LUT University
School of Energy Systems
Energy Technology

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UTILIZATION OF VISUAL ANALYSIS IN RECOVERY BOILERS

Examiners: Professor, D.Sc (Tech.) Esa Vakkilainen
Research Director, D.Sc (Tech.) Juha Kaikko
Instructor: M.Sc. Heikki Lappalainen

ABSTRACT

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Utilization of visual analysis in recovery boilers

Master's Thesis

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80 pages, 44 figures and 4 tables

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Keywords: Recovery boiler, visual analysis, black liquor, char bed, smelt flow, carryover

The aim of this thesis was to study potential of visual analysis in recovery boilers. Performance of recovery boilers is measured with traditional ways, which are measurements of temperature, volume flow or pressure. Still there are places that are not accessible by traditional measure methods. In this thesis, the aim is to study the possibilities of visual analysis to expand knowledge of the recovery boilers' operation. If something can be seen, it can be measured by a computer-based visual analysis system. That system can measures things from images or videos and feedback is a numerical value, which can be recorded for later review.

In this thesis is studied the images and video footages of black liquor spraying, char beds, smelt spouts and carryover. Footages for research were from a small Finnish recovery boiler. Many phenomena were discovered in the studied material.

It is possible to see phenomena from the recovery boiler that have not been measured or monitored in more detail before. With visual analysis system, the things that are seen in the recovery boiler are easier to study with other process data. That could be a great help for understanding operation of recovery boilers. Also unwanted situations, like uneven black liquor spray or too fast growing char bed can be detected sooner with the visual analysis system. With proper visual analysis system could be possible to ensure more stable and safety recovery boilers.

TIIVISTELMÄ

Lappeenrannan-Lahden Teknillinen Yliopisto LUT
School of Energy Systems
Energiatekniikan koulutusohjelma

Markus Lahtinen

Visuaalisen analyysin hyödyntäminen soodakattiloissa

Diplomityö

2019

80 sivua, 44 kuvaa ja 4 taulukkoa

Tarkastajat: Professori, TkT Esa Vakkilainen
Tutkimusjohtaja, TkT Juha Kaikko
Ohjaaja: Diplomi-insinööri Heikki Lappalainen

Hakusanat: Soodakattila, visuaalinen analyysi, musta lipeä, kiintoainepeti, sulavirta

Tämän diplomityön tavoitteena oli tutkia visuaalisen analyysin mahdollisuuksia soodakattilassa. Soodakattilan suorituskykyä on mitattu perinteisin keinoin, joita ovat lämpötila-, virtaus- tai painemittaukset. Silti on olemassa paikkoja, joita ei ole mahdollista mitata perinteisin keinoin. Tässä työssä tavoitteena on tutkia visuaalisen analyysin mahdollisuuksia lisäämään tietoa soodakattilan toiminnasta. Jos jotain voidaan nähdä, se voidaan mitata visuaalisen analyysin järjestelmällä. Kyseinen järjestelmä voi mitata asioita kuvista tai videoista ja antaa takaisin numeerisia arvoja, jotka voidaan tallentaa myöhempää tarkastelua varten.

Tässä työssä on tutkittu kuvia ja video materiaalia musta lipeä ruiskuista, kiintoainepedistä, sulakouruista ja carryoverista. Materiaali tutkimukseen oli pienestä suomalaisesta soodakattilasta. Useita ilmiöitä löydettiin tutkitusta materiaalista.

Soodakattilasta on mahdollista nähdä ilmiöitä, joita ei ole aikaisemmin mitattu tai seurattu tarkasti. Asioita, joita mitataan visuaalisen analyysin avulla, voidaan helposti tutkia muun prosessidatan kanssa. Siitä voisi olla suuri apua soodakattiloiden toiminnan ymmärtämisessä. Myös epätoivotut tilanteen, kuten epätasainen mustalipeä ruisku tai liian nopeasti kasvava kiintoainepeti voidaan havaita aikaisemmin visuaalisen analyysin avulla. Kunnollisen visuaalisen analyysin avulla voitaisiin mahdollisesti varmistaa vakaampi ja turvallisempi soodakattila.

ALKUSANAT

Tämä diplomityö on viimeinen askel syksyllä 2013 alkaneeseen matkaan. Olin silloin 20-vuotias juuri armeijan suorittanut nuorukainen ja olin jostain kumman syystä päättänyt lähteä Lappeenrantaan opiskelemaan sähkötekniikkaa. En ollut ikinä käynyt Lappeenrannassa, saati Etelä-Karjalassa, ja sen takia muutto uudelle paikkakunnalle tuntui hypyltä tuntemattomaan. Kuitenkin ensimmäisten viikkojen jälkeen paikka tuntui uudelta kodilta. Haluan kiittää siitä Lappeenrannan Teknillistä Yliopistoa ja erityisesti fuksiviikoista lähtien mukana kulkeneita kavereita. Erityiskiitos Äidille ja Isälle, joiden luokse pääsin (ja pääsee edelleen) karkuun opiskelijaelämän hektisyyttä.

Vuodet kuluivat ja matkaan mahtui monenmoista. Ylämäkiä, alamäkiä, paljon uusia tuttavuuksia, hienoja muistoja, alanvaihto energiatekniikkaan, mahtavia kesätöitä ja nyt viimeisimpänä diplomityö Andritzille. Haluan kiittää työni ohjaajaa Heikki Lappalaista ja tarkastajana toimivaa Esa Vakkilaista. Teiltä sain tarpeen vaatiessa hyviä vinkkejä ja uusia näkökulmia työn tekemiseen.

Matka jatkuu kohti uusia haasteita.

Varkaudessa 25.10.2019
Markus Lahtinen

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SYMBOLS AND ABBREVITATIONS

Roman

T	temperature	[ºC]

Subscript

$_{DSC}$	dry solid content
e	excess

Abbreviations

C	carbon
CNCG	concentrated non-condensable gases
CO	carbon monoxide
CO_2	carbon dioxide
DCS	distributed control system
DNCG	diluted non-condensable gases
ESP	electrostatic precipitator
H_2O	water
H_2S	hydrogen sulfide
HHV	higher heating value
IIoT	Industrial Internet of Things
ISP	intermediate size particles
KOH	potassium hydroxide
NaCl	sodium chloride
$NaCO_3$	sodium carbonate
NaOH	sodium hydroxide
Na_2S	sodium sulfide
Na_2SO_4	sodium sulfate
NO_x	nitrogen oxides
OOT	Optimum Operating Temperature
PDA	Phase Doppler Anemometry
PLC	programmable logic control
SO_2	sulfur dioxide
TRS	total reduced sulfur

1 INTRODUCTION

A Recovery boiler is the powerhouse of the kraft pulp mill. It uses black liquor as fuel. Black liquor is the byproduct of the pulp cooking process. Functions of the recovery boiler are to produce energy for the pulp mill and be part of liquor cycle. The liquor cycle is a process where chemicals used in the cooking is recycled to be usable again. Due this double purpose of the recovery boiler, it is one of the most important component in the kraft pulp mill.

Efficiency of the recovery boiler is measured by produced energy and a reduction rate of sodium sulfate to sodium sulfide. Design parameters limit how much black liquor the boiler can handle and how much combustion air can be fed. Conditions of the recovery boiler is measured in many ways. There are temperature sensors, volume flow measurements, pressure sensors and many other traditional measure methods. Still there are places that are not accessible by traditional measure methods. In this thesis, the aim is to study and explore the possibilities of visual analysis to expand knowledge of the recovery boilers' operation.

Term *Visual analysis* means using machine vision to analyze image or video footage. The computing power of current computers enables near real-time analysis. An analysis tool is possible teach to find specific colors or shape from the footage and give back numeric value. If something can be seen, it can be analyzed and measured.

The research questions are as follows:

1. What are things that can be measured visually?
2. What new visual analysis can offer for recovery boiler operation and research?
3. What are benefits of visual analysis in a recovery boiler?

In the literature part of this thesis it is focused on theory behind things that have been studied in the research part of this thesis. In the second chapter is explained the main components of the recovery boiler. Properties of black liquor and how they affect spraying and fouling of the recovery boiler is described in the third chapter. In the fourth chapter is explained the functions of the char bed and how they affect many things in the recovery boiler.

In the fifth chapter, which is the research part of this thesis, is shown and explained possibilities of the visual analysis in recovery boilers. Researched objects were black liquor spraying, char bed, smelt spouts and carryover. Each object is researched with real images from real recovery boiler. Point of view is to show things that may be difficult or impossible to detect other than visually. In addition, the benefits of seeing these things have been considered.

This thesis has been done in the order of ANDRITZ. ANDRITZ is an international technology group and it was founded in Austria in 1852. It is globally leading supplier of plants, equipment, and services for hydropower stations, the pulp and paper industry, the metalworking and steel industries, and for solid/liquid separation in the municipal and industrial sectors. ANDRITZ operates over 280 sites worldwide and has a staff approximately 29,600. Digitalization and Industrial Internet of Things (IIoT) are part of future pulp mills. Visual analysis in recovery boilers is one part of this product development. (Andritz 2019.)

2 RECOVERY BOILER

Pulp production can be separated by what method is used to defibrate wood fibers. In mechanical pulp production defibration is achieved using mechanical stressing and heating wood material. In a chemi-mechanical method, wood chips are defibrated mechanically after short chemical treatment. In a chemical method, pulp is produced by cooking wood chips with heat and chemicals, which remove fiber binding lignin. Sulfate process is the most common chemical pulp process and it uses chemical mix called white liquor in the cooking process. The chemicals are too expensive to be used once so it is more profitable to recycle them. For that is developed liquor cycle, which is presented in Figure 1. The recovery boiler is part of the liquor cycle.

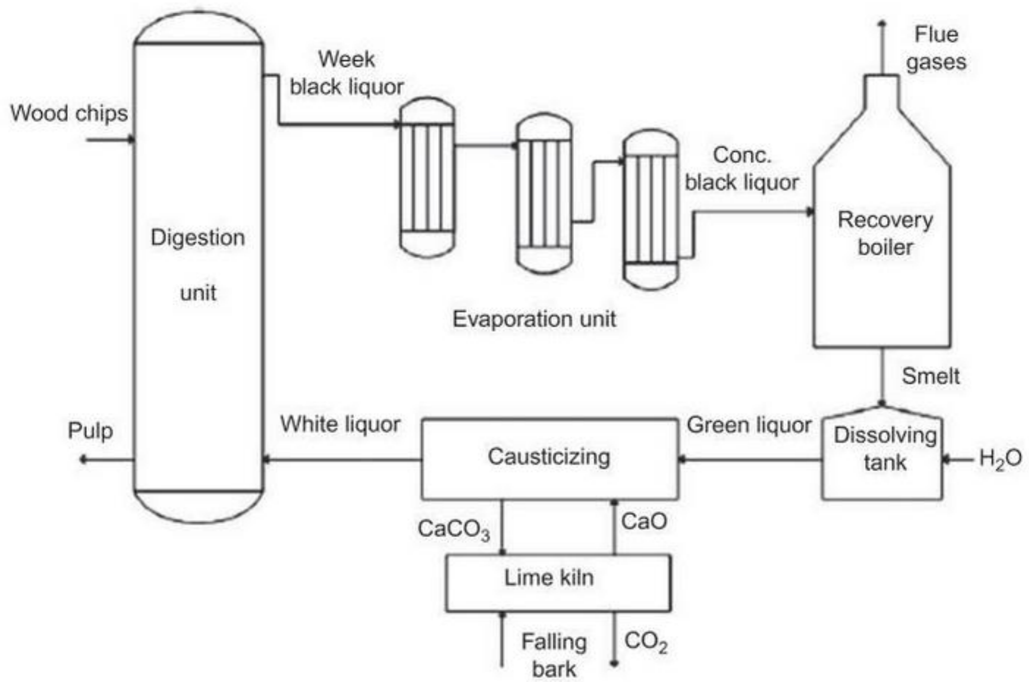

Figure 1. Liquor cycle in a kraft pulp mill. (Bajpai 2017, 12)

In the digestion unit wood chips are cooked with chemical to produce pulp. Digestion unit uses chemicals and heat to remove fiber binding lignin that chips defibrate easily. Chemical that cooking process uses is white liquor, which is mixture of sodium hydroxide (NaOH) and sodium sulfide (Na_2S). During cooking, lignin is separated from the fibers of the wood and blended to chemicals. That compound is called weak black liquor. The water content of the weak black liquor is too high for the recovery boiler so it has to go through an evaporation unit. Dry solid content for black liquor is above 75%. (Knowpulp 2017.)

Concentrated black liquor is burned in the recovery boiler. The recovery boiler has several unit processes (Vakkilainen 2005, 1-2):

1. Combustion of black liquor and use released energy to produce process steam and electricity.
2. Reduction of inorganic sulfur compound to sodium sulfide
3. Production of molten inorganic flow of mainly sodium carbonate and sodium sulfide and dissolution of said flow to weak white liquor to produce green liquor

Recovery boiler products smelt, which flows to dissolving tank. In the tank, smelt is dissolved to weak white liquor, which produces green liquor. Last step for cooking chemical is causticizing. In that process, green liquor is converted to white liquor with lime compounds. After that, white liquor is ready to be used in the digestion unit again.

2.1 History

First recovery technology is from late 1800s and it concentrated on chemical recovery. Step by step heat economy got better and in the 1930s there was couple recovery boiler design that had a lot of common with modern recovery boilers. Those common ideas are that the black liquor is sprayed as a droplet, a char bed is controlled by primary air and smelt is removed from a furnace by spouts. (Vakkilainen 2014, 19-21.) Modern recovery boilers can be compared by black liquor firing capacity. Used unit is total dry solid per day (tds/d). Capacities of the recovery boilers have increased significantly during last decades. During the 1970s capacities of boilers were around 1000 tds/d. In the 1980s capacities increased to 2000 tds/d and it was common opinion that the recovery boilers had reached their maximum capacity. First so called XL size recovery boiler started up in Finland in 1990. It has black liquor firing capacity of 2600 tds/s, high dry solid firing, concentrated non condensable gas (CNCG) combustion and bio sludge combustion. At the end of the 1990s maximum capacity had increased to 4000 td/s. In the year 2004 first so called XXL size 5500 td/s boiler was delivered to China and it reached 6000 td/s peak load already in 2005. In the year 2010 two 7000 td/s boiler started up in Indonesia and China. During four decades capacities have increased 11.7 times, floor area is 7.9 times bigger, furnace total height is 2.1 times taller and furnace is 16.9 time bigger. (Haaga 2014, 96.) At this moment the world's largest recovery boiler is in Indonesia at Ogan Komering Ilir (OKI). The boiler is designed and supplied by Andritz and has total capacity of 12000 tds/d. With that capacity recovery boiler could easily supply power to a European city of one million inhabitants with output of 10000 – 12000 MWh per day. It produces steam that is 515 C at 110 bar, which are also world's top steam data. (Andritz 2018, 50.)

2.2 Structure

Structure of the modern recovery boiler is presented in Figure 2. All modern recovery boilers have same kind features. Recovery boiler has two main sections: a furnace section and a convective heat transfer section. The furnace is unique in comparison with traditional power boilers. Heat transfer section and back end of the recovery boiler are generally similar to other types of boilers.

Floor and walls of the furnace are made of tubes. Used material is different depending in the circumstances. Floor tubes must withstand corrosive smelt and hot conditions. For that most common tube material is Sanicro 38 type composite material. Wall tubes must withstand hot conditions and for that good material is either 304L composite or carbon steel. (Vakkilainen 2005, 10-14.) Behind the furnace are smelt spouts, which way smelt flows to dissolving tank. Spouts have to withstand hot and corrosive smelt, so they need constant cooling and intermittent replacement. Combusting air is usually injected in three stages. Primary air level is at the same level as char bed, secondary air is above those and tertiary air is at the top and ensures that volatiles burn properly. Above secondary air, there are liquor guns that inject black liquor to the furnace. Each wall has at least one liquor gun. Organic matter of black liquor burns and release heat energy. Inorganic matter ends up to the char bed or as small particles along the flue gases.

Recovery boilers generate energy in the same way as traditional power plant boilers. By heating water to steam and using that steam as process steam or producing electricity by running it through a turbine. The boiler contains many heat exchangers that use heat from furnace or flue gas as energy source. Circulating water is preheated in the economizer, which is last heat exchanger before flue gas exits the boiler. Steam is generated on tube walls by heat released from combustion and in the generating bank by heat from flue gas. Steam is superheated in the superheater, which is after the furnace. Steam drum is located above the furnace and its function is to distribute the circulating water to the heat exchangers and separate the steam from the circulation water. Older recovery boilers usually have two steam drums, but modern boiler has only one. One steam drum is easier to control and there are much less leakages. (Adams 1997a, 13.)

