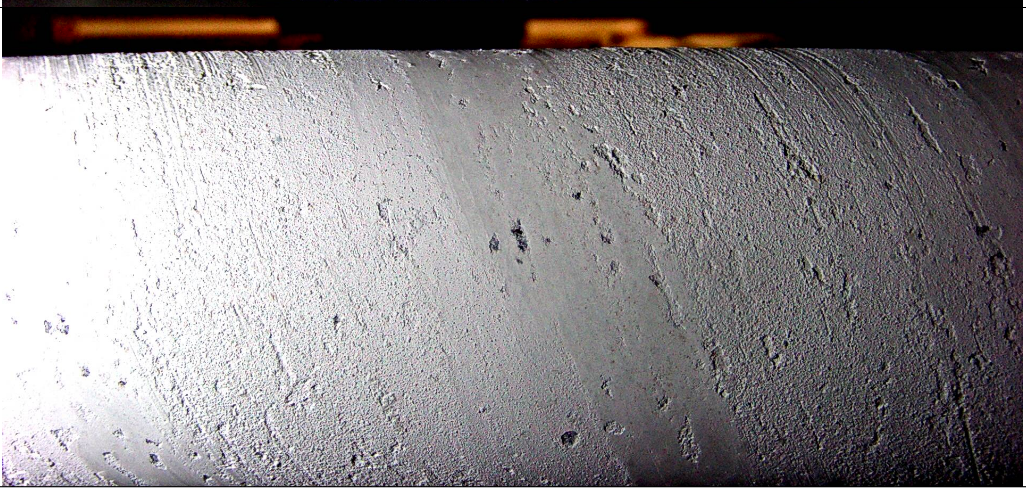
A

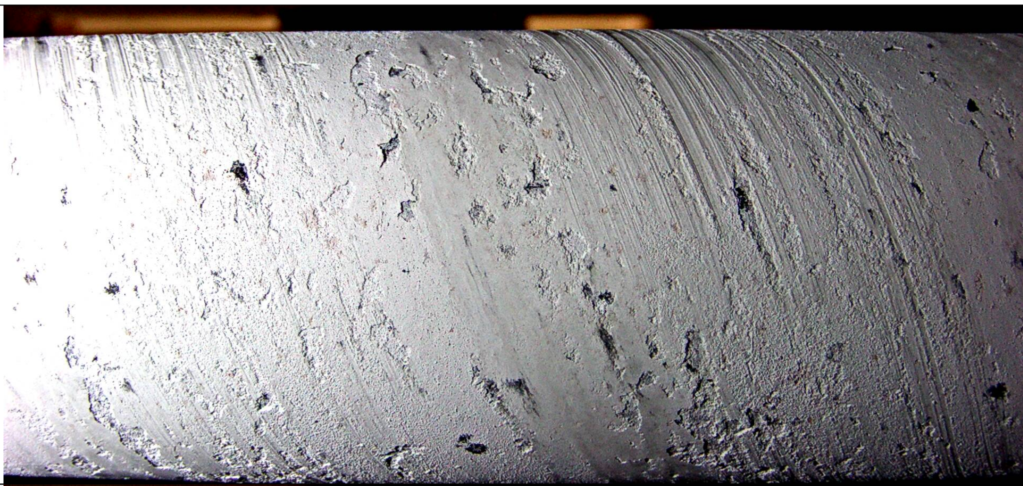
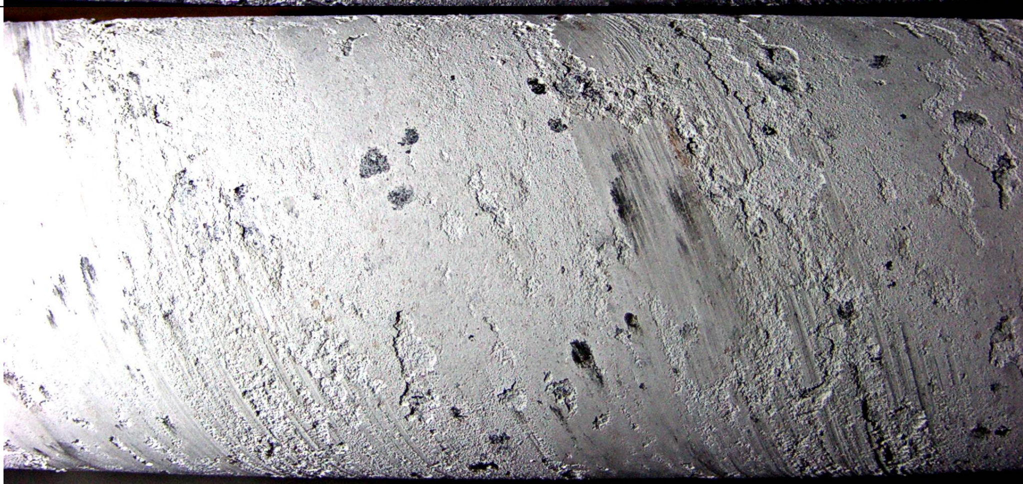
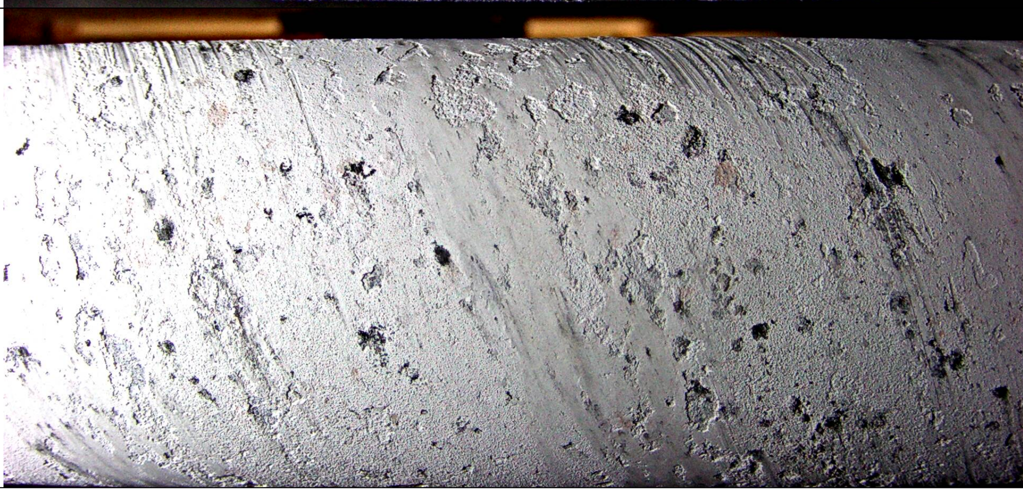
Carryover scales

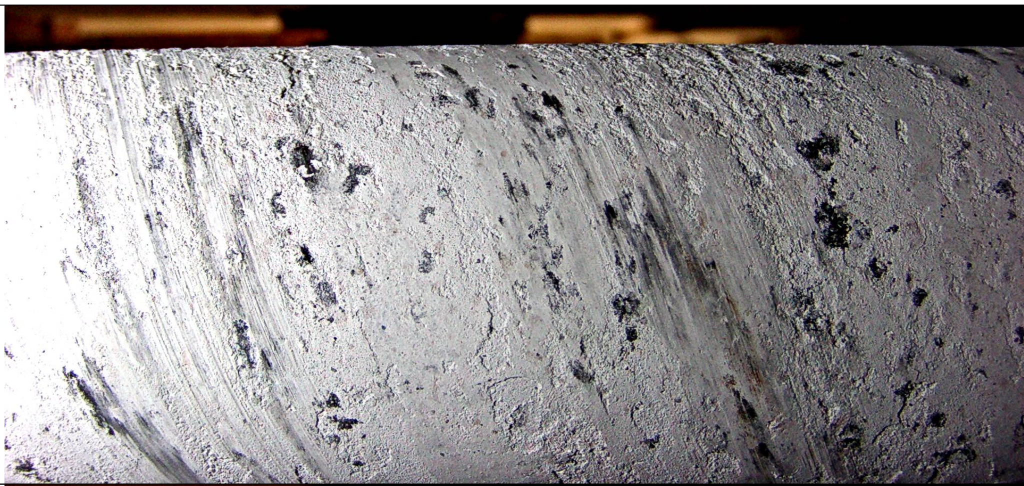
A.1 Reference scale for black carryover

In this section, the scale used for the ocular analysis of black carryover on a sootblowing lance is presented in Table A.1. The scales are created specifically for this project and are based on a subjective analysis of the amount of carryover present at Nordic Paper Bäckhammar. Since all recovery boilers are unique, these scales might not be valid to use for other mills than the one in Bäckhammar.

Table A.1: A scale from 0-6 of the amount of black carryover on a sootblowing lance.

0	
1	

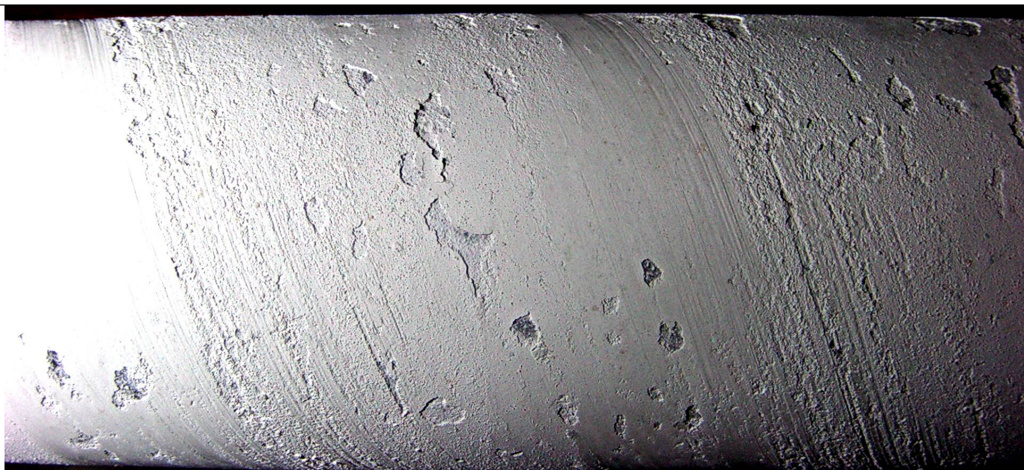
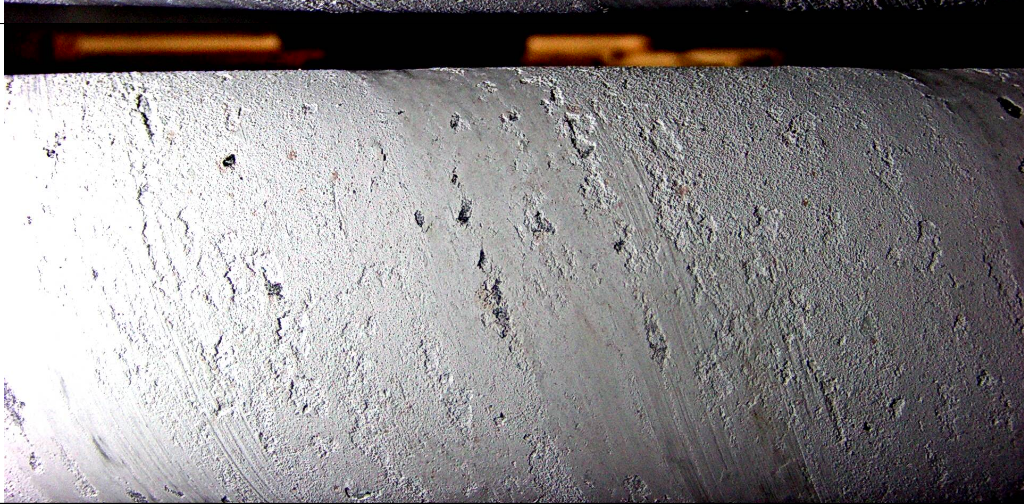
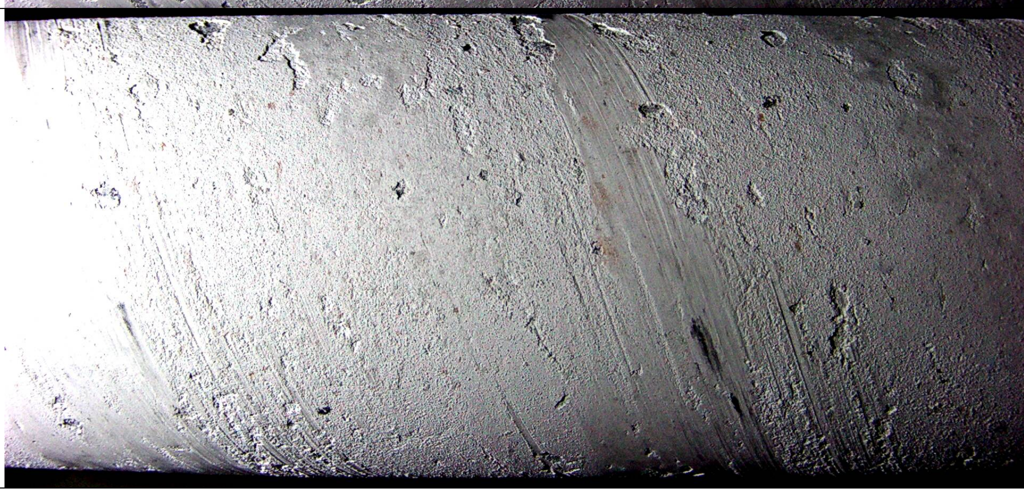
2	
3	
4	