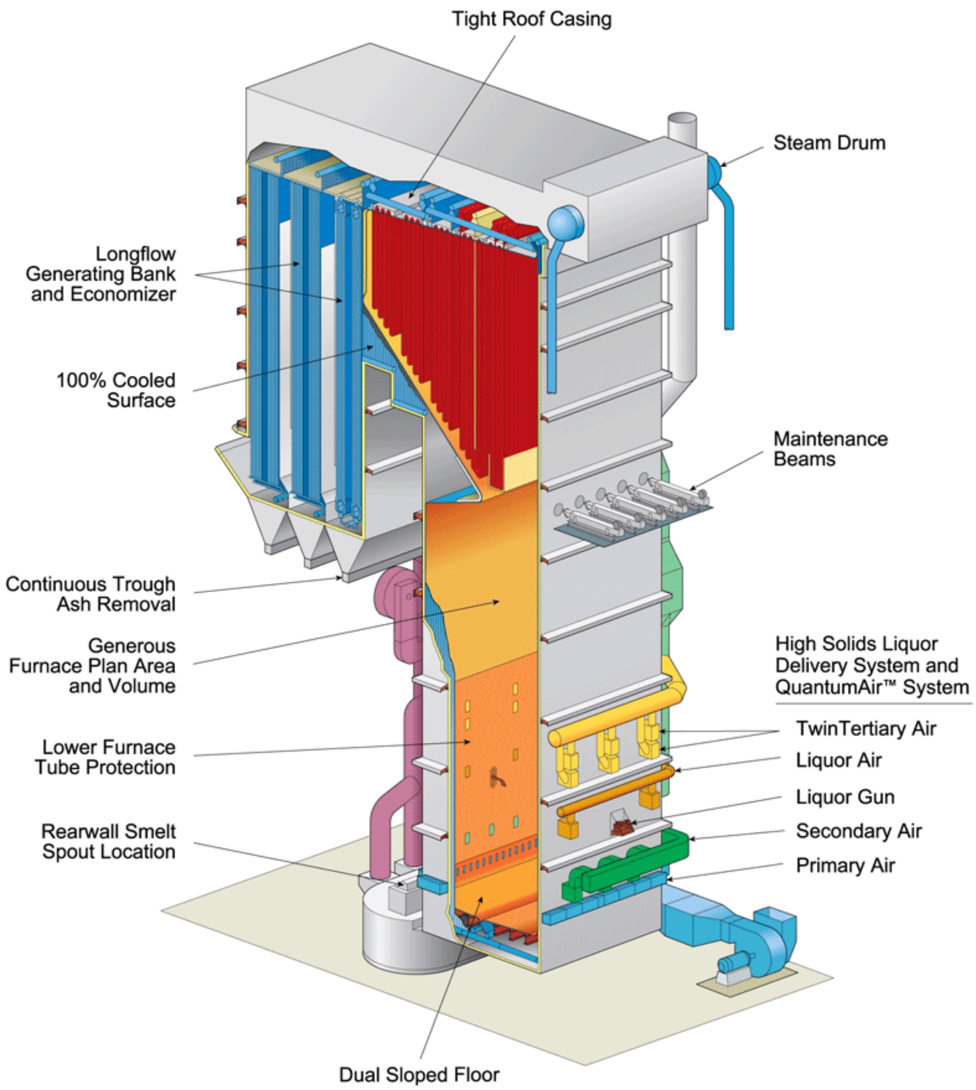

Figure 2. Structure of recovery boiler (Babcock & Wilcox 2019)

Black liquor contains a lot of ash and other compounds that do not burn and that is why recovery boilers need much attention to controlling fouling. Fouling weakens the performance of the heat exchangers and for that is developed sootblowers. Those are located among heat exchangers and use pressured steam to clean fouling. Other significant structural solutions are that boiler and heat exchangers are hanging from steel beams. This ensures that the thermal expansion of structure occurs downwards. In the next chapters, components and process of the recovery boiler is described with more detail.

2.3 Fuel system

Primary fuel for the recovery boiler is black liquor. Secondary fuels are light fuel oil or natural gas, which are commonly, used in startup- or backup load burners.

Black liquor from the evaporators does not go straight to the recovery boiler. Virgin black liquor from the evaporator and the ash collected from recovery boiler hoppers and an electrostatic precipitator (ESP) is introduced to mixing tank. The ash contains significant amount of the sodium sulfate (Na_2SO_4) and sodium carbonate ($NaCO_3$), which kraft pulp mill do not want to lose. After the mixing tank, liquor goes back to the evaporator center where it is concentrated one more time. The temperature of the black liquor is set to the desired level when the liquor flows out of the pressurized evaporator container (Vakkilainen 2019). The spraying temperature and pressure of black liquor have great impact on the viscosity of black liquor. Viscosity significantly affects the size of the black liquor droplet and therefore efficient combustion. Normal spraying temperature is 115 – 130 ºC and even a couple of degrees of change can have an effect on combustion. Black liquor is sprayed to the boiler by liquor guns. (Knowpulp 2017)

2.3.1 Liquor guns

Liquor guns are located above the secondary airports. Components of a liquor delivery system are a ring header, a piping to individual liquor shut-off valve, shut-off valves, flexible hoses, the liquor guns and the nozzles (Adams 1997a, 9). Objective of the Ring header is to distribute the black liquor evenly to each liquor guns. The individual liquor gun may need some simple cleaning or changing the nozzle and then it is unnecessary to interrupt the other process. Every liquor gun has its own shut-off valves, which allows one liquor gun to be cleaned and repaired without disrupting others.

The nozzle is the most important part of the liquor gun. Type of the liquor gun nozzle can effect dramatically to the behavior of the recovery boiler. Nozzle affects shape and direction of the liquor spray and size of the droplets, which affect char bed and carry over. The most common liquor nozzles types are splashplate nozzle (Figure 3) and beer can nozzle (Figure 4).

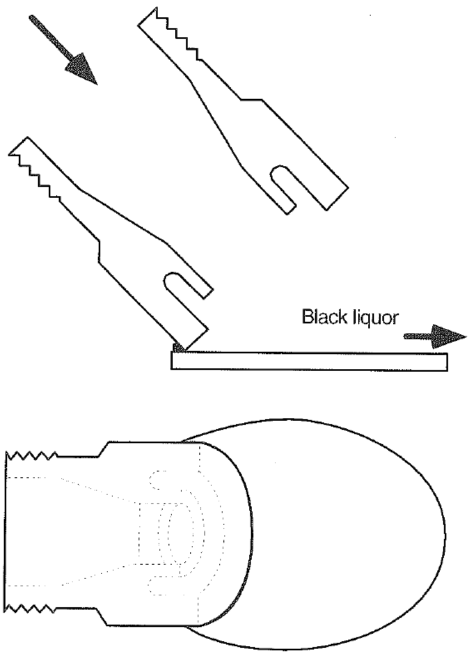

Figure 3. Splashplate nozzle (Adams 1997b, 104)

The most common nozzle type is splashplate nozzle. It consists of round flat plate attached at an angle to the end of the pipe. The angle of the plate can vary between 35º and 55º depending on a manufacturer and application. Black liquor flows through the pipe and exits at high velocity. Liquor strikes the plate and forms broad flat sheet that expand to the furnace. (Adams 1997b, 103.)

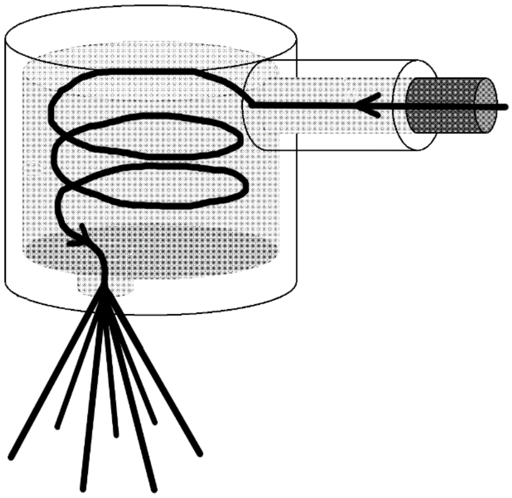

Figure 4. Beer can nozzle. Edited from: (Jameel & Higgins 2008, 2)

In the beer can nozzle, the black liquor is delivered to an inner cavity. The black liquor swirls around the cavity and eventually leaves the nozzle through a discharge orifice. The liquor forms cone shape spray, which eventually breaks up into the droplets. The spray is directed at the center of the char bed, no downwards like Figure 4 lets assume. (Jameel & Higgins 2008, 5). The beer can nozzle is more common in small recovery boilers with a capacity of about 1000 tds/d. The Splashplate is mostly used in the bigger recovery boiler.

Swirlcone and V-type nozzles (Figure 5) are older and nowadays almost completely disappeared from recovery boilers. The swirlcone nozzle looks different then beer can nozzle, but a droplet formation process is similar. Inside the nozzle is a block or swirl plate with spiral grooves which cause black liquor flow to rotate as it flows along the walls of the nozzle cap. The black liquor exits from the nozzle in the form of a conical sheet. This sheet of liquor breaks down and forms the sheet of droplets. The V-type nozzle consists of a cylinder tube which top has been cut across with V-shaped channel. An exit of the nozzle is smaller than a pipe, so black liquor flow accelerated and discharged in a flat sheet. The operation of the V-type nozzle can be described as water hose, which exit is squeezed and water come out as flat and fast sheet. (Adams 1997b, 104-107.)

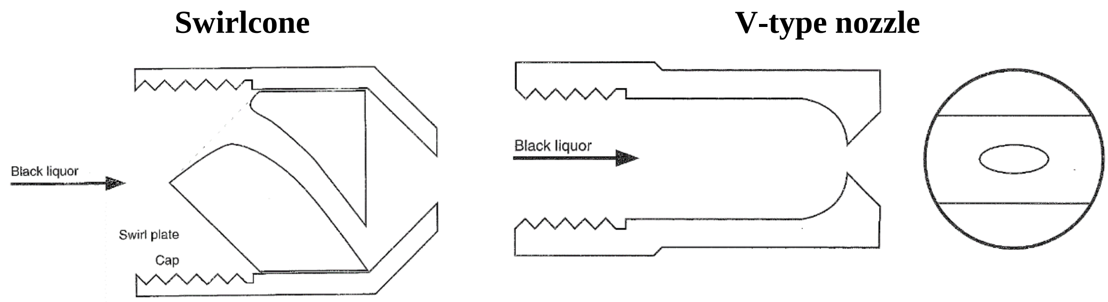

Figure 5. Older black liquor nozzles. On the left swirlcone and on the right V-type nozzle. (Adams 1997b, 106-107)

2.3.2 Startup and backup burners

Due to the characteristics of black liquor, the recovery boiler cannot be startup only with it. Black liquor combustion is relatively slow and requires proper conditions to ignite. Boiler needs startup burners, which role is to heat up the char bed during startup and low loads. Those burners can be used also during a shutdown to burn the char bed away. Burners are located near the char bed above a primary air channel and they are usually on all four walls. It is important that burners do not foul or produce a lot of ash, and that is why their fuel is oil or natural gas. (Vakkilainen 2005, 7-20.)

Startup burners are line with their name and only participate during startup and low loads. Steam cannot be produced with startup burners. There can be situation where the recovery boiler has to produce energy, but the black liquor system is out of order. Then needed energy is produced by a backup burner. In the recovery boiler, there is at least one backup burner and it use oil or natural gas. All the new and modernized recovery boilers must have emergency shutdowns that stop oil flow if flame in the furnace go out for any reason. (Knowpulp 2017)

2.4 Air system

An air system of the recovery boiler has multiple objectives. The primary objective is to supply air for the boiler to complete combustion of the black liquor. Effective combustion needs just right amount of the oxygen. If there is not enough air in the combustion process, not all fuel burns or combustion can be incomplete. For example, incomplete combustion may mean that carbon does not form carbon dioxide, but instead end reaction is carbon monoxide. Too much excess air is not good either. Excess air does not react in the boiler, only get hot, and therefore flows through the system and takes usable energy with it. The second objective is to control the temperature and chemical environment around the char bed. Shape of the char bed can be controlled by changing the flow rate of the air or air pressure of the primary- and secondary air inlet. Third objective is to minimize the carryover of the black liquor spray that can lead to fouling of the superheaters. Fourth is to control the emissions of flue gas, example carbon monoxide (CO), nitrogen oxides (NO_x), total reduced sulfur (TRS) and sulfur dioxide (SO_2). Last objective is to ensure uniform flue gas flow and temperature distribution entering to the superheaters. By achieving that, can be ensured balanced heat transfer to the steam. (Wessel 2015, 1). In Table 1 is listed how the development of the air system has evolved.

Table 1. The development of the air system. Edited from: (Vakkilainen 2012, 11-7)

Air system	**Primary purpose**	**But should also**
1. generation	Stable combustion of black liquor	
2. generation	High reduction	Combust black liquor
3. generation	Minimizing sulfur emissions	Combust black liquor, high reduction
4. generation	Minimizing nitrogen emissions	Combust black liquor, high reduction, low SO2 emissions
5. generation	Reduce fouling of superheater and steamboiler	Combust black liquor, high reduction, low emissions

A Typical air system of the recovery boiler is shown in Figure 6. An Air inlet duct located high in the boiler house. The air of the boiler house is typically already warm because of heat loses of the boiler. Inlet duct include a silencer, because amount the air that flows in the air system cause a lot of noise. After the inlet is a venturi, which job is to measure total air flow. Air flow can be controlled by an air blower or damper in the duct. Primary, secondary and tertiary air have their own air fans. That enables controlling each individual stage without having significant effect on the others. The air controlling by furnace air damper produce high-pressure air, but increase blower power consumption. The air is heated before it is distributed to different air stages. (Vakkilainen E2005, 7-2.)

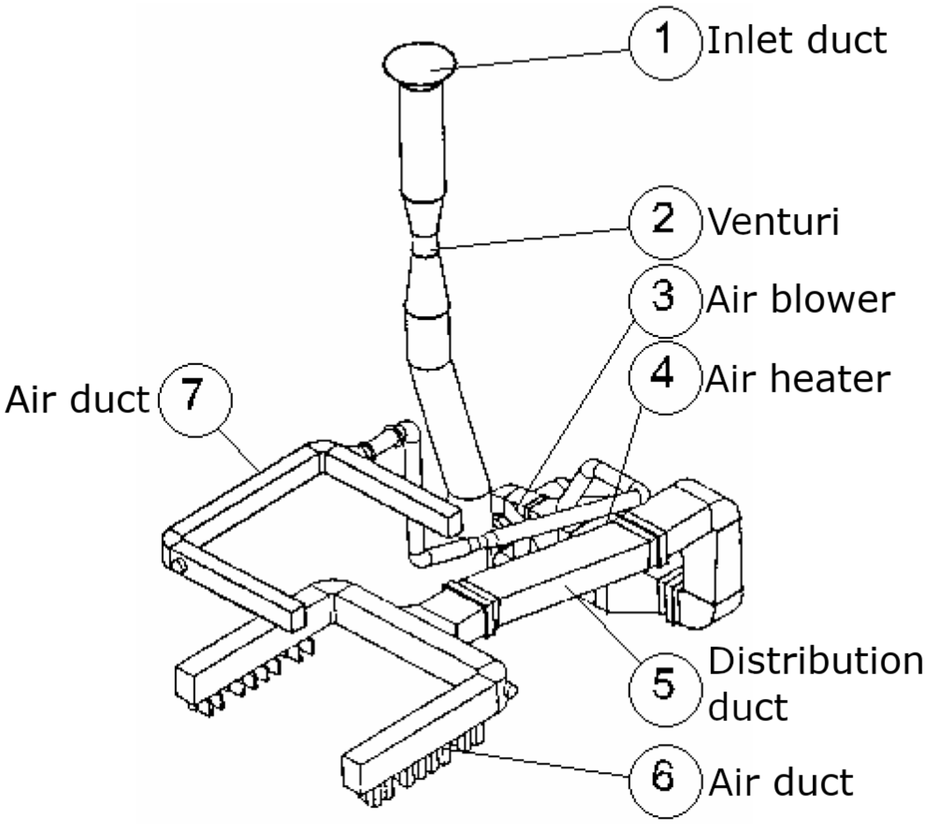

Figure 6. Basic components of the air system for a small boiler. (Vakkilainen 2005, 7-2)

2.4.1 Preheating

Purpose of the preheating air is to increase furnace temperature. Increased temperature enables smaller heat transfer surface and increase heat transfer to steam. Heated combustion air temperature is from 125ºC to 200ºC. Usually only primary and secondary air is heated. At the tertiary air level furnace gas are nearly 1100 ºC so air preheating is not required. Cold air has higher density, which increase jet penetration and mixing of the flue gases. Traditional power boiler usually uses flue gas to preheat air. In the recovery boiler, flue gas is typically very dirty so for air preheating is used low- and high-pressure process steam. Low-pressure steam is used in initial stages and higher-pressure steam in the later stage. Problems with heat exchangers are poor heat transfer and excessive pressure drop. (Vakkilainen 2005, 7-2; Jones 1997, 186.)

2.4.2 Air stages

In the traditional air system, air stages can be roughly divided into three group, which are primary-, secondary- and tertiary air. In some rare case, there can be a quaternary stage. Modification that is more common is to make lower- and upper stages for secondary and tertiary air. These kind multilevel systems can control furnace temperature easier and therefore NO_x control is better. In Figure 7 are shown the traditional locations for the air supplies.

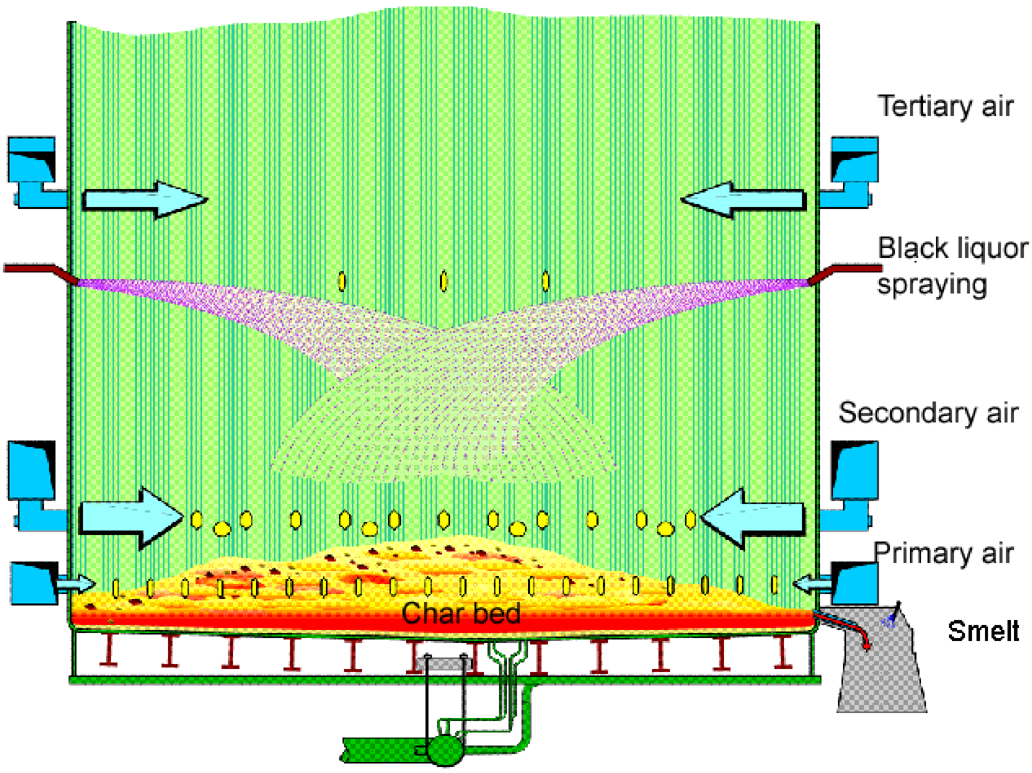

Figure 7. Air supplies in recovery boiler (Knowpulp 2017)

Primary air

The most important function of the primary air is to keep the char bed in good shape. The char bed can be shaped by changing the velocity of primary air. In Figure 8 is shown how the velocity of primary air impacts to the char bed. In three stage system, the volume flow of the primary air is usually 30 – 40 % of total air. (Wessel 2015, 2.)