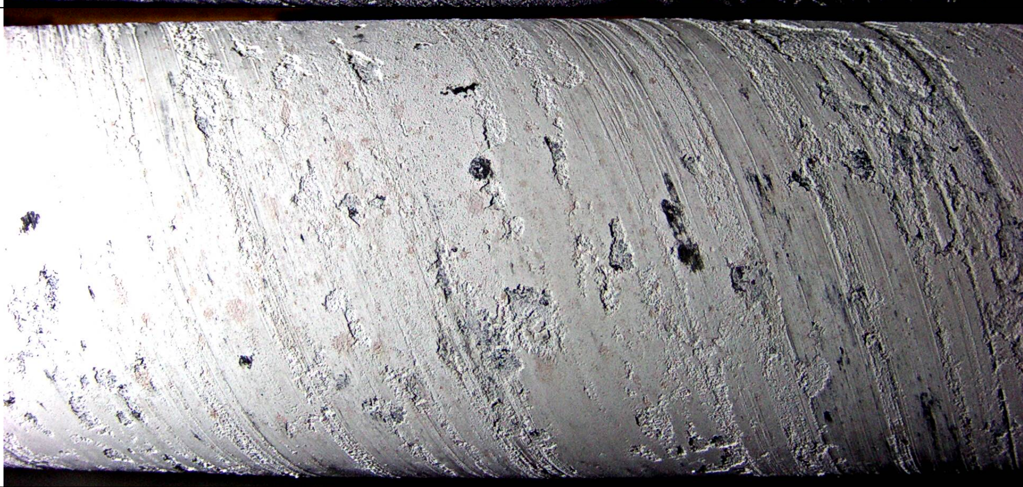
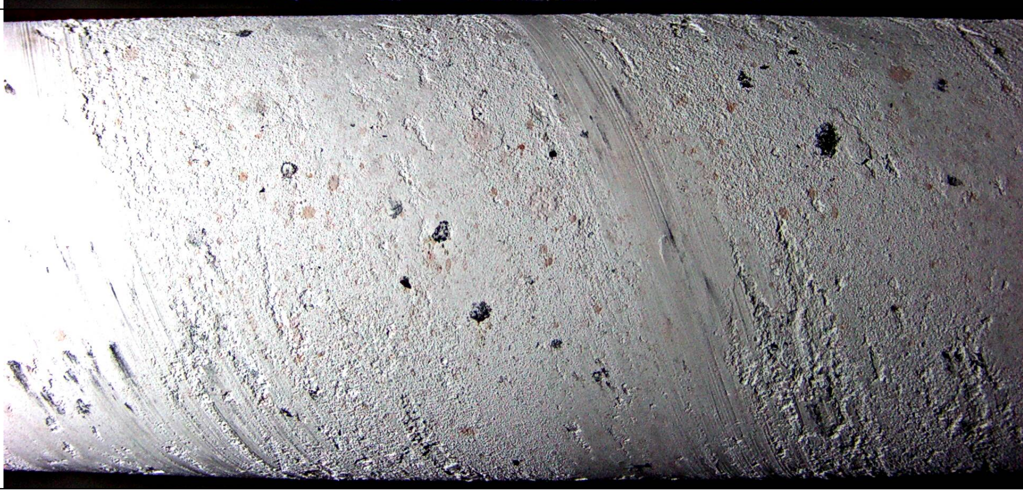
5	
6	

A.2 Reference scale for red carryover

In this section, the scale used for the ocular analysis of red carryover on a sootblowing lance is presented in Table A.2.

Table A.2: A scale from 0-5 of the amount of red carryover on a sootblowing lance.

0	
1	
2	

3	
4	
5	

B

Supporting examples

In the results in this report, several examples are presented, indicating different things. In this chapter, further examples are presented to support the ones previously presented.

B.1 Example I

In Section 4.2.1, an example was presented, indicating that a drastically increased air and/or black liquor flow rate occurred simultaneously as the carryover period. In this section, a similar example is presented, indicating the same thing.

The time period in this example is between 2020-12-12 at around 09.00 and 2020-12-15 at around 05.00. During this time period, carryover is present after a drastically increased air and/or black liquor flow rate. Figure B.1 presents a Voodoo picture of the soot-blowing lance, taken 2020-12-13 at 03.37. It shows an example of the amount of carryover that was present during this period in time. The waterfall plot showing the mentioned time period with carryover is presented in Figure B.2.

Figure B.1: A Voodoo picture, taken 2020-12-13 at 03.37, showing the presence of carryover during the time period 2020-12-12 09.00 to 2020-12-15 05.00.

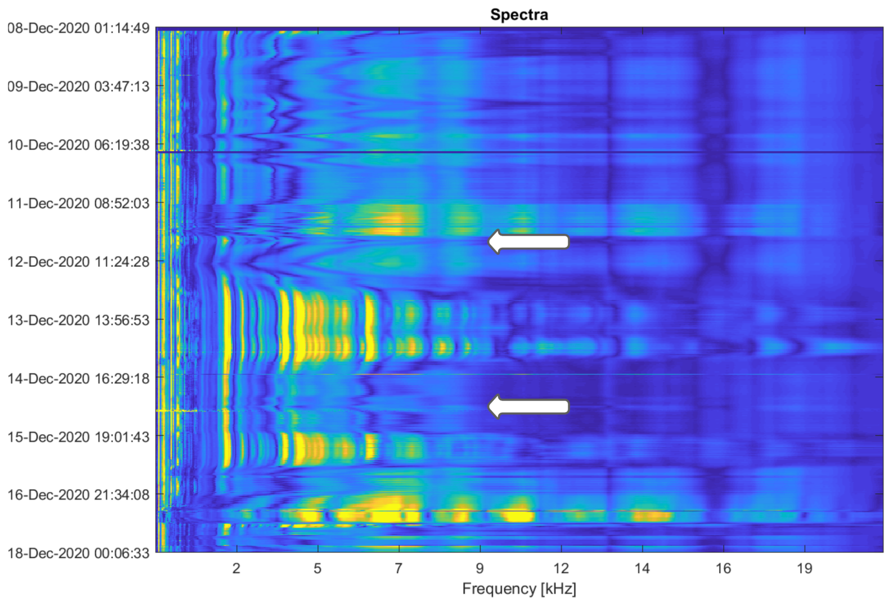


Figure B.2: A waterfall plot from ACO HBL 03 showing the time period between 2020-12-08 at 01.14 to 2020-12-18 at 00.06, when black carryover was detected. The white arrows indicate when the carryover started and stopped according to the Voodoo pictures.

The white arrows in Figure B.2 indicate when the carryover started and stopped according to the Voodoo pictures. It can be seen that this specific waterfall plot shows some unexpected patterns, which does not seem to overlap with the complete time period of carryover. This type of unexpected pattern is examined further in Section 4.5. Further, the total air flow rate and the black liquor flow rate were both plotted with respect to time and the graph is presented in Figure B.3.

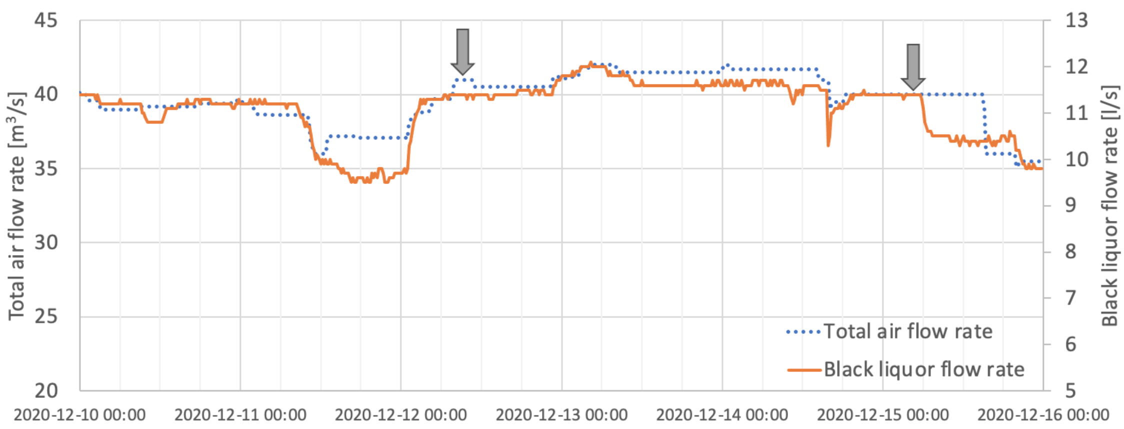


Figure B.3: Total air and black liquor flow rate plotted with respect to time during the time period 2020-12-10 - 2020-12-15. The grey arrows indicate when time period with carryover starts and stops.

In Figure B.3 the blue dotted line is the total air flow rate in m^3/s and the orange line is the black liquor flow rate in l/s. The grey arrows indicate when the carryover starts and ceases to appear. It can be seen that prior to the starting point of the carryover, both the plotted flows increases in a short time. The last time black carryover was seen in the Voodoo pictures, the flow rate of air and black liquor was still high. Similar to the example presented in Section 4.2.1, there is an error margin of a few hours for these points in time. This depends on that the sootblowing lances only enters the recovery boiler every three to four hours.

To conclude, from this example it can be seen that a carryover period is occurring short after a drastically increased air and black liquor flow rate.

B.2 Example II

In Section 4.2, two examples considering the air and black liquor flow rate were presented. Example 1 indicated that a time period with carryover would happen simultaneously or short after a drastically increased air and black liquor flow rate. Further, the previously presented Example I supported this result. However, Example 2 in Section 4.2.2 instead indicated that this is not true for all cases, as in that example, no carryover was present after a drastically increased air and black liquor flow rate. In this Example II, a time period of generally high flow rates of both air and black liquor is considered. Figure B.4 shows an example of the appearance of the sootblowing lance during this time period and as can be seen, no carryover is present. In Figure B.5 the waterfall plot considering the same time period can be seen.

Figure B.4: A Voodoo picture showing the absence of black carryover 2020-12-24 at 08.40.

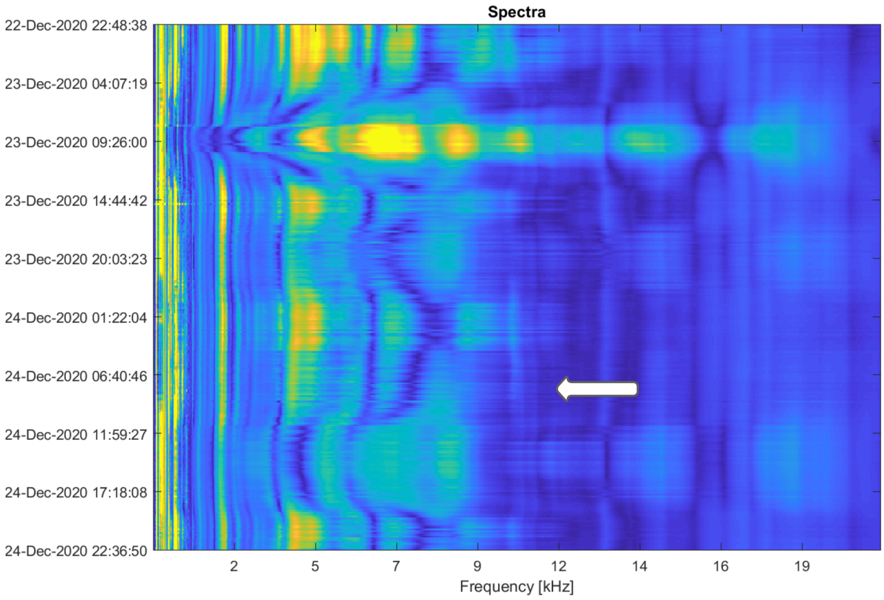


Figure B.5: A waterfall plot from ACO HBL 03 showing the time period between 2020-12-22 at 22.48 to 2020-12-24 at 22.36, when no black carryover was detected. The white arrow indicates the time of the Voodoo picture.

As can be seen in Figure B.5 the waterfall plot show a pattern of unexpected formations, dampened pattern and irregular formations. Further, the air and black liquor flow rates of time period between 2020-12-22 to 2020-12-25 can be seen in Figure B.6

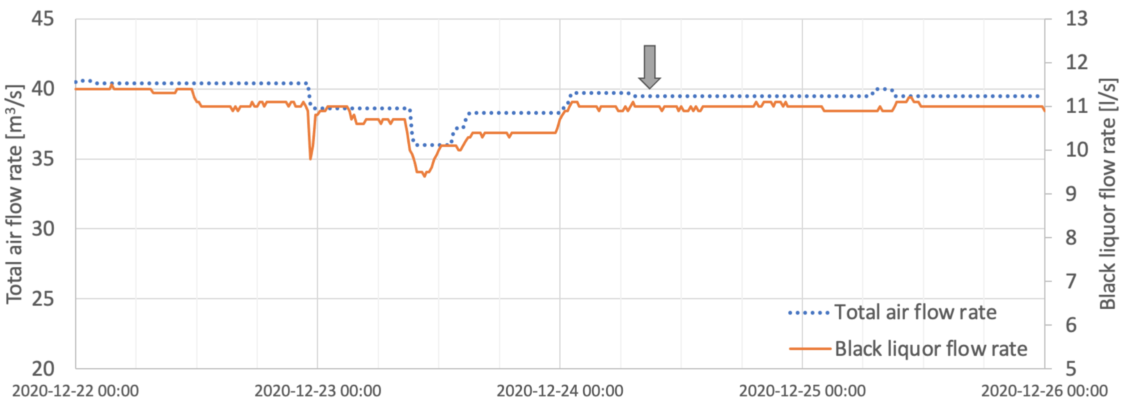


Figure B.6: Flow rate plotted with respect to time during the time period between 2020-12-22 to 2020-12-25. The grey arrow indicates when the Voodoo picture was taken.

It can be seen in Figure B.6 that the flow rates of air and black liquor were high during the time when the Voodoo picture was taken. The black liquor flow rate is around 11 l/s and around 40 m^3/s for the air flow rate. This example shows the result that high flow rates does not always give black carryover.

B.3 Example III

In Section 4.3, other operational parameters than the air and black liquor flow rates were investigated. These parameters were the pressure, temperature and dry content of the black liquor. In this section, a further example is presented when black carryover was present and the mentioned three parameters were investigated.

The time period considered is between 2021-01-01 at around 11.00 to 2021-01-02 at around 15.00. An example of the amount of carryover present at the studied sootblowing lance during this time period is presented in Figure B.7. The specific Voodoo picture is taken 2021-01-02 at 02.00.

Figure B.7: A Voodoo picture, taken 2021-01-02 at 02.00, showing the presence of carryover during the time period 2021-01-01 11.00 to 2020-12-02 15.00.

The waterfall plot from ACO HBL 04 corresponding to the same time period is presented in Figure B.8. The white arrows indicate when the carryover was first and last observed on the sootblowing lance in the Voodoo pictures.

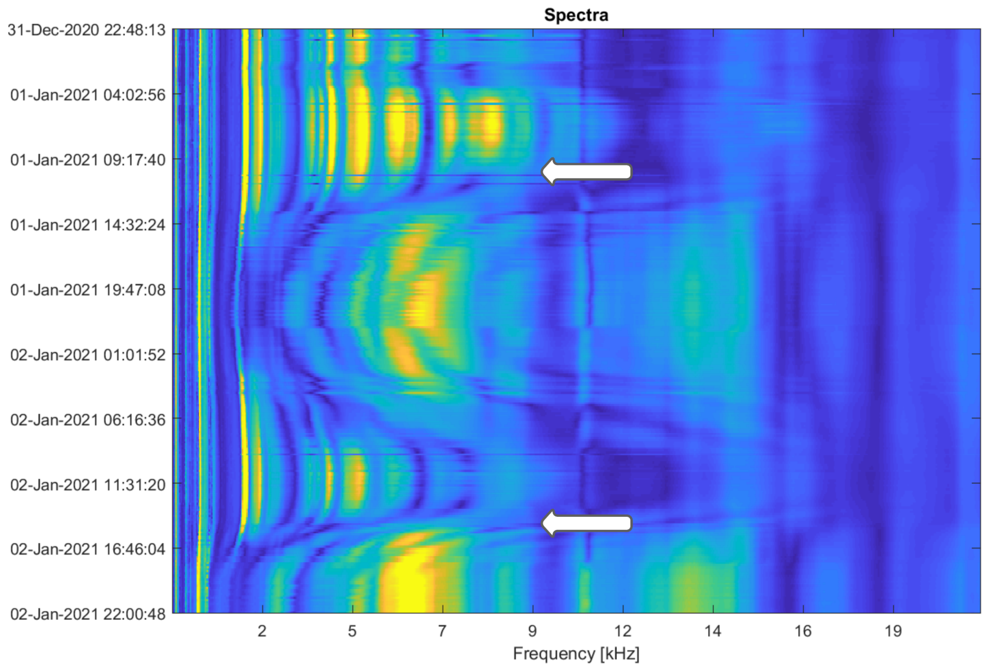


Figure B.8: Waterfall plot from ACO HBL 04 during the time period between 2020-12-31 22.48 to 2021-01-01 22.00. The white arrows indicate when the first and last Voodoo picture showing black carryover was observed.