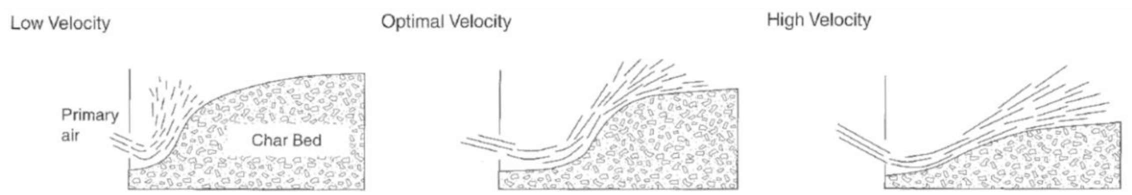

Figure 8. Impact of primary air on char bed. (Jones 1997, 200)

Airports of primary air are located on each wall. The number of airports is relatively high when compared to other stages. By small air injection ports, primary air can be injected with high speed and pressure. It ensures that the char bed remains in good shape. Primary airports needs constant cleaning because char bed material can fell inside the port and plug it. Cleaning is done by an automatic system where machine uses a rod to push and shake the char bed material away from port. The plugging of the airports can also be controlled by directing ports downwards. Purpose of this is because then smelt or char cannot flow to port. However, port must not direct too downward, because then it can dig a hole to char and reveal smelt, which can lead to lower reduction. (Vakkilainen 2005, 7-4.)

Secondary air

While primary air has the biggest impact on the char bed, secondary air has the biggest impact on combusting. Secondary airports located just above the level where the top of the char bed's mound can reach. Secondary air can control the temperature in the lower furnace. By doing that, it is possible to maintain low emissions and high reduction. Low emissions are possible by keeping the temperature not to get too high. However, for good reduction, char bed temperature cannot get too low. If the top peak of the char bed grow too high, it is usually stopped at secondary air level. (Vakkilainen 2005, 7-5.)

Airports of secondary air vary by the design and age of the recovery boiler. In older model airports located on every wall. Nowadays secondary air ports locate on front and rear wall. Usually secondary air is divined to upper and lower secondary and its air distribution is interlaced. In three stage system, the volume flow of the secondary air is usually 20 – 50 % of total air. (Wessel 2015, 2.)

Tertiary air

Tertiary air functions are to ensure full combustion and mix the flue gas before they enter to superheaters. It reduces NO_x, CO and TRS emission and minimizes the corrosion of furnace's wall tubes. Airports of the tertiary air are located typically on the front and rear wall and arrangement is interlaced. Totally mixing of flue gas is ensured by high enough air pressure, not preheated air temperature and interlaced airport placement. In three stage system, the volume flow of tertiary air is usually 15 – 40 % of total air. (Wessel 2015, 2)

In normal situation, the boiler air controlling is done by changing the parameters of primary and secondary air. Flowrate of tertiary air depends on that how much air is going to other stages and then the rest of needed air is injected from tertiary airports.

2.5 Ash handling

The combusting of black liquor is very fouling for the boiler. Black liquor contains inorganic components. During the combustion, some of those inorganic components vaporize or break down to small particles. Those vapors and small particles are components of fume gases. Components of the flue gas and ash are introduced in Chapter 3.4. Ash handling in the recovery boiler contains sootblowers, ash collecting device and flue gas cleaner.

2.5.1 Sootblowers

Fume and carry over deposits weaken heat exchanger efficiency so they need constant cleaning. Sootblowers use high velocity steam to clean heat exchanger areas. They located among superheaters and other heat exchanger. Typical sootblower is a rotating lance and it is inserted from the wall of the heat exchanger surface. At the tip of the rod is a hole that spray steam at above sonic speed of steam. Surrounding gases causes fast degrades to the speed of steam. An effective range of sootblowers is 1 – 1.5 meter. When sootblower is ready, it is pulled out of the boiler. (Vakkilainen 2005, 7-18 & 8-21.)

In older sootblowers is used high-pressure steam, which is taken directly from the superheater and reduced by a poppet valve to 7 – 24 bar. Sootblowers consume 3 – 12 % of the total superheated steam produced by the boiler. In a newer recovery boiler has been used low-pressure steam to reduce energy consumption. Low-pressure steam is taken from a steam turbine exit and its pressure is 9 – 14 bar. This steam is less valuable to a factory than high-pressure steam, which can be used to produce electricity by the turbine. Efficiency of the sootblowers have developed during the years. First sootblowers were operated manually by pushing buttons next to the sootblower or in the control room of the recovery boiler. Later an automatic system with programmable logic control (PLC) and distributed control system (DCS) controlled sootblowers blindly without the feedback of the state of fouling or boiler cleanliness. Nowadays is possible to direct sootblowing to right areas. The weakened efficiency of the superheater indicates deposit of fouling. It is possible to calculate efficiency by the heat balance of heat exchanger or flue gas temperatures before and after heat exchangers. Less common method is to measure the weight of the superheaters by a strain gauge system, which is installed on the hanger rods that support superheaters. (Tran 2014, 25.)

2.5.2 Collecting devices

Ash handling does not works the same way in the recovery boiler than in the traditional power boiler. Ash is collected and returned to the boiler by mixing it with black liquor. Ash contains a lot of sodium compounds and the purpose of the mixing is to ensure that most of them eventually end up to smelt. Ash of the flue gas is collected with a flue gas vent's hopper and electrostatic precipitator (ESP). The flue gas vent's hopper is located under economizer and boiler banks. The flue gas of the recovery boiler is very fouling and thick, which mean it contains heavy particles that drop to the bottom of heat exchangers. ESP is first flue gas cleaner after boiler structure and there can be a few of them for one boiler. It separates smaller particles from flue gas by using an electrostatic field. ESP has negative charged wires and positive charged collector plates. When flue gas flows through the electrostatic field, particles become charged and are drawn towards collector plates. Ash is carried from hoppers and ESP by conveyors to mixing tank. If there is a need to add some chemicals like sulfur or sodium, those are mixed with the ash to black liquor. (Vakkilainen 2005, 7-14 & 7-18.)

2.6 Smelt spouts

One of the recovery boiler's unit process is to produce molten inorganic smelt, which contain mostly sodium sulfide. Dried and volatilized black liquor forms the char bed on the bottom of the furnace. In the char bed happens the reduction of sodium sulfate to sodium sulfide. It is called sulfite-sulfide cycle and during it carbon reacts with sodium sulfate to form sodium sulfide. The char bed and its chemical reactions are introduced more precise in Chapter 4.

Molten smelt needs some way out of the boiler. For that is developed a smelt spout, which is located below primary air ports. Molten smelt is drained from furnace to dissolving tank. The temperature of the smelt is about 900 ºC and that is why spouts need constant cooling. It is done by circulating water inside the spout. Most of the corrosion caused by smelt is avoided by cooling water. The temperature of the cooling water cannot be too low due the risk of the condensate water droplets on the sides of the spouts. Droplets may contact smelt or cause corrosion to spout by itself. High cooling water temperature has risk to boil inside cooling tubes and causing heat transfer problems, which lead to overheat and damage spouts. Recommended temperature for spouts cooling water is for inlet 60 ºC and for output 80 ºC. If smelt and water contact, it causes a reaction that can lead to an explosion. Due to risk causing the smelt explosion, smelt spouts are recommended to change after one year. The longer use of the spout can weaken it and causes cracks and manufactures do not want to take risk by promising longer service life. (Tran 1997, 302; BLBRAC 2016, 60.)

In **Figure 9** is an example of the normal water-cooled smelt spout. A water inlet and outlet are plugged with yellow caps. During maintenance outage old spouts are removed from the furnace and replaced with new ones.

Figure 9. New smelt spout. (Andritz 2010)

2.7 Dissolving tank

After spouts, smelt flows to dissolving tank, where it is mixed with water or weak wash and forms green liquor. Smelt flow is broken by steam jet to provide for safe, effective dissolution. Dissolving is loud, vibrating and heat releasing action. The tank where it happens is well insulated and has thick concrete wall. Tank also has a vent system to remove the steam and other gases released during dissolution. (Tran et al 2015, 41.) Dissolving tank and its basic configuration is illustrated in Figure 10.

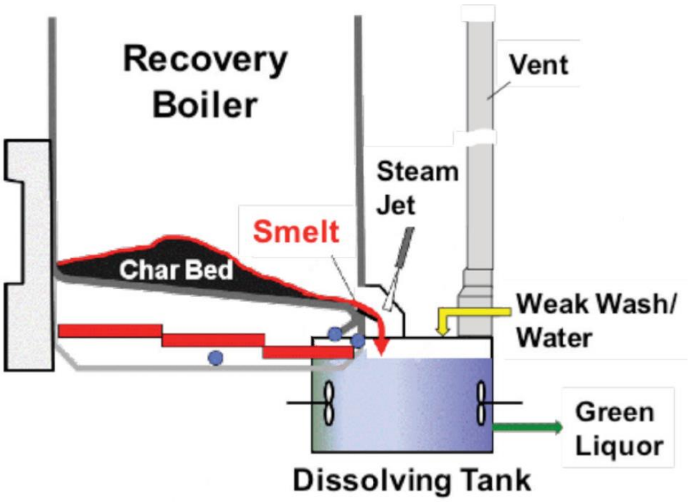

Figure 10. Configuration of the lower furnace and dissolving tank. (Tran et al 2015, 41)

2.8 Malodorous gases

First thing that come to people mind about the pulp mills is malodorous gases. Many people remember how areas with a pulp mill smell sulfur. Nowadays most of the malodorous gases are burned or disposed proper way. Gases have been burned in separated incinerators, lime kilns or recovery boiler. The recovery boiler is the most common way to disposal malodorous gases. The odor nuisances have now disappeared or decreased significant.

Malodorous gases can be separated to weak malodorous gases (dilute non-condensable gases, DNCG) and strong malodorous gases (concentrated non-condensable gases, CNCG). Gases are separated from each other because strong odorous gases have high sulfur content and are explosive. Gases are generated in every process device that handles liquor and it contain sulfur, water and air. Weak malodorous gases are collected from different vessels, chutes and washers. To avoid the danger of smelt explosive, water from the gases are removed by cooling, after which the gas is warmed in a dry space. Weak gases contain oxygen almost as much as normal air and that is why gases can replace combustion air. Gases are injected to the recovery boiler with separated nozzles or they can be mixed directly with secondary or tertiary air. Strong malodorous gases are collected from evaporation plants, strippers, digesters and concentrators. The amount of sulfur in strong gases are significant high. It does not matter because of the sodium, which have been released in the furnace, binds the sulfur to flue ashes. Strong malodorous gases have their own burner and it is usually located the same level or below the liquor gun. Handling and burning strong gases are not easy as weak gases, due to their toxicity and explosiveness. The burner is similar to natural gas burners, expect that more safety features are employed. Gases collecting devices and vessels is secured from sparks and prevented air from leaking in. If there is some disturbance in regular gas burner, the gas is directed to spare burner, which is torch burner on the roof of the builder building, or to the lime kiln. (Knowpulp 2017)

3 BLACK LIQUOR

Black liquor is generated in the cooking process. Cooking chemicals dissolve lignin and other organic compounds in the wood. This dissolved material is called dirty pulp. It contains pulp, water and black liquor. Weak black liquor is separated from pulp in washing. Weak black liquor is not suitable for burning because it has high water content. Water is separated from black liquor in the evaporation unit. Sometimes dried black liquor is called strong black liquor. Dry solid content of black liquor as fired must be at least 58 %, because there is danger of mixing water and smelt in the recovery boiler, which can cause the smelt explosion. Typical dry solid content of black liquor is above 75 % (Knowpulp 2017.)

3.1 Composition and properties

Black liquor composition and properties are very important in the design of the evaporation plant, a condensate treatment plant and recovery boiler. Composition of black liquor determines heat value as fired and how fouling burning can be. The exact composition of black liquor depends on many things. One of the main thing is type of the raw material and origin of it. Most common wood material can be divined to softwood (pine) and hardwood (birch). Other materials are straw, bagasse and bamboo. (Bajbai 2017, 26.)

Black liquor composition can be separated roughly to organic and inorganic substances. Approximately two-third of the solids are constituted of organic and the remaining is inorganic material. The main organic compounds in black liquor are lignin, carbohydrates and extractives. Inorganic substances in black liquor are cooking chemicals, which most of are sodium compounds. Due the effect of the oxygen in the air, the black liquor may oxidize in pulp washing. The elemental composition of black liquor as fired is listed in Table 2. Compositions are typical values of black liquor from Scandinavian softwood (pine) and hardwood (birch). There are also a large number of other elements, which concentrations are below 1 g/kg of dry black liquor. Those elements can be magnesium, iron, manganese, phosphorus, silicon, aluminum, etc.

Table 2. Compositions of black liquor from softwood and hardwood. (Bajbai 2017, 28)

	Softwood (pine) (%)	Hardwood (birch) (%)
Carbon, C	35	32,5
Hydrogen, H	3,6	3,3
Nitrogen, N	0,1	0,2
Oxygen, O	33,9	35,5
Sodium, Na	19	19,8
Potassium, K	2,2	2
Sulfur, S	5,5	6
Chlorine, Cl	0,5	0,5
Inert	0,2	0,2
Total	100	100

The physical properties of black liquor are density, viscosity, thermal conductivity, specific heat and surface tension. Studies have proven that most of the physical properties can be determined by knowing observed properties as dry solid content, the temperature and composition of the black liquor. Physical properties affect combustion properties, which are droplet formation and heating value. Black liquor properties and how they affect each other is shown in Figure 11. (Knowpulp 2017)

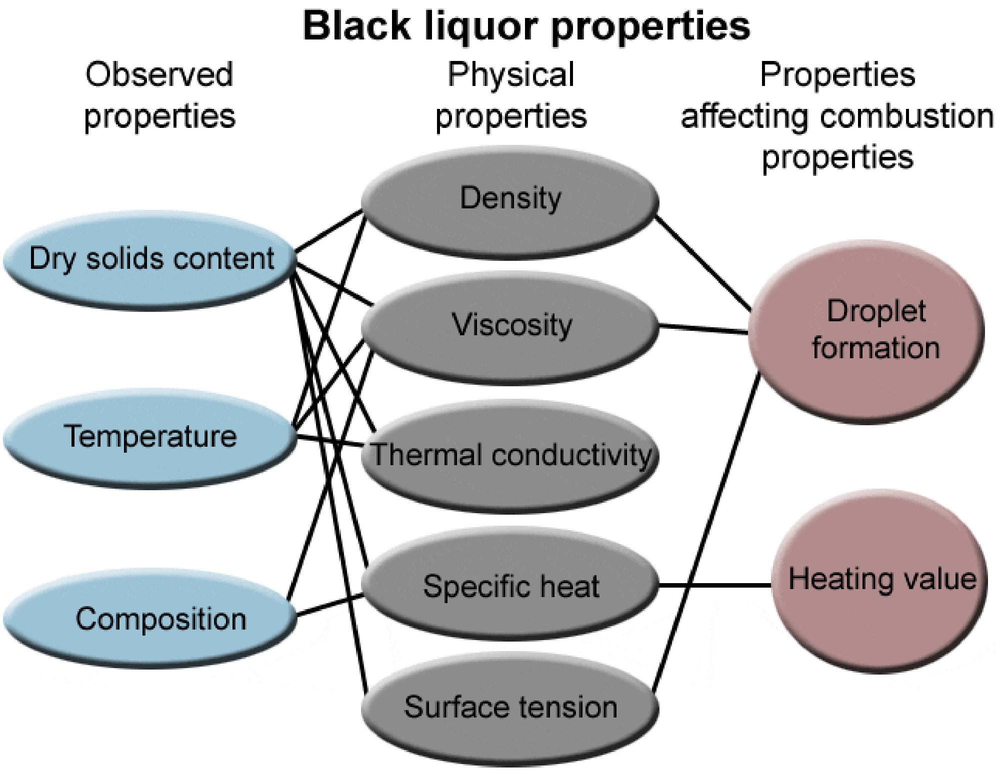

Figure 11. Black liquor properties (Knowpulp 2017)

For droplet formation, density, viscosity and surface tension are the main properties. Density of black liquor is important in the calculation of flow characteristics. Dry solid content and temperature affect the density of the black liquor. At the low solid content, density is closer to water at the same temperature. Most of the organic material have the same density as water. Inorganic components have almost two times higher density and that is why they have the strongest effect on the density of black liquor. The viscosity of black liquor is one of the main properties. It determines how liquor fluid, spray behave and droplet form. Viscosity is determined by its compositions, the temperature and the dry solids content. At dry solid content of about 15 %, black liquor viscosity is almost like water. At 50 % dry solid content black liquor behaves as a polymer blend with water as plasticizer. Viscosity increase exponentially with solid content. With too high viscosity, pumping the black liquor is impossible. To enable pumping, limits for black liquor in atmospheric conditions are 70 – 75 % dry solid content and maximum temperature 115 ºC. For higher dry solid content is needed pressurized storage tank, where dry solid content can be 75 – 85 % and maximum temperature 125 – 150 ºC. The surface tension of black liquor is affected by the dry solid content. It is one of the most important factor in the assessment of drop formation in black liquor firing. The low-surface tension black liquor has tendency to foam, but that is more problem in the evaporator then in the recovery boiler.