In Figure B.8, a pattern of more thin vertical lines can be seen. These patterns occurred occasionally during this thesis work and could not be connected to any operational parameters. This was further elaborated in Section 4.5. A graph of the black liquor nozzle pressure plotted with respect to time during this specific period is presented in Figure B.9.

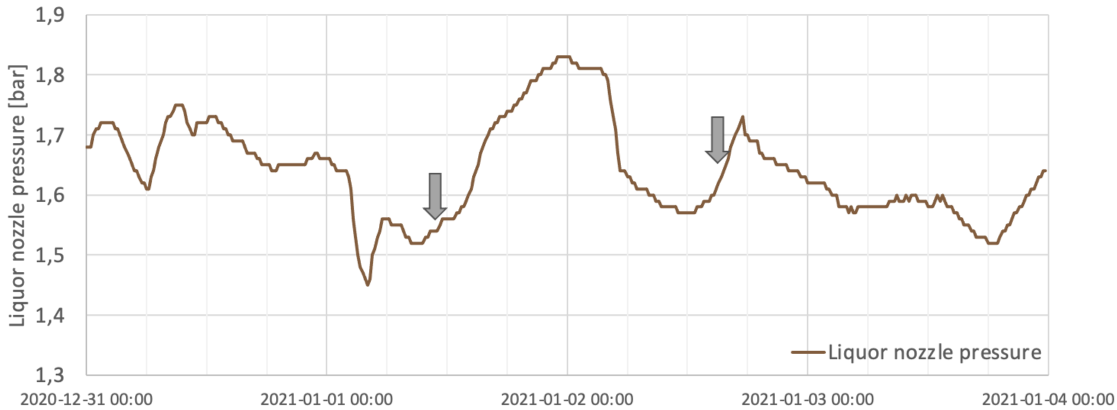


Figure B.9: A graph showing the variations in pressure in one of the black liquor nozzles in the time period between 2020-12-31 and 2021-01-03. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

In Figure B.9, both a major pressure increase and decrease of approximately 0.27 bar can be observed. The pressure is clearly varying during this time period.

The black liquor temperature in the nozzles was also plotted with respect to time during this period, the graph can be seen in Figure B.10.

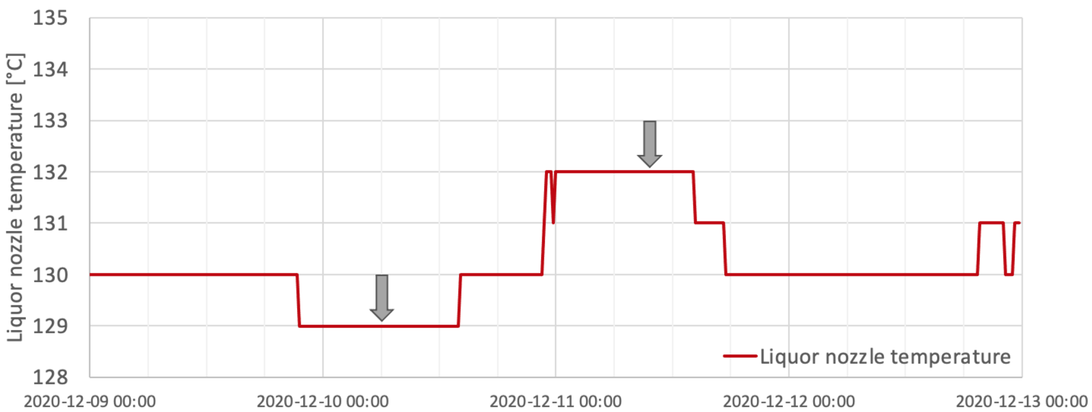


Figure B.10: A graph showing the variations in temperature of the black liquor in the time period between 2020-12-31 and 2021-01-03. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

As can be seen in Figure B.10 there is an increase of the black liquor temperature of 1°C during this period in time. However, this increase occurs in the middle of this period, i.e. the carryover had already started to appear when the temperature increased. The dry content variations during this period in time can be seen in the graph presented in Figure B.11.

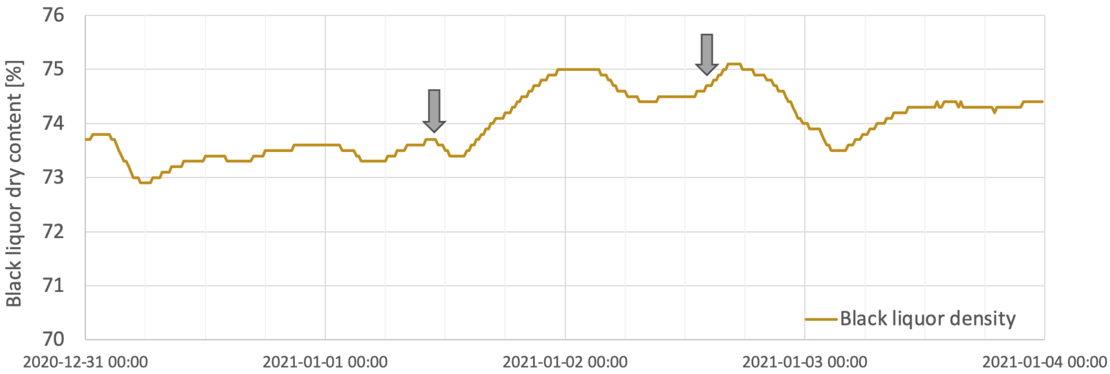


Figure B.11: A graph showing the variations in dry content of the black liquor in the time period between 2020-12-31 and 2021-01-03. The arrows indicate when the first and last Voodoo picture showing black carryover was observed.

In Figure B.11, it can be observed that the dry content varies during the mentioned time period, but overall, it increases. To conclude, the results from this example show no specific parameter that seems to be the cause of the carryover.

C
Operational data

Since operational data covers a wide range of dates, this appendix has been dedicated to easier view a longer time frame of some of the operational parameters. The parameters that can be seen are the following:

- Black liquor flow rate
- Total air flow rate
- Primary, secondary, tertiary air flow rate
- Black liquor nozzle pressure
- Black liquor temperature in nozzles
- Black liquor dry content

One date to be careful about is 2020-12-17. During this date, there was no black liquor combusted in the recovery boiler due to operational issues at the plant. Thus, some values during this period in time may be deviating more than ”normal”.