Thermal conductivity indicates the ability of material to conduct heat. It is important property to know and it is used to estimate heat transfer in evaporators and for drying of droplets in the furnace. The thermal conductivity of black liquor will increase while temperature increase or dry solid content decrease. Specific heat capacity indicates needed energy to increase one kilogram black liquor by one-Celsius degree. It is necessary to know when the energy balance of the recovery boiler is estimated. The heat capacity of black liquor increase while dry solid content decrease. It can be calculated when constituents of black liquor are known. (Bajbai 2017, 34.)

The heating value of the black liquor indicates how much heat energy can be produced when burning it. It depends on the composition and heat capacity of the black liquor. Organic matter, which are lignin, carbohydrates and extractives, emit heat when burning, is source of the black liquor thermal value. The higher ratio of inorganic compounds in black liquor decreases the heating value. The higher heating value (HHV) of black liquor vary between 12 and 15 MJ/kg. (Knowpulp 2017.)

A boiling point of the black liquor is an important factor for liquor spraying. It varies between 110 ºC and 125 ºC depending mainly on the dry solid content and especially amount of the inorganic components (Kankkunen 2018, 18). A variation of a few degree Celsius with constant dry solid content is possible for different black liquors. The boiling point has to take into account when firing the high dry solid content black liquor. The temperature control is an important factor for controlling viscosity of the fluid. In a high dry solid content scenario, the temperature of the black liquor has to be increased over the atmospheric boiling point. Boiling is avoided by increasing the pressure of black liquor. High temperature of the black liquor causes flashing in the nozzle. Flashing is explained more precise in Chapter 3.2.1.

3.2 Spraying

Liquor gun and its nozzle forms the spray pattern of black liquor. Nozzles were introduced more specifically in Chapter 2.3.1. Proper spraying has effect on the char bed and carryover.

Objective of optimal spraying is to form a good size of droplet and uniform spray formation. Good droplet formation ensures that black liquor spreads evenly to the bottom of the boiler.

Droplet size is the most important property of the spray. Size of the black liquor droplets should be approximately 0,75 – 3,5 mm. Proper size black liquor droplet should has enough time to dry and volatize before hitting the char bed. Too small a droplet has risk to get with uprising flue gases and causing fouling, corrosion and increased emissions. Large droplet contains too much volatizes or even water when hitting the char bed, which can cause the char bed fast growing and its temperature cooling. Desired droplet size is 3 mm or even larger for high dry solid content black liquor. (Kankkunen 2018, 5)

Spray velocity determines a flight path of the droplet. With old recovery boiler, spray velocity was easy to calculate from the mass flow and pressure of black liquor. Nowadays recovery boiler use high dry solid black liquor as fuel, which has high viscosity. Because of that, the liquor must be pressurized and heated. When that black liquor is fired to the boiler, it starts to boil and cause phenomenon called flashing. Flashing is introduced more precise in the next chapter. In newer recovery boiler spray pattern and velocity is hard to simulate, because of the flashing.

In Figure 12 is the spraying image of beer can nozzle. The image is taken above the nozzle, which is pointing slightly downwards. Red lines illustrate a cylindrical shape of the nozzle. Beer can nozzle forms cone shaped spray, which differs from splashplate nozzle. The splashplate nozzle forms a flat sheet of liquor, which breaks down to droplets. From the image can be seen how liquor sheet breaks and forms different size and shapes droplets. This image is captured just at the right moment when conditions around the spray are relatively calm. Normally, flue gas flows and flying particles make visibility poor.

Figure 12. Black liquor spraying of beer can nozzle.

Droplet formation and spraying are complex phenomena that are difficult to model properly. The only reliable way to get information on droplet size and spraying distribution is to make experimental measurements. Experimental research have been done in test chambers and in real recovery boiler conditions. In general, droplet size is measured by a laser light scattering-based method. Another method is Phase Doppler Anemometry (PDA), where the phase changes of reflected or refracted laser light are detected. These systems are fast and accurate. An image-based droplet size measurement system is more challenging but has some advantages. Proper lighting, overlapping droplets and the focus area can cause some difficulties. Advantages are possibility to see droplet shape and measure velocity on double or triple exposures. From image is also possible to see the shape of droplet formation and its direction. Problematic for measurement devices in real conditions are that they have to withstand harsh conditions. The temperature in the furnace can be about 1000 °C and black liquor and flue gas are very fouling. (Kankkunen 2018, 9)

3.2.1 **Flashing**

High dry solid content black liquor must be pressurized and heated above the boiling point, because otherwise viscosity would be too high and pumping of liquor would be impossible. When the pressure is dropped in the nozzle, black liquor starts to boil. It causes increase in velocity by forming and growing vapor bubbles inside the nozzle pipe. This phenomenon is called flashing. Intensity of flashing depends on mainly how much liquor is heated over the boiling point. Flashing is hard to measure or simulate. It is an important, but mostly unstudied, spraying regime. (Kankkunen 2018, 5). Flashing has to take into account when studying the images of liquor spraying.

Droplet formation under flashing conditions is shown in Figure 13. The test has done with splashplate nozzle. Even couple degree change in the firing temperature or boiling point can change the droplet formation significantly. Excess temperature (ΔT_e) tells temperature difference between firing temperature of the black liquor and boiling point of the black liquor at atmospheric pressure. Flashing occurs more powerful when the excess temperature is higher. In the figure can be seen how droplet formation changes significant when excess temperature rise from 14 ºC to 16 ºC. In Chapter 3.1 is mentioned that boiling point of black liquor can change depending of cooking conditions or wood material. The change can be a couple of degree. It means that droplet formation and flashing can change not only because of the excess temperature rise, but also because of the boiling point of black liquor change.

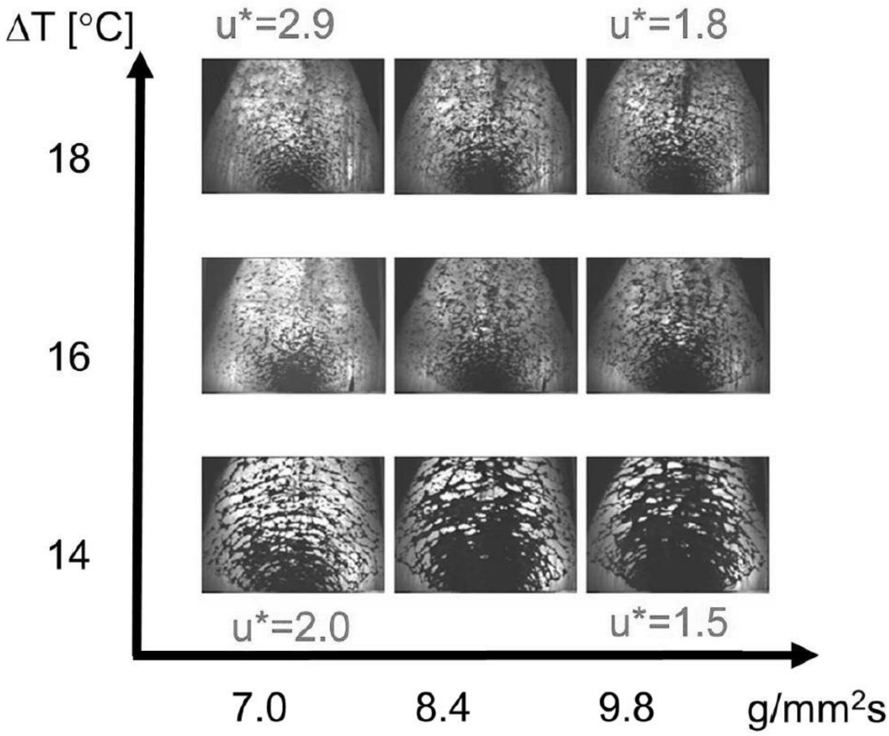

Figure 13. Spray formation as a function of excess temperature and mass flux (Miikulainen et al. 2009).

3.3 Combustion

Black liquor combustion differs from other industrial fuel. It has lower heat value, high water content and huge ash content than other fuels. A typical sprayed fuel droplets are much smaller compared to black liquor droplets. Black liquor objective is to reach the bottom of the furnace and ensure optimal conditions to reduction. During the air flight, liquor is desirable to dry and combust volatiles.

Combustion has three stages, which are drying, devolatilization and char burning. Other noticeable characteristic behavior for black liquor is swelling. Other fuels do not swell as much. In Figure 14 is shown stages of combustion and swelling for a 2 mm black liquor droplet. In reality, some stages can happen the same time in the droplet. On the surface of the droplet can be undergoing volatiles release and same time the center of the droplet is still drying.

During drying water evaporate from the black liquor droplet. It happens without the absence of visible flame. Drying needs heat and process is faster as how much there are heat available. In the furnace's temperatures, drying is limited by the heat flux to the droplet. Swelling is not remarkable during drying. Droplet diameter increase 1.3 – 1.6 times the original diameter and density decrease.

Devolatilization starts at the end of drying. It is characterized by the swelling, the release of volatile gases from the droplet and appearance of visible flame. Visible flame is used to determine the length of the devolatilization reaction. When it ends, the next stage is ready to start. Devolatilization is fast process, but a lot happens during it. A peak of swelling happens during devolatilization. It can multiply the droplet volume, which increase the rate of combustion. It can be explained by the larger available area for combustion reactions. It has been studied that properties of black liquor and cooking time of pulp have affect to the rate of swelling.

In the real furnace process char burning starts during devolatilization. It is objective that char burning happens in char bed and volatiles has been released during air flight. Black liquor char contains carbon, sodium, carbonate, sodium sulfate and sodium sulfide. About 25 % of char is carbon and other are inorganic compounds. Char burning and char bed reactions is introduced more specifically in Chapter 4.2. In char burning, volume of the droplets decrease and only inorganic smelt compounds are left. Burning happens without visible flame. (Vakkilainen 2005, 4-1; Raiko et al. 2002, 535.)

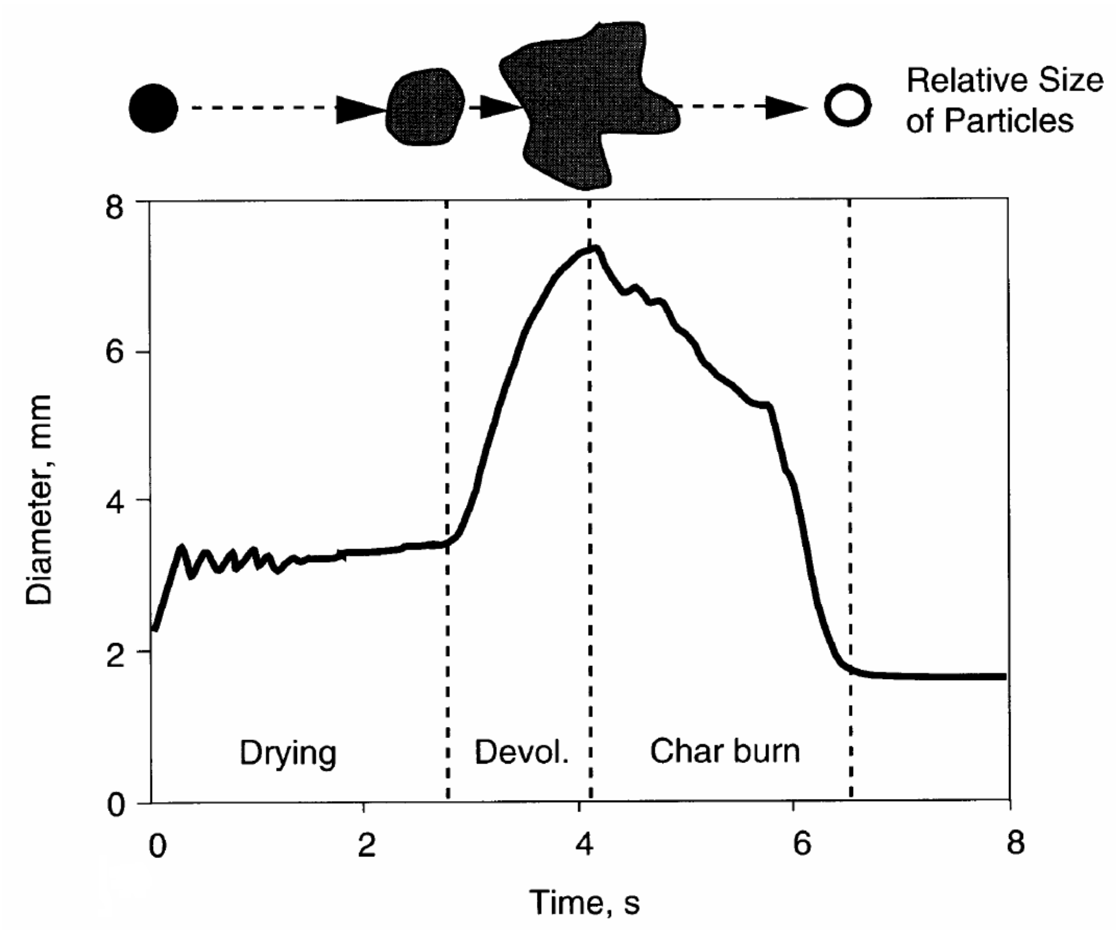

Figure 14. Combustion stages and swelling for black liquor droplet. (Vakkilainen 2005, 4-1)

There are a lot of differences between black liquors from a different pulp mill. Especially swelling of the liquor can be completely different depending on where the liquor comes from. Swelling affects to time of combustion and a flight path of droplets in the furnace, which have great importance for the furnace conditions. This difference behaviors of the black liquor affect the control of recovery boiler. Recovery boilers with the same design might have different air supply and liquor injection solutions, because of the black liquor difference. (Raiko et al. 2002, 539.)

3.4 Flue gas

Flue gas can be viewed from many different places. One place is after the furnace and other after a stack. Flue gas compound are different depending the view place. In this thesis, focus is in flue gas after furnace. Flue gases contain particulates and emission components. Particles can be separated to fume, intermediate size particles (ISP) and carryover. In the recovery boiler ash particles and carryover are big problem by fouling heat exchangers and causing deposits to them.

3.4.1 Fume

Fumes are very small particles that form from vaporized alkali elements. There are some chemical and physical reactions that enable vapor to condensate. Small liquid particles collapse to each other and form new spherical particles. Those particle's sizes are less than 10 µm and average sizes are 0,5 – 1,3 µm. Fume formation and black liquor firing rate are almost directly proportional. (Vakkilainen 2005, 8-6.)

Fume composition are different in a lower furnace than an upper furnace (Figure 15). The lower furnace fume deposit contains significant amounts of sodium hydroxide (NaOH), potassium hydroxide (KOH), sodium sulfate (Na_2SO_4) and sodium carbonate (Na_2CO_3). The Upper furnace deposit is mainly sodium sulfate. Sulfur dioxide in the upper furnace reacts with sodium hydroxide and sodium carbonate and form sodium sulfate. It also reduces the amount of the sulfur dioxide in the flue gas. (Tran 2015a, 3.)

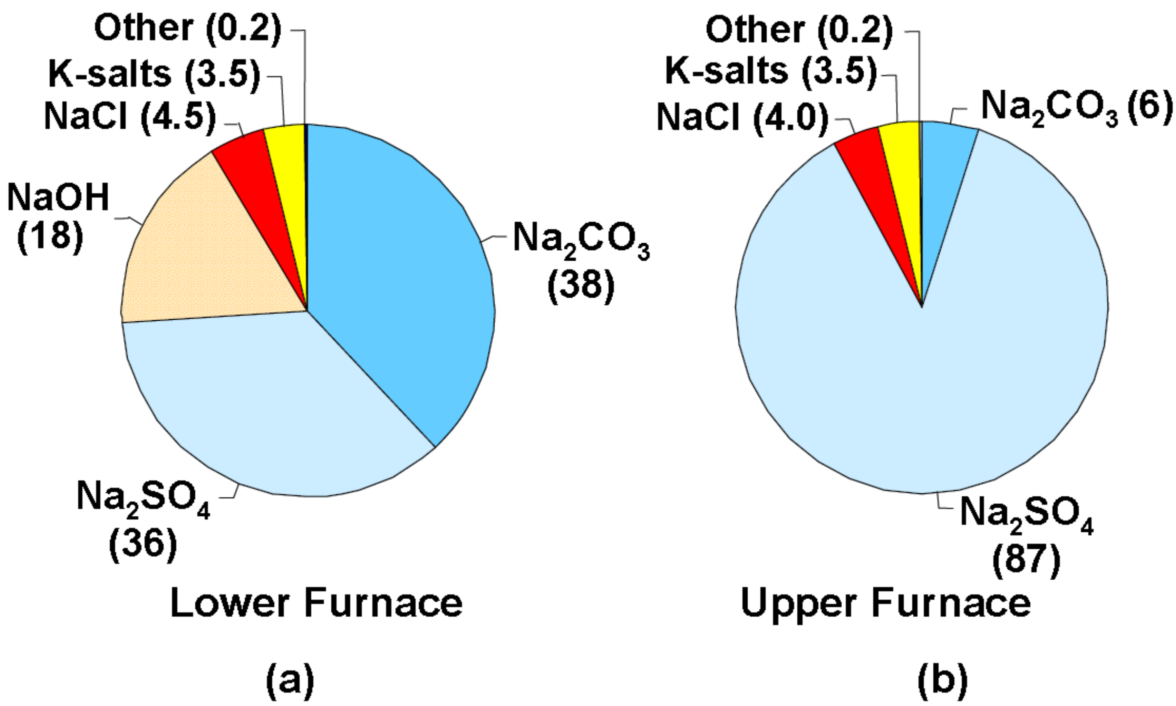

Figure 15. Composition of fume at lower and upper furnace. (Tran 2015a, 3)

Fume end up to be a deposit on heat exchangers or collected by ESP. Small amount of the fume end up with the rest of flue gases to stack and into atmosphere.

3.4.2 Intermediate size particles

If fume particles are very small and carryover particles are almost size of black liquor droplet, the intermediate size particles are all thing between them. ISP can be sintered fume that have been soothblowed from heat exchangers. They can be mineral impurities from black liquor. Possible sources are many and that is why ISP are difficult subject to study. ISP deposits are expected to have composition similar to carryover deposits with lower chloride, lower potassium, lower carbonate and higher sulfate contents and with no sulfide (Tran 2015a, 3.)

3.4.3 Carryover

Carryover particles can be molten or partially molten smelt particles and partially burned or unburned black liquor that got caught with the flue gases. Carryover particles are one of the main reasons for a plugging of lower part of the superheaters. Carryover deposits are formed by relatively large particles (0.01 – 3 mm) compared to fume particles (0.1 – 1 µm). (Tran 2015a, 1.)

Content of the carryover depends of stage of black liquor combustion. If boiler is not hot enough and black liquor does not have enough time to ignite, it swallow and can be seen as black sticky layer on superheater. If upper stage of boiler is hot, carryover black liquor can burn while rising up. Because burning liquor droplet is hotter than surrounding flue gas, it can be seen with thermal camera. Temperature of flue gas drop after nose, so liquor's carbon reaction stop and hit superheater as partially burned. Partially burned particles can be also seen as black color on surface where it have been hit. Fully combusted carryover particles can be seen as light red or red. Those particles contain much sodium sulfide and have high reduction number. (Vakkilainen 2005, 8-8.)

Carryover deposition on surface of superheater go through some chemical reactions. Most of the sodium sulfide is oxidized to sodium sulfate. A portion of sodium carbonate may react with sulfur oxidies in flue gas and form sodium sulfate. The composition of the carryover deposit is shown in Figure 16. From figure can been seen that composition of carryover is almost same as composition of fully oxidized smelt. (Tran 2015a, 3.)

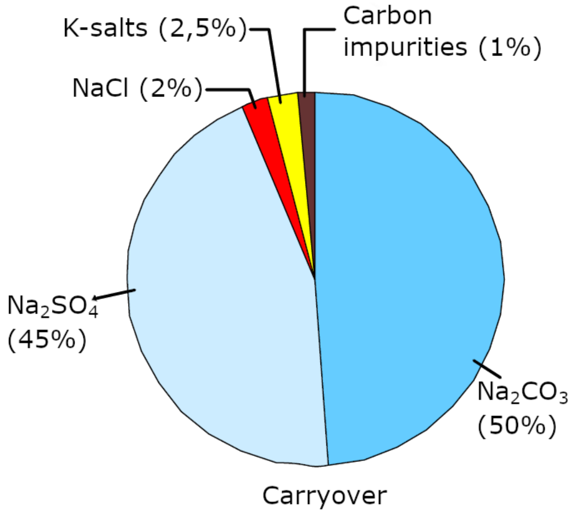

Figure 16. Composition of Carryover deposit. (Tran 2015a, 3)

There are several causes for carryover. The size of the black liquor and the droplet formation process are related to the formation of the carryover. In optimal situation, black liquor spray is steady as it is described in chapter 2.2. Sometimes black liquor nozzle is stuck and spray pattern is uneven or stopped entirely. It can cause problems in droplet formation, which effect on char bed and carryover. Other black liquor problems are connected with its properties. One of the main property in droplet formation is viscosity. Because of the low viscosity, the black liquor degrades into too small droplets. Droplets are caught with flue gases and do not fall to char bed as them should do.

Secondary air model has impact on carryover. Different air models is shown in Figure 17. If the secondary air is old kind conventional, where air is injected evenly from every wall, there are high gas velocity at the core of the furnace. High velocity gases have force to take black liquor droplet with it and cause that way carryover. In swirl air model core velocity is lower than in conventional model and that is why carryover is decreased. Best air model is interlaced, where air is mixed totally and gases have lowest velocity. (Vakkilainen 2005, 9-10.)

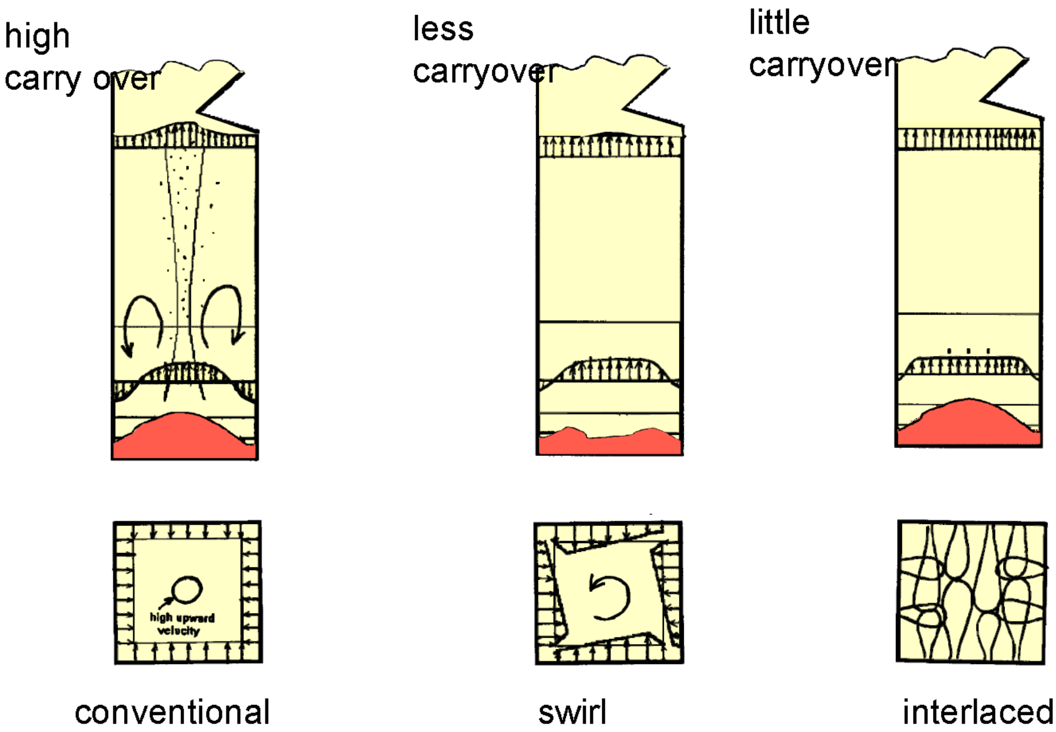

Figure 17. Effect on secondary air model on carryover. (Vakkilainen 2005, 9-10)

Carryover can be controlled by keeping the black liquor spraying in good shape. Operators can affect to it by keeping the liquor nozzles clean and ensuring that they work as they should. Air distribution has an effect on the carryover. Combustion air can be controlled by adjusting dampers of the airports or changing the air’s volume flow difference between different air stages. Volume flow of the different air stages can be controlled, but it can also affects to other functions of the recovery boiler, as reduction efficiency and power generation.

4 CHAR BED

In this chapter is introduced the hearth of the recovery boiler. Char bed is what makes a recovery boiler different compared with other combustion power plants. The whole recovery boiler is designed to ensure that the char bed has proper condition to produce heat for circulating water and makes the reduction happen to sodium sulfate. The main focus in this chapter is char bed's chemical reactions and optimal conditions.

4.1 Composition and structure

The char bed includes molten and frozen smelt, carbonaceous char and partially pyrolyzed black liquor solids. Char itself is residual after the devolatilization of the liquor solid. It contains about 50 – 66 % carbon, and less than 33 % hydrogen from the organic of the original black liquor. All the oxygen in the char bed come from inorganic smelt. Most common chemical compounds of the char bed are carbon (C), sodium carbonate (Na_2CO_3), sodium sulfide (Na_2S) and sodium sulfate (Na_2SO_4). There are also small amounts of inorganic salts as sodium chloride (NaCl) and potassium chloride (KCl). Small quantities of the anions such as sulfite, thiosulfate and polysulfide may also be present.

A physical shape of the char bed depends on how the recovery boiler is operated and what are furnace conditions. Most common shapes are a flat bed at the height close to the primary airports or bed with one or more large mounds. Shape of the bed usually changes between these two shapes, even though the bed with a mound is more desirable. Other bed shapes can be bare smelt pools with small char mounds or a cratered bed where the bed is higher around the perimeter than in the center. First one can occur when the recovery boiler is starting up or shutting down. Second is not desirable and can be the consequence of faulty primary air or black liquor spray.

Char bed material is not uniform. Char Bed has top made of char and inside mostly inorganic compounds. It can contain pockets of liquid smelt, frozen smelt or carbonaceous char. Char bed do not have uniform density, because of porosity of the material. Porosity is not uniform and it decrease in moving away from the bed surface towards the floor. (Grace T 2004, 21-22.)

In Figure 18 is shown structure and layers of the char bed. On the surface of the char bed is a chemically active layer. It can be separated to pyrolysis, combustion and reduction layers. Pyrolysis and combustion occur on the surface and reduction below them. Combustion is heat release reaction and reduction is heat absorbing. That is why most of the reduction occurs near the combustion layer and not at the bottom of the char bed. Liquid smelt flow to the bottom of the char bed and it is drained out of the furnace by the smelt spouts. Solid smelt is the lowest layer of the char bed. It acts as an insulating layer for the floor tubes. Cracking floor tubes has been a wide spread industry problem and one reason for it is most likely the liquid smelt. Hot and flowing liquid causes thermal spikes, that cause thermal fatigue, and liquid smelt itself is corrosive substance. That is why solid smelt is important layer at the bottom of the char bed. (Vakkilainen 2005, 10-7.)

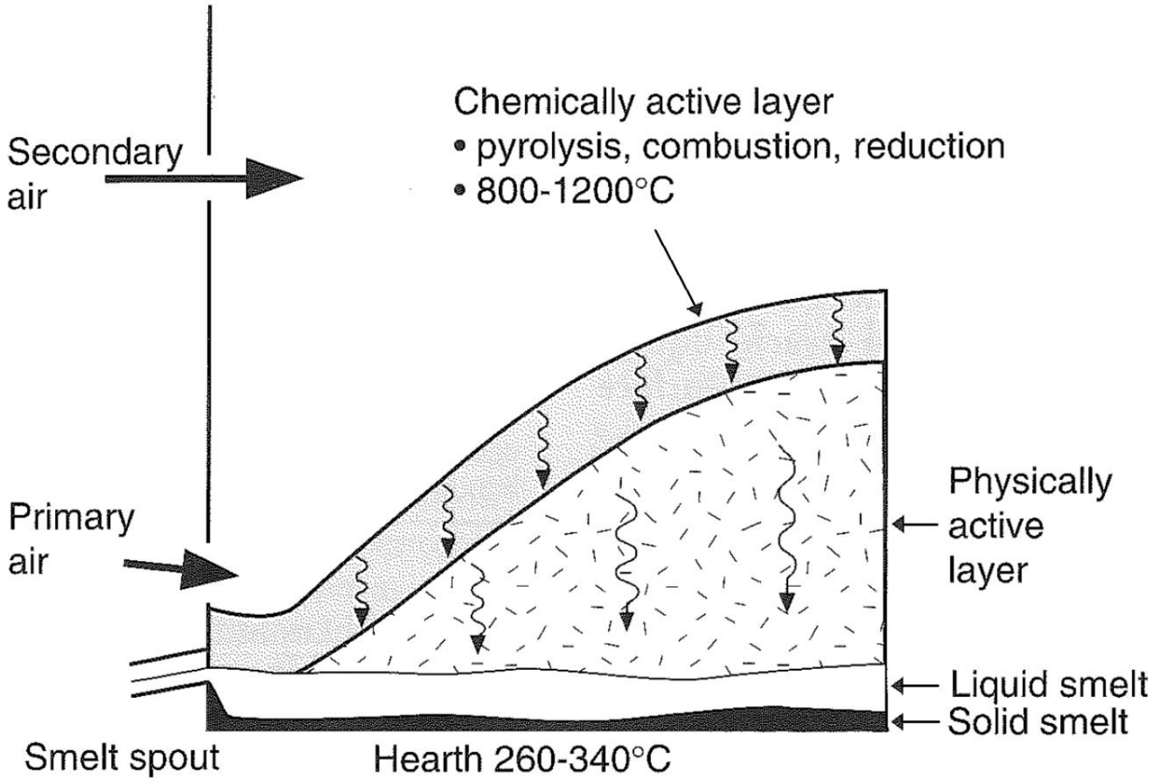

Figure 18. Structure and layers of the char bed. (Grace T 1997, 165)

4.1.1 **Material balance**

Char beds do not form automatically, they are built. A building process is easier when the material balance of the furnace is known. The bed grown locally if the rate of material reaching the bed exceeds that of material leaving the bed and decays if the rate of material reaching the bed is less than the rate of material leaving. Main sources of material to the bed are liquor droplets from the black liquor spray. Some of the material runs down from the wall or drops from the upper furnace. Some of the material is removed from the char bed by the combusting process where carbon oxidizes and gasifies or inorganic material vaporize. Most of the material is removed as molten smelt by flowing out of spouts. In an ideal recovery boiler, the char bed would be self-stabilizing. In reality there is no inherent reason for that to happen and experience shows that it can be difficult to maintain a stable, moderately size char bed. Char bed controlling happens mostly by observing if the bed is growing or decaying and making small adjustment to liquor spray temperature or combusting air flow rates. (Grace 2004, 22-24.)

The smelt flow corresponds typically from 0,400 to 0,480 kg per kilogram of incoming black liquor dry solid flow (Vakkilainen 2005, 5-8).

4.2 Char bed reactions

Two the most important chemical processes in the char bed are the combustion of the char and reduction of sodium sulfate to sodium sulfide. Both reactions have carbon as the main element in the chemical reaction. Combustion of the char happens surface of the bed and it is exothermic, which mean it is heat releasing. Reduction needs oxygen-free conditions so it takes place inside the char bed. Reduction is endothermic reaction, which mean it is heat absorbing.

In the char burning end product of the reactions is carbon dioxide. Reactions can occur by direct oxidation by oxygen in the combustion air. Other way is by gasification with water vapor (H_2O) or carbon dioxide (CO_2). The relevant reactions are:

$$C + \frac{1}{2}O_2 = CO \tag{1}$$

$$C + O_2 = CO_2 \tag{2}$$

$$H_2O + C = H_2 + CO \tag{3}$$

$$CO_2 + C = 2CO \tag{4}$$

$$H_2 + \frac{1}{2}O_2 = H_2O \tag{5}$$

$$CO + \frac{1}{2}O_2 = CO_2 \tag{6}$$

Reaction (3) and (4) are gasification processes, which are endothermic. However, by combining reaction (3) to reactions (5) and (6), the result is reaction (2), which is the exothermic oxidation of carbon to carbon dioxide. Carbon burning need access to combustion gases, which mean that burning can only take place on the surface of the char bed. The thickness of this layer is about more than a few liquor particle diameters, probably less than 5 cm. (Grace 2004, 23.) Heat releasing reactions are needed for reduction that is described more precise in the next chapter.

4.2.1 Reduction

Reduction is the one of the main reasons why recovery boilers exist. Used chemicals in the cooking process are more profitable to recycle than buy new ones. Sodium sulfide is a specially desired end product in the recovery boiler. Reduction is part of sulfate-sulfide cycle, which is illustrated in Figure 19. Inorganic chemicals sodium sulfate (Na_2SO_4) and sodium sulfide (Na_2S) oxidize or reduce depending if there are oxygen, carbon or high enough temperature in the char bed.

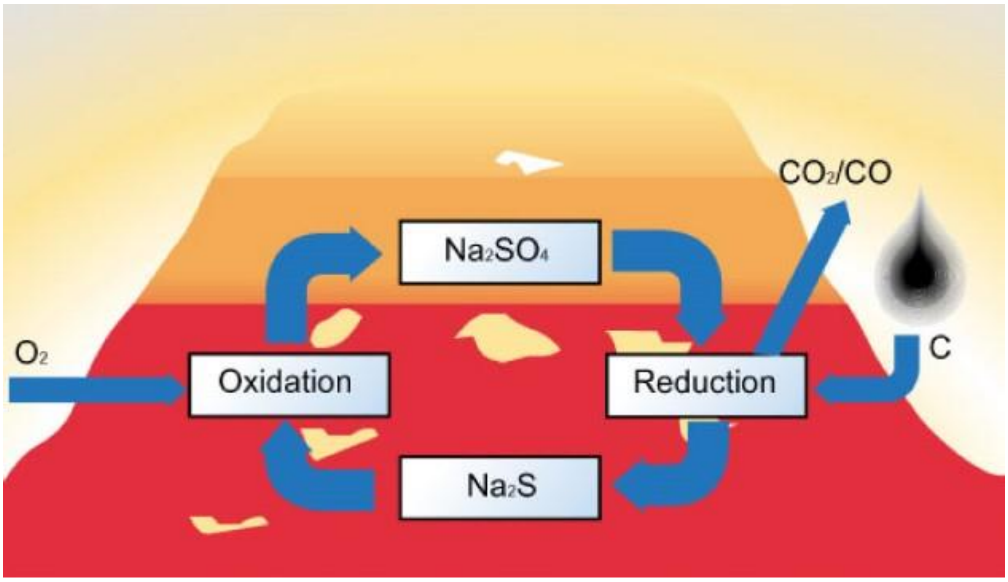

Figure 19. Sulfate-Sulfide cycle in the char bed. (Knowpulp 2017)

Sodium sulfide oxidizes to sodium sulfate during time between the cooking process and the recovery boiler. Reaction to oxidize is next:

$$Na_2S + 2\ O_2 = Na_2SO_4 \tag{7}$$

Reduction of sulfate to sulfide needs favorable conditions, which has to be high temperature and low oxygen content. Otherwise carbon that should take part to reduction would react with oxygen and release more energy to char bed. The chemical reactions of sodium sulfide are as follows:

$$Na_2SO_4 + 2\ C = Na_2S + 2\ CO_2 \tag{8}$$

$$Na_2SO_4 + 4\ C = Na_2S + 4\ CO \tag{9}$$

Reactions (8) and (9) are endothermic. Reaction (8) is more common in sulfate-sulfide cycle, because it is less endothermic than reaction (9). If there are carbon and oxygen present in the char bed, reactions (7) and (8) can be going simultaneously on the same burning char particle. By combining reactions (7) and (9), the results is simply carbon burnup (2). (Grace 2004, 24.)