November 2020

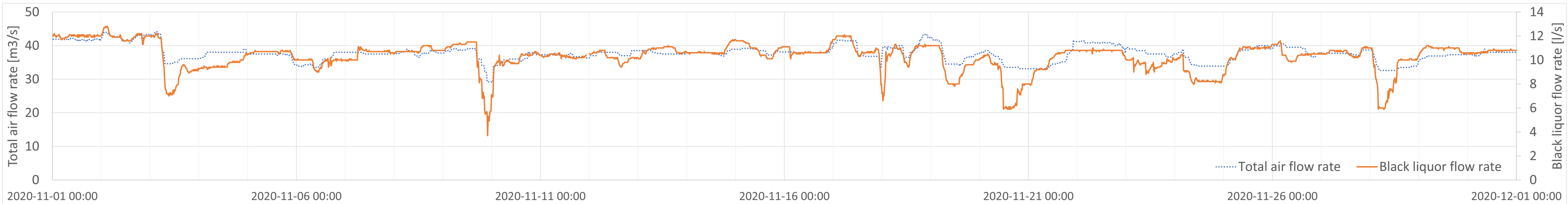


Figure C.1: Operational data for total air flow rate and black liquor flow rate in November.

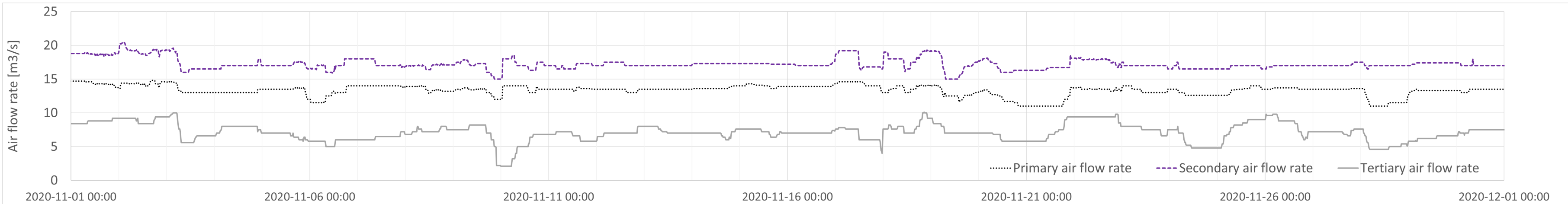


Figure C.2: Operational data for each of the three levels of air flow rates in November. Primary, secondary, and tertiary air flow rates can be seen.

Figure C.3: Operational data for pressure in the liquor nozzles in November.

November 2020 continued

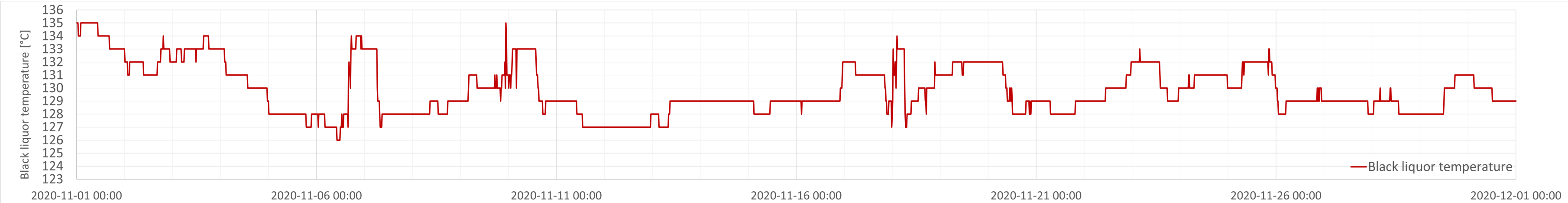


Figure C.4: Operational data for temperature in black liquor nozzles in November.

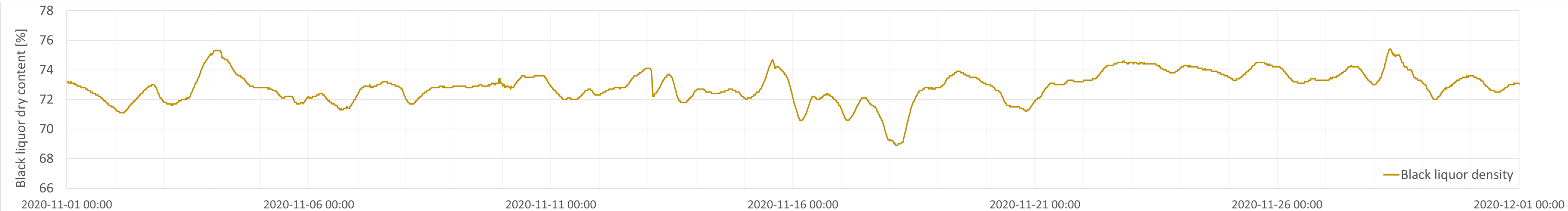


Figure C.5: Operational data for the dry content of the black liquor in November.

December 2020

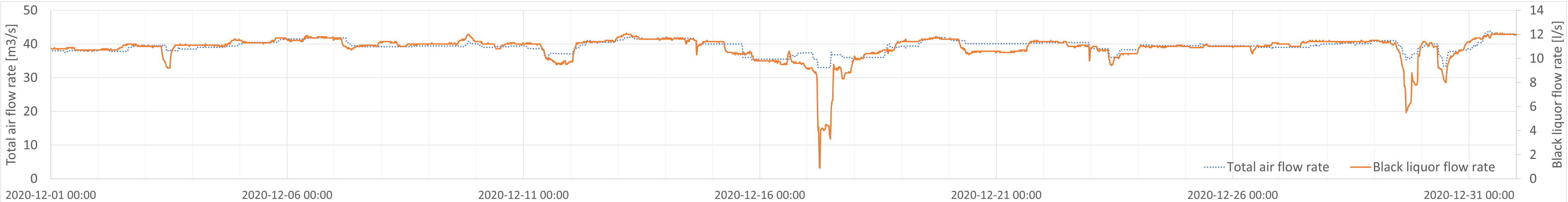


Figure C.6: Operational data for total air flow rate and black liquor flow rate in December.

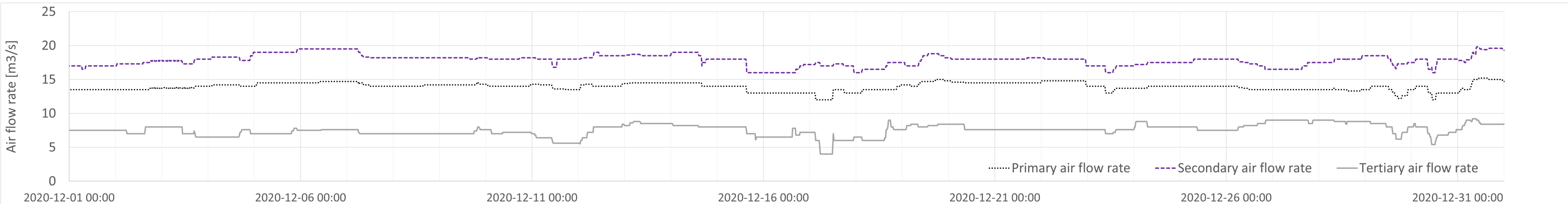


Figure C.7: Operational data for each of the three levels of air flow rates in December. Primary, secondary, and tertiary air flow rates can be seen.