Objective of sulfate-sulfide cycle and reduction is to gain high as possible ratio of sodium sulfide over the sodium sulfate. A reduction rate is measured from smelt from spouts or after dissolving tank. It is usually expressed as the molar ratio of sodium sulfide to sodium sulfate:

$$Reduction = \frac{Na_2S}{Na_2S + Na_2SO_4} \tag{10}$$

Common reduction rates for modern recovery boilers are 95 – 98 %, which is theoretical maximum. One hundred percent is practically impossible to achieve. Usually, the reduction rate is lower after dissolving tank than what is measured from smelt. That is because sodium sulfide reacts with oxygen outside of furnace and very small part of sodium oxidized back to sodium sulfate. (Vakkilainen 2005, 5-9.) The reduction rate depends on the concentrations of sulfate, carbon and the temperature. Time of reduction is the temperature depending. At 1000 ºC sulfate reduction to 90 % would be completed at 1 to 3 second and at 1100 ºC it would be completed in 0.5 to 1.5 second (Grace 1997, 173).

4.3 Optimal conditions

For the best possible reduction and clean combustion of carbon, the conditions of the char bed have to be optimal. The bed's shape, size and temperature are the main things to observe and influence when it comes to making the boiler more efficient. Good reduction is the first objective to achieve in the char bed. In his article MacGallum (2015, 1) claims that reduction efficiency increase of 2 – 3 % saves 300 000 – 400 000 $ every year on 1000 tsd/d recovery boiler.

Every furnace has an Optimum Operating Temperature (OOT) at which temperature the reduction efficiency is a maximum. Effect of the char bed temperature on reduction efficiency is illustrated in Figure 20. After certain temperature, further increase in temperature do not have enough impact on reduction efficiency. After modifications in a boiler in Finland, the temperature of the lower furnace increased 150 ºC and reduction efficiency increased from 90 % to 95 %. There are many other things that affect to reduction efficiency, but clearly char bed temperature has a big role in it.

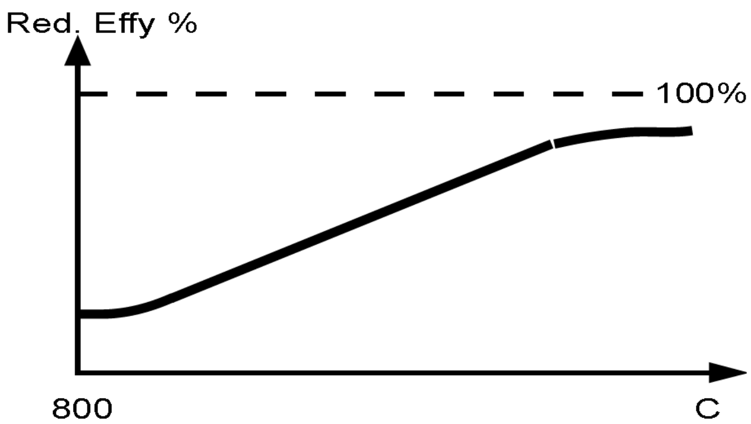

Figure 20. Reduction efficiency as a function of temperature. (MacCallum 2015, 2)

The Optimum Operating Temperature is determined by various factors, which are boiler load, combustion air system, char bed shape and black liquor temperature and pressure. Boiler load is predefined and cannot be affected much by operators. A combustion air system has some flexibility, but mainly it is limited by the original design. Operators can control operating temperature by air distribution changes between primary- and secondary air and by controlling black liquor pressure and temperature. (MacCallum 2015, 1.) Char bed surface temperature can be measured by infrared cameras. They can show a good estimates about the surface temperature and the temperature difference across the bed. The char bed bottom temperatures are usually measured with separate bottom-mounted temperature sensors. By knowing surface and bottom temperature, is possible to estimate a temperature gradient through the bed.

The shape and size of the optimal char bed are not well defined. Certain limits can be deduced from what is known about the characteristics of the bed. For good reduction sodium sulfate needs carbon, oxygen-free conditions and high temperature. The char layer on the smelt must be thick enough to ensure that reduction have oxygen free conditions. Bad shape can make the surface temperature uneven, because of the primary air do not spread evenly. That can create the low-temperature zones of poor combustion and therefore generate CO, TRS and hydrogen sulfide (H_2S) and lowers the reduction efficiency. Too high bed can have ramparts, which can deflect the air jets upwards, creating a central gas column in the furnace. These gas columns can cause carryover by taking char bed material with them or by catching light black liquor droplets on the way up. A stable char bed improves the reduction efficiency. A problem is that shape and size of the char bed may change many times during the day and reduction efficiency with it. Reasons for the shape changes can be changes in liquor solids, liquor nozzle fouling, boiler load and operator inattention. (MacGallum 2015, 3.)

Overall the char bed has to be high enough and right shape to ensure the following things:

- There is a protective char layer on the surface of the char bed.
- Enough space under the char layer to ensure that reduction occurs.
- High enough to protect floor tubes from too high surface temperatures.
- Not too high so primary air ports are not damaged by high surface temperatures of the char bed.
- Primary air can reach every place of the char bed surface and ensure even combustion.

The stable char bed can be achieve by controlling black liquor spraying and air jets distribution. For that, monitoring black liquor conditions should be improved. The problem has been that condition of black liquor spraying has been monitored by looking the conditions of the char bed. If char bed start to grow asymmetric, there can be some problem in black liquor properties or spraying is not even. Problems in black liquor spraying should be noticed before it causes big changes in the char bed.

4.4 Smelt

Smelt is molten inorganic material from char bed flowing out of the furnace through the smelt spouts. In the modern recovery boiler, typical smelt temperatures are 800 – 850 ºC. Smelt compositions do not vary much, but some difference is between different wood species. Typical smelt composition for softwood and hardwood is listed in Table 3.

Table 3. Typical smelt composition for softwood and hardwood. (Vakkilainen 2005, 5-10)

	Softwood (%)	Hardwood (%)
Na_2S	25 – 28	19 – 21
Na_2CO_3	66 – 68	72 – 75
Na_2SO_4	0,4 – 1,0	0,6 – 1,4
$Na_2S_2O_3$	0,3 – 0,4	0,2 – 0,4
Others	5 – 6	3 – 5

Smelt is not all the time pure molten material. From smelt spout cameras can be seen that sometimes smelt contains impurities like char or frozen smelt. If the carbon content of smelt is greater than 2 %, material is not flowing but rigid. It is not desirable, because most of the organic matter should be burn in the furnace.

Smelt solidifies typically at about 550 ºC. That temperature can easily vary depending of the content of the smelt (Vakkilainen 2005, 5-10). A small part of smelt can solidify to spout and cause uneven flow. Spouts should be cleaned frequently to avoid plugging that can cause the corrosion of the spouts or other danger situations to the recovery boiler. Smelt flow is not steady all the time. Common phenomenon is so called smelt flashing, which can be seen as the small bursts and flashes of the smelt. Usually, these flashes do not spread from the spout and are mostly harmless. Sometimes if the spout is dirty from frozen smelt, small flash can splash and hit a nearby worker. There are many reasons for smelt flashing. Something causes sudden movement inside the furnace near the spouts and it can be seen as a small burst of smelt. Sudden movement can be caused by falling material from upper furnace or char bed hill collapsing.

Greater damage can be caused by a smelt surge. It is phenomenon where huge amount of the smelt burst out through the spouts. Hot smelt spread over a wide area and causes a big mess. There are two basic requirements to a heavy smelt surge to occur. First is accumulation of smelt to the furnace. It may be a plugged spout, dams near the spout opening or craters in the char bed. The smelt accumulate to the furnace and collect pressure. The second requirement is a sudden release of the accumulated smelt. It could be triggered by cleaning a plugged spout, bed collapse, bed burn down, falling deposit etc. Eventually, something broke the dam and smelt burst out of the spout causing danger situations to anyone who are nearby (Tran et al. 2015b, 46.)

Most of the damage can cause a smelt-water explosion. It can happen when water mixed with hot smelt. When water is contact with smelt it evaporate very fast and cause the sudden increase of volume and a pressure wave of some 10 – 100 000 Pa. This force is strong enough to bend the furnace walls and cause a lot of damage (Vakkilainen 2005, 5-8.) Smelt spouts cannot handle all the heat stress without proper cooling. Most of the smelt spouts have a circulating water cooling system. There is always risk of spout breakage and therefore the risk of the contact of the water and smelt. That is why the spouts should be changed every year.

After spouts, smelt flows to dissolving tank, where it is mixed with water or weak wash and forms green liquor. Dissolving is loud, vibrating and heat releasing action. Tank where it happens is well insulated and has thick concrete wall. Because of the violent action of the dissolving tank, the flow of the smelt has to be controlled. Heavy smelt flow can cause an explosion and it can occur the same way as the smelt surge. This time the smelt flow to dissolving tank, but with extraordinary heavy flow. Dissolving tank cannot handle all the smelt, which cause loud sound and vibration to tank and in the worst case, a dissolving tank explosion. The tank explosion between 1973 and 2005 was investigated and it was found that 24 of 27 incidents was related to heavy smelt runoff. Boilers with a sloped furnace floor are more vulnerable to the dissolving tank explosion. (Tran et al. 2015b, 42.)

5 VISUAL ANALYSIS

The purpose of this chapter is to examine the possibilities of visual analysis in the recovery boiler. Covered subjects are black liquor spraying, char bed, smelt spouts and carryover. Those things are especially important for recovery boiler operating or offer an easy way to integrate visual analysis into them. The boiler has many components or phenomena that could be combined with visual analysis, but not all can be handled due to keep scope of this thesis reasonable. For this thesis there was available real image and video footage from an Eastern Finnish recovery boiler. Footage was from char bed, smelt spouts and black liquor spray. Andritz has under development way to utilize those footages for visual analysis. This thesis does not try tell how to utilize or what visual analysis technique Andritz should use. The purpose is to find out what things are possible to analyze in the recovery boiler and what their benefits to the process are. The benefits can be sought on the following issues: chemical recovery, power generation, maintenance efficiency or components durability, low-emissions, safety and research opportunities.

Term *visual analysis* means using machine vision to analyze image or video footage. The computing power of current computers enables near real-time analysis. Analysis tool is possible teach to find specific colors or shape from the footage and give back numerical value. If something can be seen, it can be analyzed and measured. From still image, can be measured dimensions, areas of something or detect specific colors. From those data is possible to make algorithm that combines values from multiple measurements. From many consecutive images, in other words from moving pictures, is possible to detect changes of objects over the time. For example, those can be velocity, acceleration and change in volume. Things to observe from video footage can be separated to two class. Fast and slow phenomena. Fast phenomenon can be sudden collapse of the char bed or something drop from the upper furnace. Slow phenomenon can be growing of the char bed or plugging of the smelt spout. Those thing can be detected in time and intervene if necessary.

There are already many visual based analyses around recovery boilers. Experienced operator can make conclusion about boiler condition by looking carryover probe sample, smelt reduction sample or live footage from char bed or smelt spouts. However, human image interpretation is always relative and can vary by the viewer or day’s mood. It is possible to find out what details or color changes operators is trying to detect from the samples. By knowing these things, it is possible to create image analysis tool and algorithm, which work every time same way. Data from analyzed image is possible to record for later use and changes over time are easier to study. At beginning visual analysis tools should be help of the operators, but after a certain amount of time and experience, it could be possible to combine with automatic system.

5.1 Black liquor spraying

By controlling black liquor spraying, it is possible to affect directly or indirectly to big part of the recovery boiler operations. In optimal situation black liquor spray is distributed evenly to the furnace, droplet size is desired and there are not any plugging or malfunctions in the nozzles. Spray velocity is also important property that affects the combustion phases and flight paths of droplets. There are not any direct way to measure or observe spray behavior. From the furnace camera, operators can see that char bed grown asymmetric and therefore spray might not be evenly. Increased carryover can indicate that droplet size is not proper.

Many properties of black liquor affect to spraying and droplet formation. Density, surface tension and viscosity are the main properties of droplet formation. Flashing is phenomenon that is the result of increased dry solid content of black liquor. High dry solid content black liquor has high viscosity so it has to be pressurize and heat up over the atmosphere boiling point. Heating the black liquor lower the viscosity. Flashing during spraying affects spray pattern, the velocity of spray and size of droplet. Even couple degree change in the temperature of black liquor or boiling point can make a difference. Boiling point of black liquor can be different depending of used wood and cooking conditions. The temperature and pressure of fired black liquor can stay the same, but variations in black liquor properties can make spray pattern complete different.

In the recovery boiler, a camera for black liquor spray could be of huge help. With a proper visual analysis system it is possible to see how spray behaves in different furnace conditions and with different black liquor properties. Above the black liquor gun is very hot and dirty conditions and that brings problem for camera durability. Solutions could be a camera system, which is temporarily placed above the liquor spray and withdrawn after a certain time. The camera takes a short video or pictures and saves them to the server, where the software analyzes them. From the footage could be seen black liquor sprays’ opening angle, the direction, velocity and maybe even the size of droplets. With those data, there could be chance to found the reasons for high carry over and asymmetric char bed.

In an optimal situation, with the visual analysis system of black liquor spraying, operators would learn what style spraying should be. They would take a look what kind spraying is and would know if there was something wrong with it. By seeing the spray pattern, the operator would know if there are need to change liquor pressure, the temperature or clean nozzle.

5.1.1 Spraying examples

The purpose of these examples is to show what is possible to see on a video in the real furnace conditions. The spraying images are screenshots from test video footages. They are from the same recovery boiler, but might be recorded with a different camera, setup or angle of view. Black liquor is sprayed from beer can nozzle. Conditions are hot and very dirty, which makes it difficult to take a clear video.

Three distance to the camera:

The first example is filmed at three different distance. All three different view position is shown in Figure 21. The nearest angle of view (Figure 21a) shows more about the droplets and conditions of the nozzle. The picture shows how dirt is accumulated to the right side of the nozzle and it causes small disruption. The cone is a little bit directed to the left. The farthest angle of view (Figure 21c) is blurred but shows longer view of the spray cone. From it is easier to measure the direction of the spray cone. The farthest angle of view shows how much there are dirty and flying particles in the recovery boiler. Middle angle of view (Figure 21b) do not shows any particular interesting or new things compared with other angle of views.

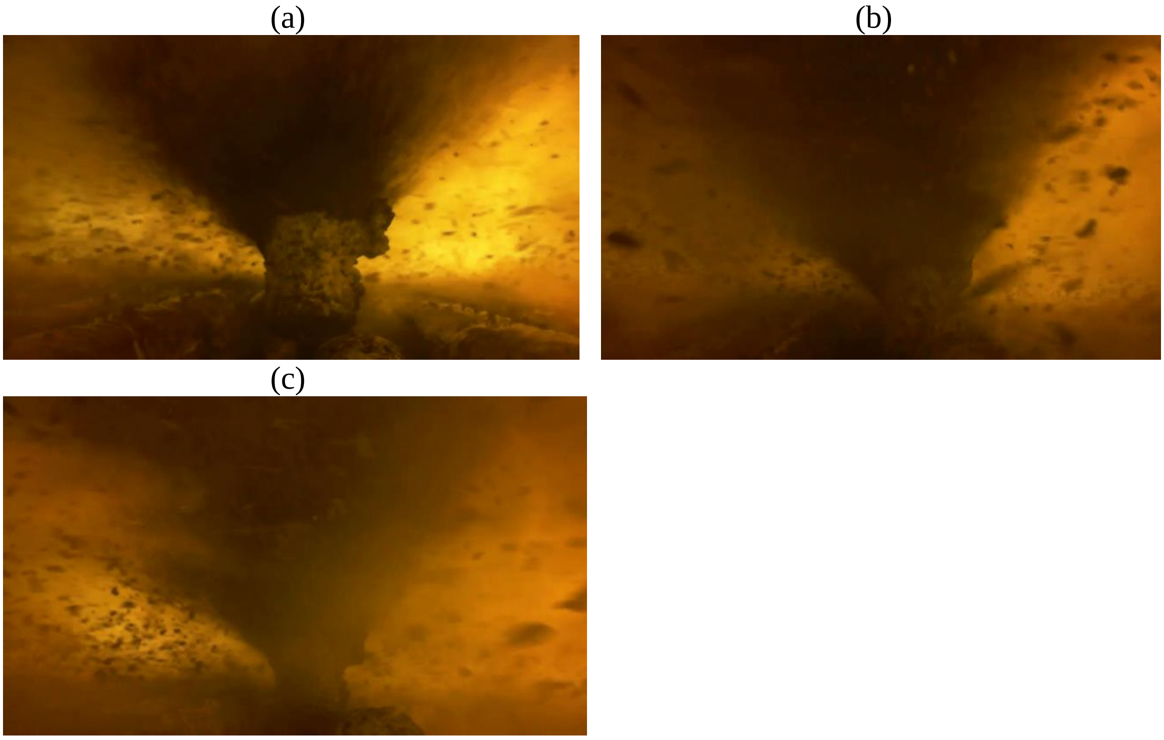

Figure 21. Black liquor spray at three different distance. (a) Is the closest view, (b) is the middle view and (c) is the farthest view.

Dirty nozzle vs. clean nozzle:

In this example, the nozzle is filmed before and after cleaning. Recording was done on the same day and with the same camera setup. Example images are from the right (Figure 22) and the left (Figure 23) side of the recovery boiler. Beer can nozzle can get very dirty and it has a dramatic effect on spraying. From the pictures can be seen that accumulated dirt changes the spray cone of the black liquor. In Figure 22a the dirt is on the left side of the nozzle and in Figure 23a on the right side. The pressure and volume flow of the black liquor is presented in Figure 24. It proves that there are no changes in them, which could change the shape of the spray. Cleaning of the right side nozzle can be detected by a little drop in the amount and pressure of the black liquor. The only thing that affect to spray is dirty on the nozzle. More research should be done on the effects of the dirt on the nozzles and the difference between the various nozzles. This kind camera setup offers a great tool for it.

(a) **Right dirty:** (b) **Right clean:**

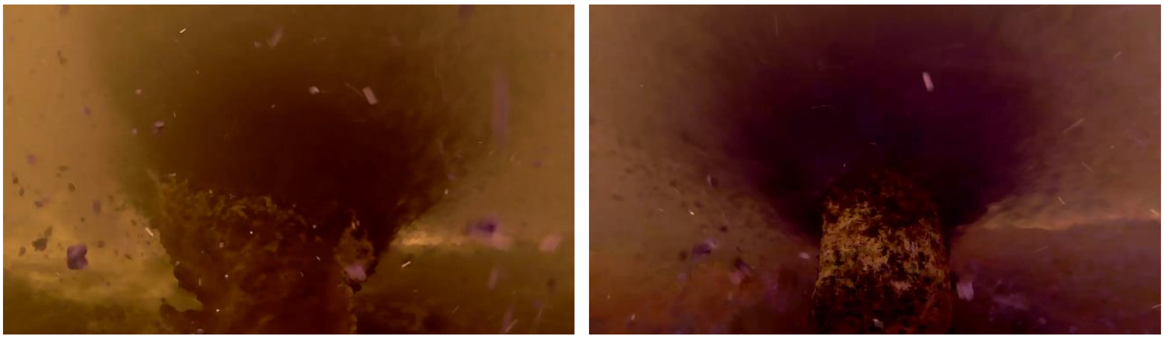

Figure 22. Right nozzle before (a) and after (b) cleaning.

(a) **Left dirty:** (b) **Left clean:**

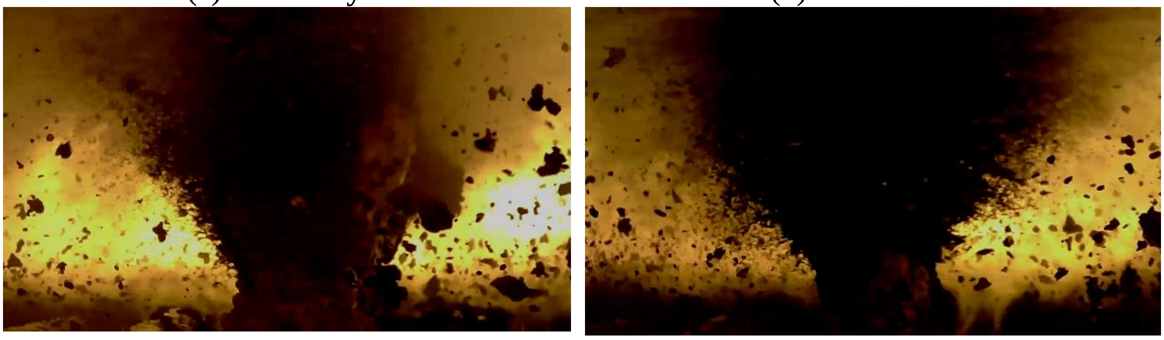

Figure 23. Left nozzle before (a) and after (b) cleaning.

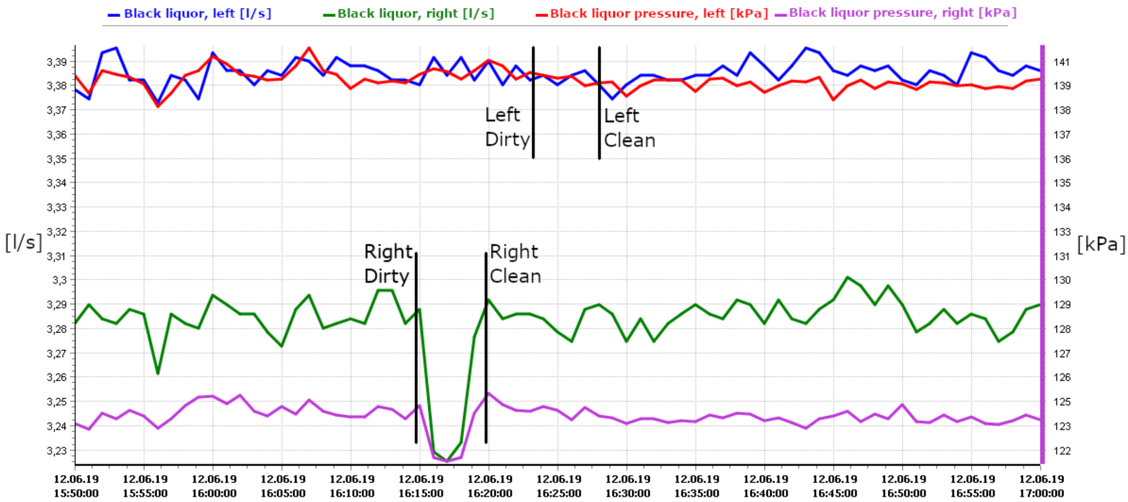

Figure 24. Black liquor properties to left and right nozzle before and after cleaning.

In Figure 25 is the example of how badly dirty can change the direction of the spraying. This kind spray could be reason why the char bed sometimes grows to other side of the furnace. Also the droplet formation suffers because of this kind uneven spray. On the right side of the picture can be seen how spray breaks down to droplets. Spray may break down too early to droplets and size of the droplets are different compared with others. Small droplets can get caught with flue gas and cause carryover.

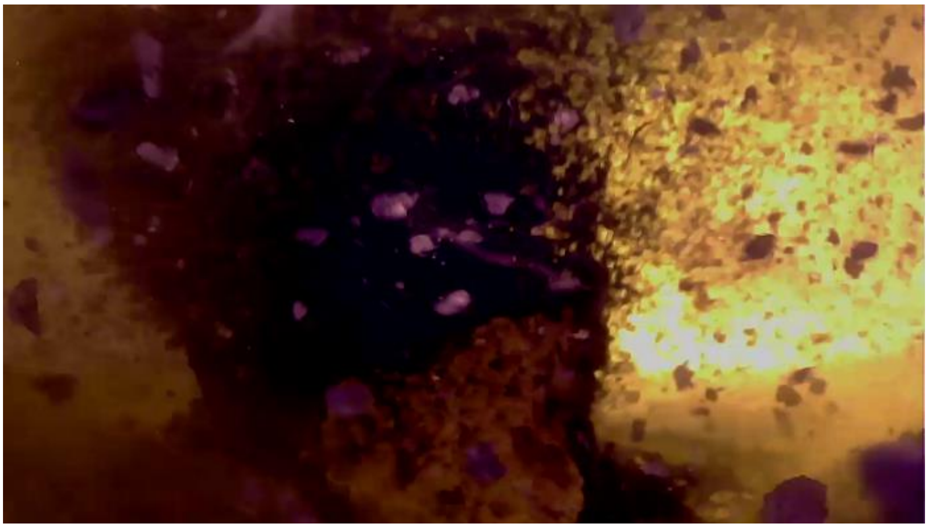

Figure 25. Totally uneven spray.

Different view angle:

If furnace conditions are too tough for the camera, one possibility is to record spray from liquor gun opening. There, the camera is safe from the worst conditions of the furnace. In Figure 26 is shown what from that view of angle could be seen. It can be seen that spray is not conical as it should be. Probably something blocks the spray to spreading symmetry or nozzle can have some design problem. This kind spray also hit partially to wall.

Figure 26. Top view of beer can nozzle.

5.2 Char bed

Char bed conditions have been visually monitored a long time. Usually there are couple char bed cameras in furnace and operators have used them to check out conditions of char bed. Normal camera is not suitable for hot furnace, so infrared cameras have been used instead. Infrared camera show shape of the char bed and temperature difference in different part of furnace. Absolute temperature it cannot tell, but it is good help to see temperature changes over time or between two places.

In chapter 4 was told that optimal char bed affect to reduction rate, distribution of heat to wall tubes, clean of combustion and conditions of lower furnace tube materials. With image analysis tool, it is possible to create 3d-model of char bed. Model can be used to keep track of height and volume of char bed. It also make possible to follow symmetry of char bed, which can affect to whole boiler conditions. For optimal reduction, temperature of the char bed has to be high enough. With infrared camera, observing temperature changes of the char bed is possible. If surface temperature of the char bed starts to decrease, is safe to assume that it has some effect to the reduction rate.

Difficulties are lack of cameras in furnace. There may be some blind spots and for 3d-model analyze software have to assume that char bed height decrease steadily to corner or bed's shape is reasonably symmetrical to use opposite side of the bed as example. Assumptions weaken the accuracy of measurement. Furnace conditions are hot and dirty. Because of that, the cameras are located between wall tubes and need a lens cleaning system. For the more accurate visual analysis, the recovery boiler should has at least four furnace camera.

5.2.1 Slow phenomena

Slow phenomena in the char bed are growing, moving of the mounds and temperature changes in the bed or wall tubes. To detect these, visual analysis software does not need to be active continuously.

Mound growth

In Figure 27, 28, 29 and 30 is presented one example of the char bed mound's development from its peak to almost flat bed. Figures 27 and 29 are taken same time, but different side of the furnace. Figure 28 and 30 are taken one hour after. Red lines illustrates development of the char bed mound during that one hour. Blue lines visualize furnace geometry. Horizontal lines in all images are at primary air level and in figure 27 and 29 one vertical line is left side corner of the back wall.

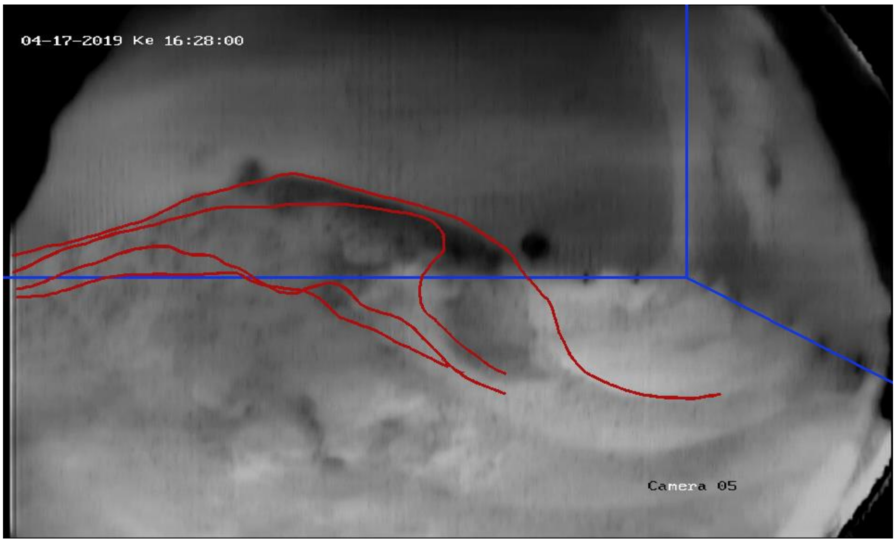

Figure 27. Highest point of char bed mound. Right side of the furnace.

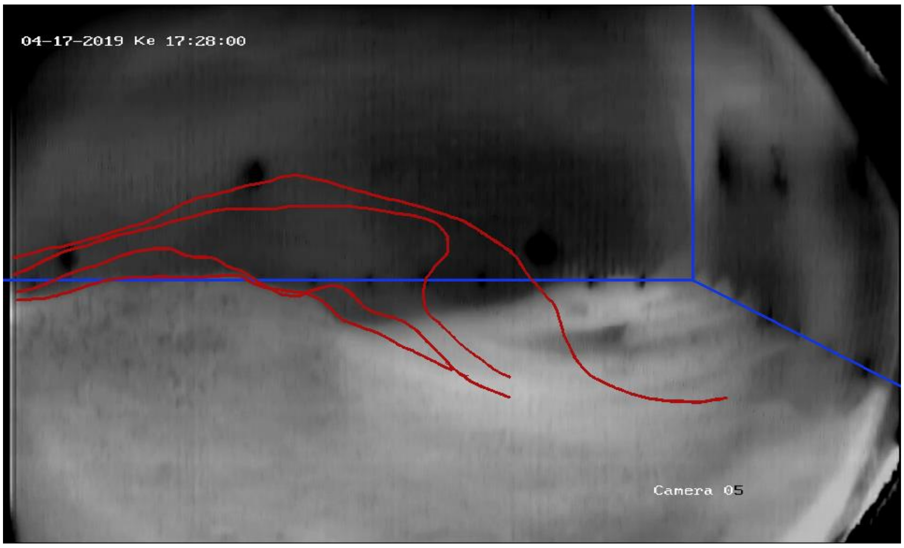

Figure 28. Lowest point of char bed mound. Right side of the furnace.

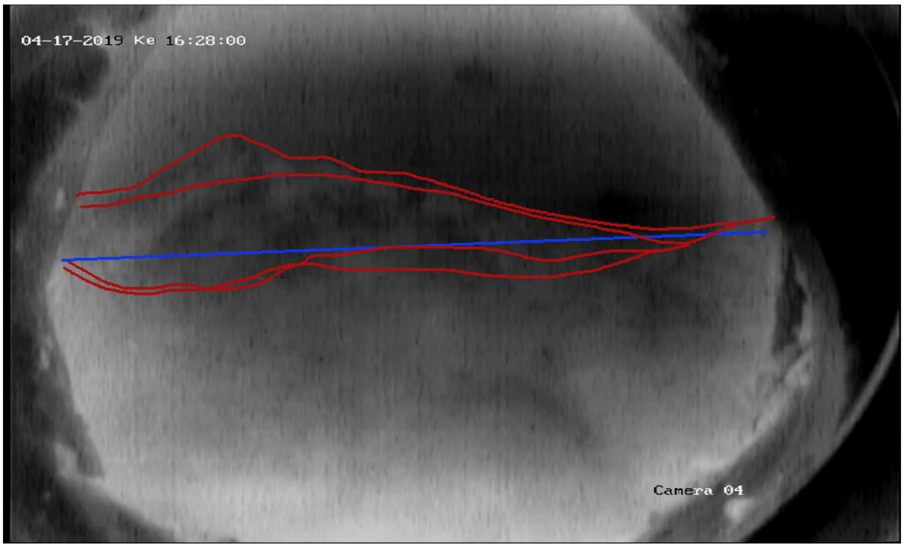

Figure 29. Highest point of char bed mound. Left side of the furnace.

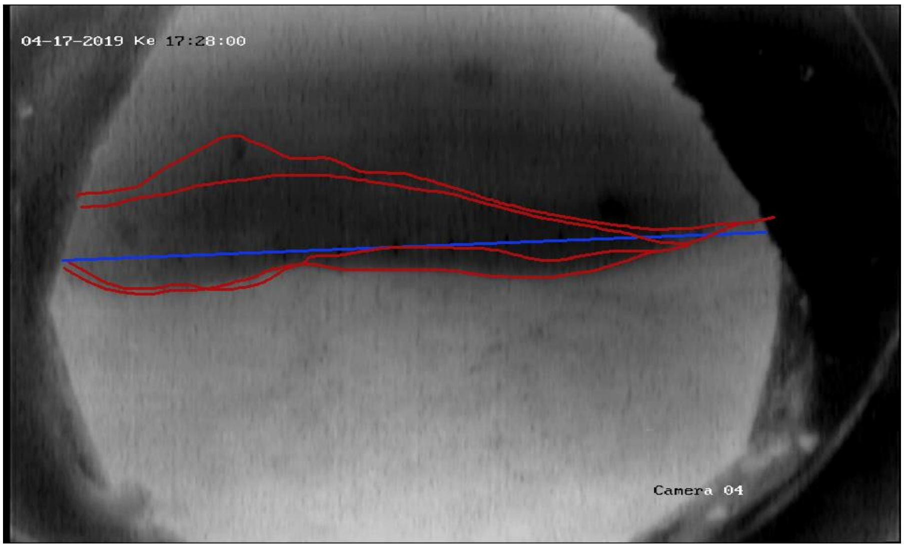

Figure 30. Lowest point of char bed mound. Left side of the furnace.

It seems that the nature of the char bed is to grow and shrink by turns. For stable bed conditions, slow growth or shrink is allowed and there is no need to control it. However, too fast bed growth or shrink indicates that something do not work as should. Visual analysis system could measure growth speed and warn when it is too fast.

Temperature changes

When the mound is growing, surface of the bed is cooler then surrounding bed. It can be seen as darker spot in the infrared image. Cooler conditions can be the results of the bad air distribution, black liquor spray is uneven or droplets are too big. Black liquor droplets do not burn or dry enough during air flight and start to accumulate on specific spot on the char bed. Figure 31 and Figure 32 are images that have been analyzed to show approximately temperature at certain points. Images are from the same time as previous char bed growth images. When bed is growing, top of it is darker and temperatures below 1000 ºC. At some point operators increase the primary air flow or top of the mound reach secondary air level. That trigger mound to burn at higher temperature and it starts to decrease. In Figure 32 can be seen that temperature on the bed surface is over 1000 ºC.