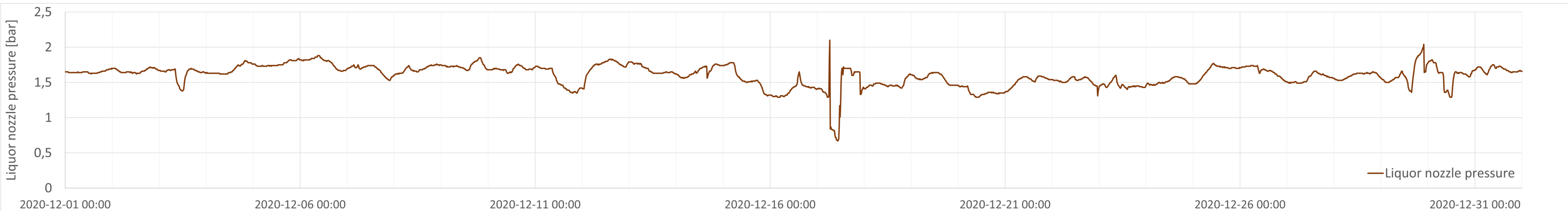


Figure C.8: Operational data for pressure in the liquor nozzles in December.

December 2020 continued

Figure C.9: Operational data for temperature in black liquor nozzles in December.

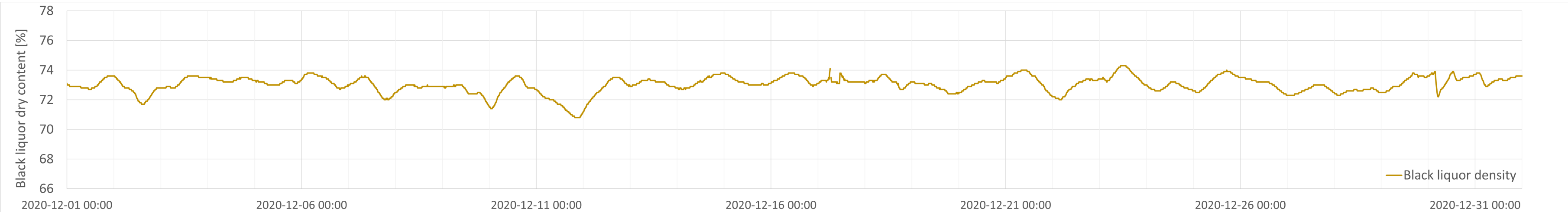


Figure C.10: Operational data for the dry content of the black liquor in December.

January 2021

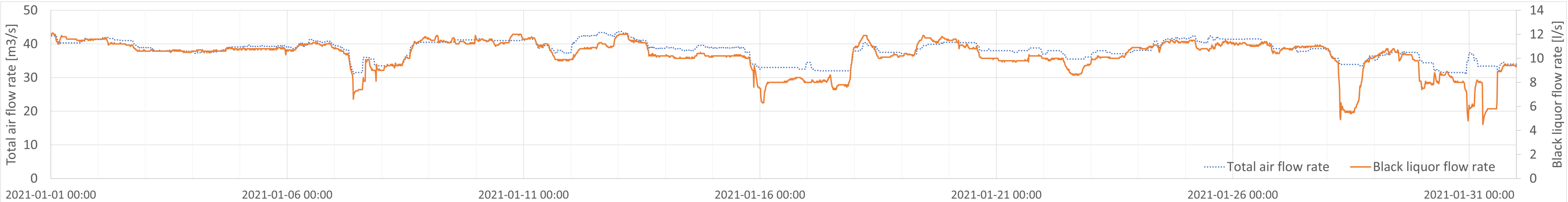


Figure C.11: Operational data for total air flow rate and black liquor flow rate in January.

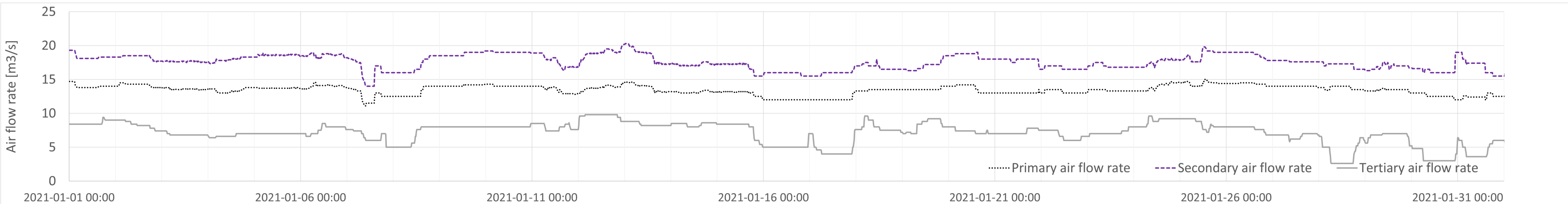


Figure C.12: Operational data for each of the three levels of air flow rates in January. Primary, secondary, and tertiary air flow rates can be seen.

Figure C.13: Operational data for pressure in the liquor nozzles in January.

January 2021 continued

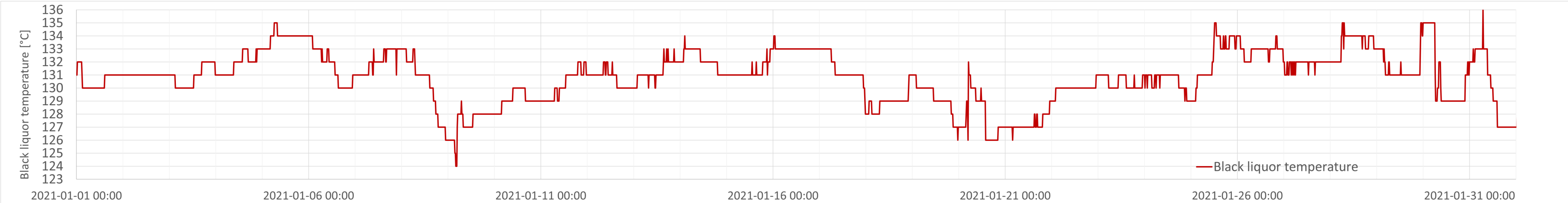


Figure C.14: Operational data for temperature in black liquor nozzles in January.

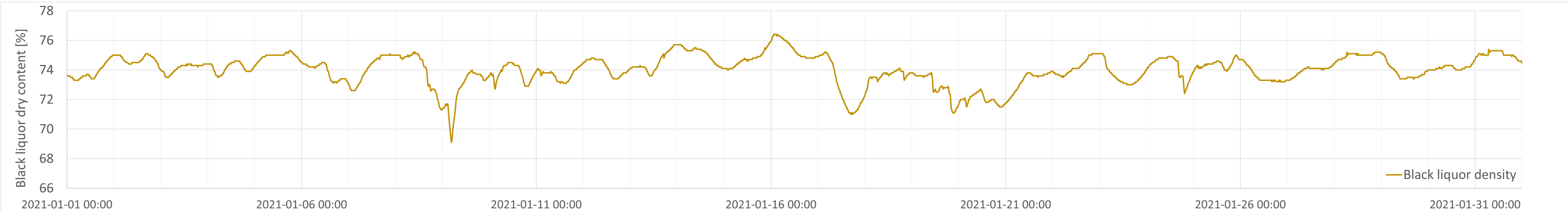


Figure C.15: Operational data for the dry content of the black liquor in January.

February 2021

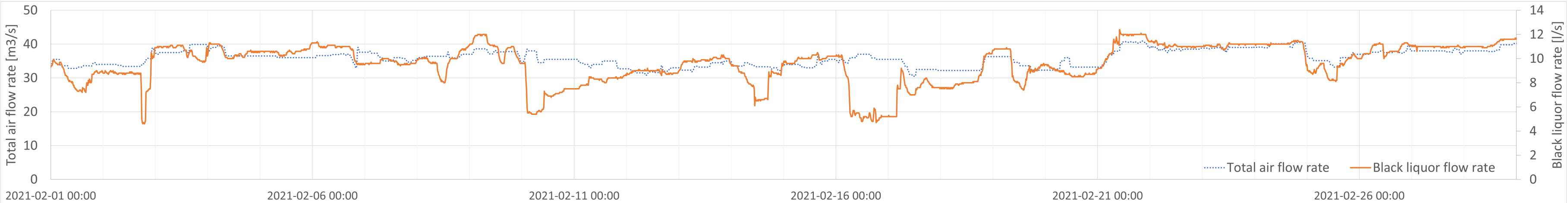


Figure C.16: Operational data for total air flow rate and black liquor flow rate in February.

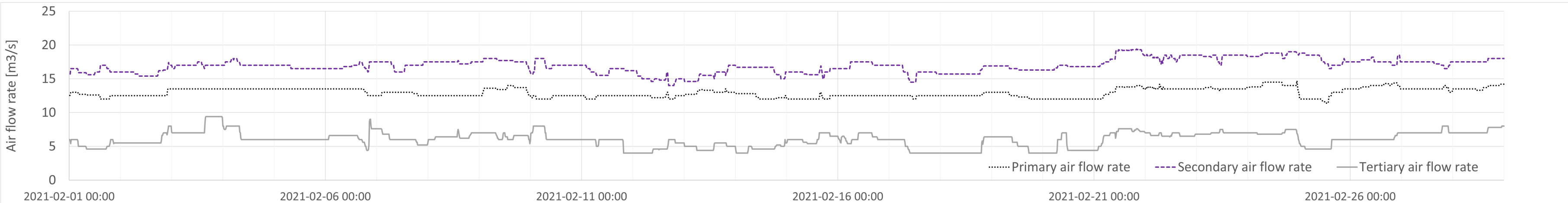


Figure C.17: Operational data for each of the three levels of air flow rates in February. Primary, secondary, and tertiary air flow rates can be seen.

Figure C.18: Operational data for pressure in the liquor nozzles in February.

February 2021 continued

Figure C.19: Operational data for temperature in black liquor nozzles in February.

Figure C.20: Operational data for the dry content of the black liquor in February.

D

Black carryover periods

In Table D.1, all the time periods when black carryover was observed on the sootblowing lances appear, along with an investigation of the operational parameters nozzle pressure, black liquor temperature and dry content. Further, a range of the valuation of the amount of black carryover during the time period is presented. These valuations are based on the reference scales presented in Appendix A.

Table D.1: Points in time when black carryover occurred at the sootblowing lance along with an indicator on how the nozzle pressure and black liquor temperature changed around the specific time interval given. Further, a range of the valuation of the amount of black carryover during the time period is presented.

Carryover starting	**Carryover stopping**	**Nozzle pressure**	**Black liquor temperature**	**Dry content**	**Valuation range**
2020-11-21 at 10	2020-11-22 at 22	Varies between 1.48-1.69 bar	Increases from 128-131°C	Increases from 73-74.4%	1-5
2020-11-29 at 00	2020-11-29 at 07	Varies between 1.57-1.64 bar	Stable at 128°C	Decreases from 73.2-72%	1-3
2020-12-01 at 00	2020-12-01 at 14	Stable, varies between 1.63-1.65 bar	Increases from 129-130°C	Stable at 72.8-72.9%	1-3
2020-12-02 at 17	2020-12-03 at 10	Varies between 1.43-1.69 bar	Varies between 129-130°C	Increases from 72-73.2%	1-5
2020-12-03 at 17	2020-12-06 at 07	Varies between 1.62-1.84 bar	Varies between 129-132°C	Varies between 73-73.7%	2-6
2020-12-10 at 06	2020-12-11 at 10	Quite stable, varies between 1.59-1.1.74 bar	Increases from 129-132°C	Varies between 71.8-73.5%	1-6
2020-12-12 at 09	2020-12-15 at 05	Varies between 1.56-1.82 bar	Varies between 130-135°C	Varies between 72.7-73.7%	1-4
2020-12-21 at 18	2020-12-22 at 09	Varies between 1.5-1.59 bar	Varies between 130-131°C	Varies between 72-73.1%	2-5

Continued on next page

Continued from previous page					
Carryover starting	**Carryover stopping**	**Nozzle pressure**	**Black liquor temperature**	**Dry content**	**Valuation range**
2020-12-31 at 02	2020-12-31 at 19	Varies between 1.65-1.71 bar	Varies between 131-134°C	Varies between 72.9-73.7%	3-6
2021-01-01 at 11	2021-01-02 at 15	Varies between 1.56-1.83 bar	Increases from 130-131°C	Varies between 73.4-75%	2-4
2021-01-04 at 12	2021-01-07 at 01	Varies between 1.48-1.7 bar	Varies between 130-135°C	Varies between 72.7-75.2%	1-4
2021-01-08 at 15	2021-01-11 at 16	Varies between 1.6-1.92 bar	Varies between 124-131°C	Strong variations between 69.1-75.1%	2-6
2021-01-12 at 12	2021-01-13 at 09	Varies between 1.69-1.99 bar	Varies between 130-132°C	Varies between 73.4-74.2%	2-4
2021-01-18 at 04	2021-01-18 at 08	Varies between 1.8-1.93 bar	Varies between 128-129°C	Varies between 73.2-73.5%	1-2
2021-01-19 at 11	2021-01-20 at 18	Decreases from 2-1.39 bar	Varies between 126-132°C	Varies between 71.2-72.6%	1-3
2021-01-21 at 18	2021-01-21 at 22	Stable at 1.44 bar, but a peak of 1.64 bar just before this period	Increases from 127-128°C	Increases from 73.6-73.8%	3
2021-01-24 at 06	2021-01-25 at 09	Varies between 1.55-1.91 bar	Varies between 129-131°C	Varies between 72.4-74.7%	1-4
2021-01-25 at 23	2021-01-26 at 04	Decreases from 1.73-1.7 bar	Varies between 132-134°C	Decreases from 74.7-74.2%	3-6
2021-02-02 at 23	2021-02-04 at 06	Varies between 1.41-1.65 bar	Varies between 126-129°C	Varies between 72.1-73.5%	2-4
2021-02-13 at 05	2021-02-13 at 19	Varies between 1.36-1.49	Varies between 128-132°C	Varies between 74.2-74.8%	1-3

E
SMHI

As presented in Section 4.5, the time periods in which the unexpected patterns appeared in the waterfall plots were compared to the temperature at the weather station in Kristinehamn. Figure E.1 presents a graph of how the temperature varied in Kristinehamn between 2020-09-01 and 2021-01-07. The red ellipses indicate when the unexpected patterns in the waterfall plots appeared.

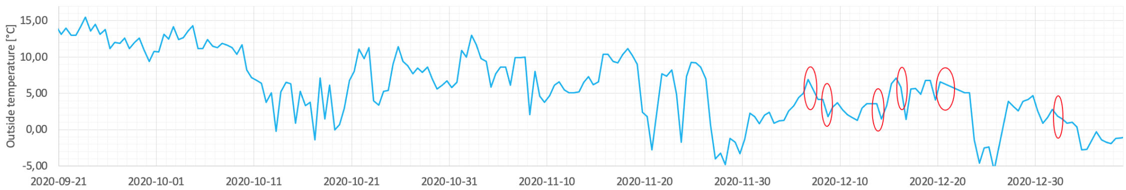


Figure E.1: A graph of how the temperature varied between 2020-09-01 and 2021-01-07. The red ellipses indicates when the unexpected formations appeared in the waterfall plots.

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