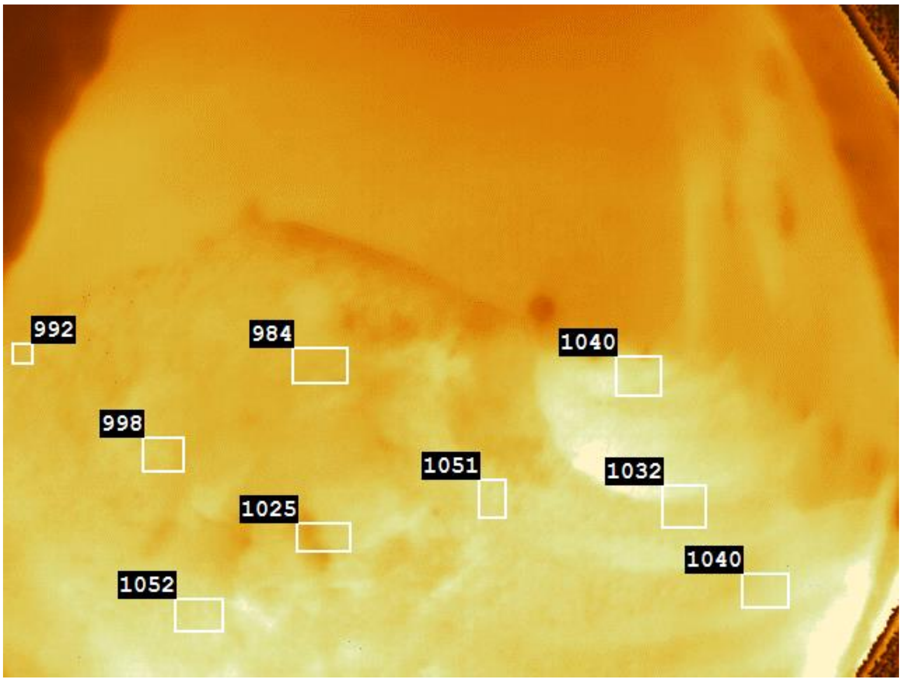

Figure 31. Furnace temperatures.

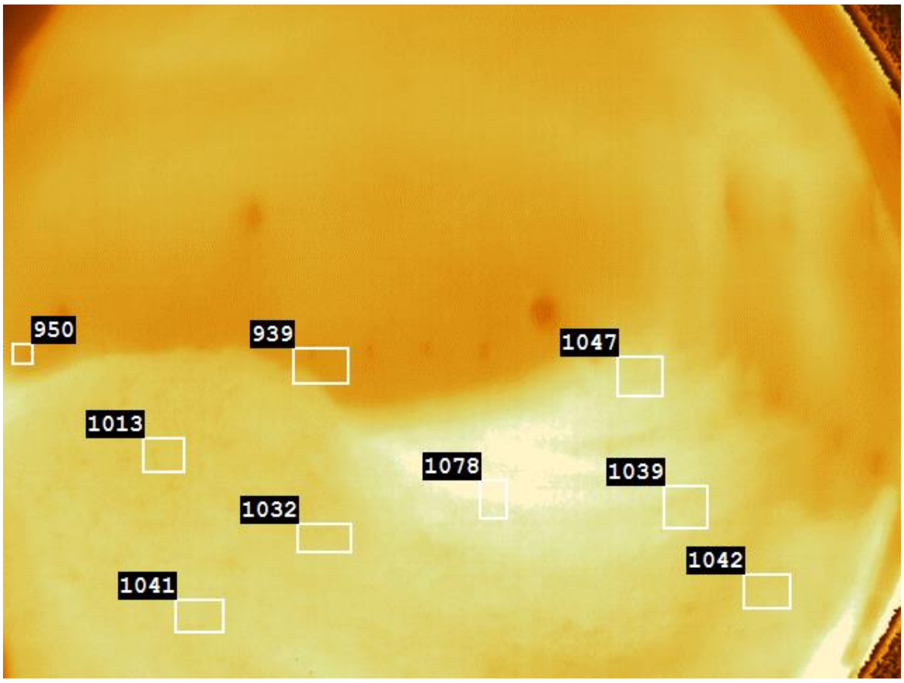

Figure 32. Furnace temperatures.

The surface temperatures affect not only the growth of the bed but also to the emissions and reduction rate. Sulfur dioxide (SO_2) emissions can be controlled by good and stable combustion. High temperatures at the lower furnace reduce the amount of the sulfur emissions. While uneven burning or the cold spots at the surface of the char bed can cause significant increase in sulfur dioxide emissions. Reduction needs high temperature and speed of it can be doubled when the temperature increase 50 – 60 ºC (Raiko 2002, 543-547). All thing considered, the surface temperature should be monitored and tried to keep reasonably high.

Wall tubes and primary airports stress

Third noticeable slow phenomenon is a deposit of the black liquor and smelt on the wall. A moment when amount of deposit is significant and hotter than surrounding tubes is shown in Figure 33. Occasional deposits have no significant effect on the tube material and are almost impossible to avoid. However, if deposits start to appear in the same place continuously, it is worth considering that is there some problems in black liquor spraying or in air injections that cause deposits formation. Primary objective is to get black liquor to char bed, not on the walls.

Figure 33. Deposits of black liquor and smelt on the wall.

Andritz has done research about how height and shape of the char bed effect on furnace conditions. As part of the research, temperature sensors were installed in tube fins at primary air level. The sensors data was compared with pictures taken from the char bed. In Figure 34 and Figure 35 is shown two situations in the furnace. Black and light red lines are values of the temperature sensors. Red vertical line is the moment when the image in the corner of the figure is captured. The exact values of the temperatures, dates and parameters of the investigated recovery boiler is left out in this thesis. In Figure 34 is situation where the char bed is low and smooth. Both values of the temperature sensors are reasonably smooth. In Figure 35 char bed is bumpy and much closer the primary air level. As can be seen from the figure, black temperature lines have huge spikes. Char bed growth has an effect on the temperatures of the lower furnace.

These kind thermal cycles can cause thermal fatigue that has been a problem in recovery boiler floors. Long lasting thermal fatigues can cause cracks to material. Sanicro 38 type composite material, which is nowadays used as floor tube material, can withstand three times the number of thermal cycles compared with 304L type composite. Sanicro 38 is usually used as lower furnace material to primary air level. Upper from primary air level is carbon steel or 304L composite. (Vakkilainen 2005, 10-8 & 10-14.)

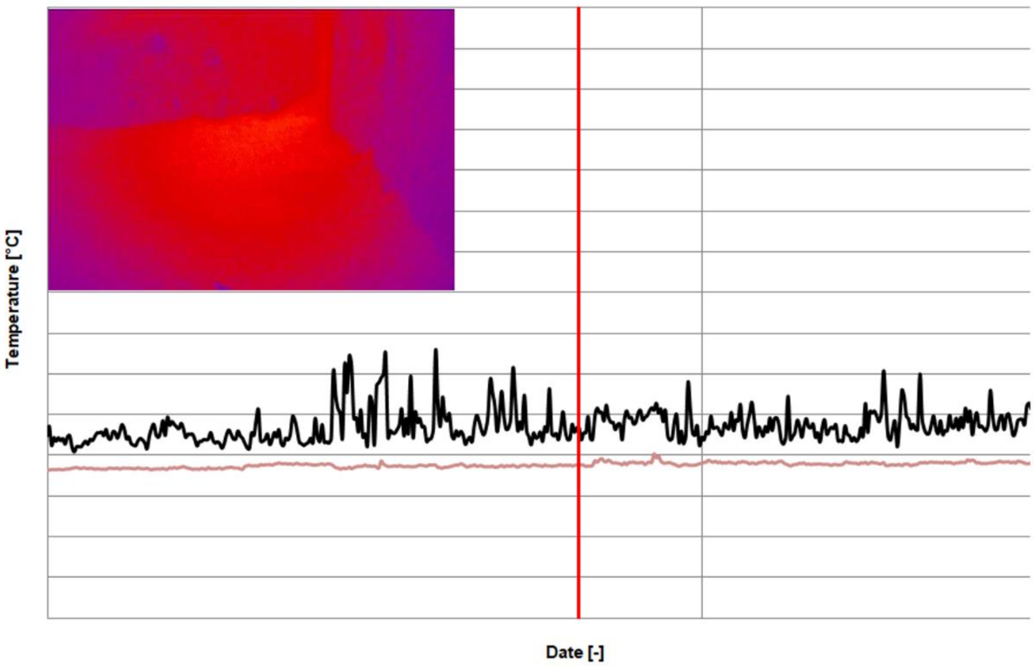

Figure 34. Low bed - Low temperature (Laitinen & Pakarinen 2019)

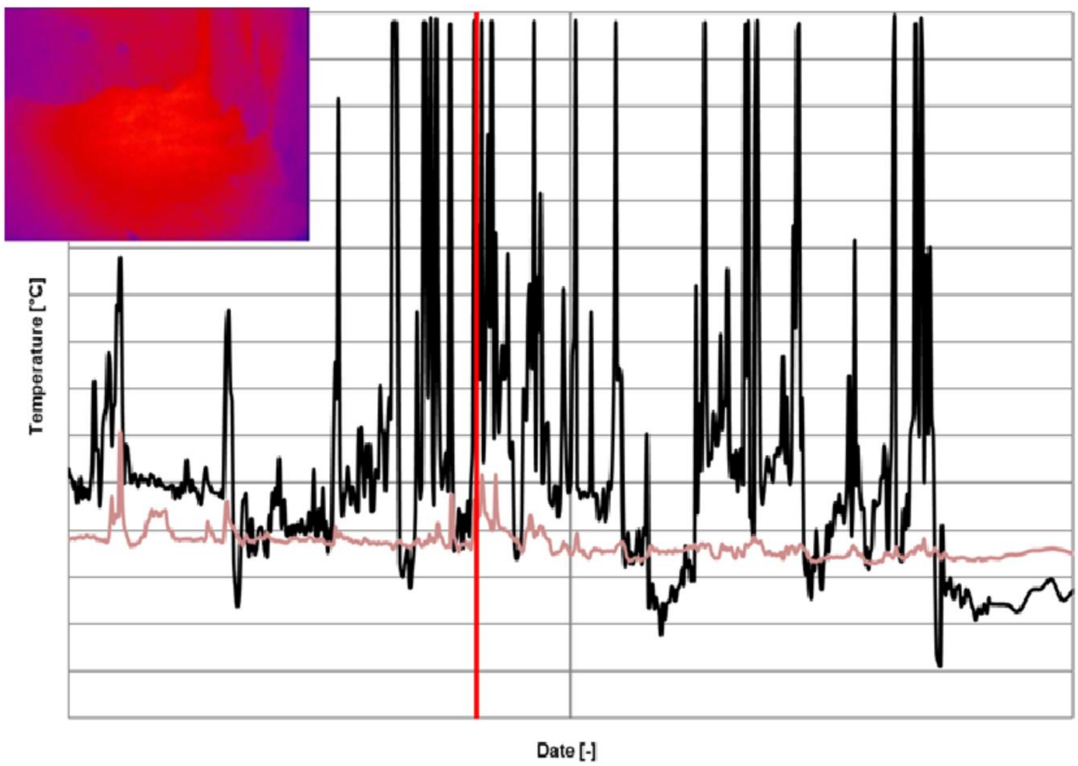

Figure 35. High bed - High temperature (Laitinen & Pakarinen 2019)

With a proper furnace camera system, it could be possible to detect the causes of thermal fatigues in the lower furnace. The height and shape of the char bed have effect on the temperature near the primary airports. Furnace cameras and visual analysis system could be also use to follow deposits on the walls. With this data and material conditions inspection during a shutdown, it could be possible to find out if there are significant correlations between the visual data and real conditions of the wall tubes.

5.2.2 Fast phenomena

Fast phenomena in the char bed are things that occur only short time. Video footages are only sources to detect these things. Phenomena can be the collapse of the char bed mound, smelt moving and air flows caused by primary air, slag falls from upper furnace or wall tubes, and black liquor spray disturbance seen as black rain.

Collapse of the mound is usually results of the uneven growth of char bed. When mound collapse it can cause a small char avalanche. In Figure 27 mound is close to collapse to the right side. If collapse happen near smelt spouts, it can increase the smelt flow temporarily. It is desirable that mound collapse does not happen near the primary air ports.

Slag falls happen because an amount of the deposit on the walls or upper furnace cannot hold its own weight. One slag fall sighting does not indicate anything about the condition of the furnace. In ideal situation, walls do not collect deposit of material. Due the fact that black liquor is sticky fuel and flue gas are fouling, the dirt deposits on the walls are inevitable. If slag falls near the smelt spouts, it can be seen as a flashing of smelt. Visual analysis system could calculate the number of the falls in a certain time. An increased number of slag falls can indicate that something is wrong in the furnace.

Black liquor spray disturbance can be seen sometimes as black rain. Black liquor droplets should have gone through drying and devolatilization before they hit the char bed. The temperature of droplets during char burning can be 400 ºC higher than the devolatilization temperature (Raiko 2002, 537). In many cases, beginning of the char bed growth started with a sighting of black liquor rain. It can cause the surface of char bed to cool down, which can cause that char bed starts to accumulate and grow.

5.2.3 **Symmetry example**

While scanning pictures taken from a char bed, it was noticed that material in bed flows to the left side of the boiler. Char bed is constantly moving and occasionally forms mounds that can be easily detected. Those mounds seemed to be on the left side of the boiler more often. Also char bed height seemed to be most of the time higher on the left side. This observation was done by comparing char bed's edges height with primary air ports. The phenomenon needed a closer look. Source material for this case was images taken with an infrared camera and at intervals of one minute.

First mission was to confirm that peak of the char bed's mounds form mostly on the left side of the boiler. It was done by looking through pictures from the char bed and finding moments when a peak is the highest. Forty mounds were observed over two weeks. Every mound is mapped to Figure 36. Figure 36 is cross-section from the boiler at primary air level. Lines around the section are primary air ports. *Ca* means a place of camera and red lines show view areas of cameras. It can be seen that there are some areas that cannot be seen. Letter *b* means places of startup burners. Those are easily located in char bed pictures and help positioning mounds to map. Two smelt spouts can be seen in char bed pictures. Spouts one and three are approximately under fourth primary airport from the corner. Spout two is at the center of back side of the boiler. Six mounds were in the center of char bed, five mounds were the right side and even 29 mounds were the left side of the boiler. The amount of mounds on the left side is significant.

This kind asymmetry indicates that something is wrong in the recovery boiler. Primary air flow does not push the mound strong enough to center of bed or black liquor gun directs the spray at wrong way. Asymmetry can also causes problems with an operation of the boiler. When the mound starts to decrease it burn much more intensively than char on the other side of boiler. That can cause unbalanced conditions at the upper furnace. Flue gas temperature, excess oxygen or carryover after the furnace can be unbalanced in a left-right axis. Objective is to operate the boiler stable and in a balanced way.

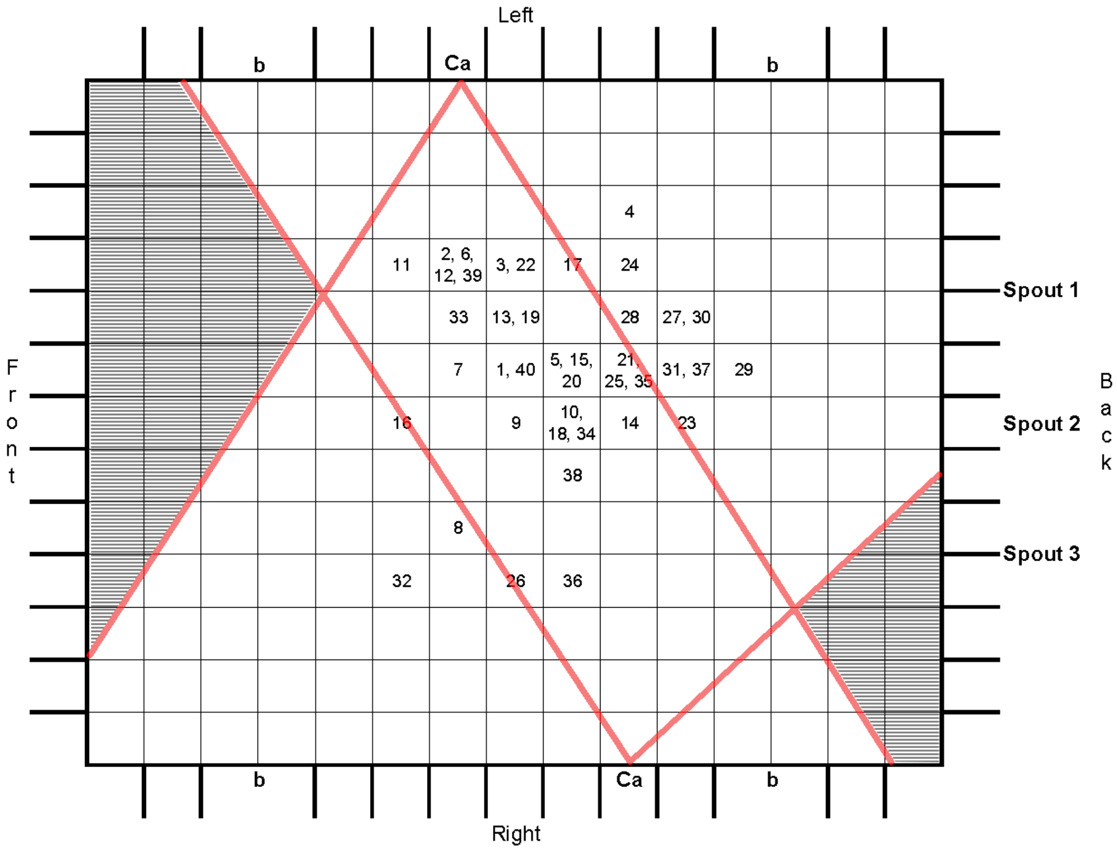

Figure 36. Cross-section of lower parts of furnace.

5.3 Smelt spouts

Smelt spouts have had camera monitoring for a long time. It has been used as help for operators to know when it is time to clean spouts or to spot some unusually events. Cameras are located above of the spouts and usually each spout has its own camera. These cameras are easy to make work with visual analysis software. Video footages from smelt spouts is researched in this thesis

Many things can be observed from smelt and its surroundings. Visual analysis can be used to see the volume flow rate and velocity of a smelt. Velocity of the smelt flow can be measured by observing how long it takes one char particles to travel from spout opening to the bottom of the spout. It is good to remember that velocity of the flow is faster on the smelt surface than near the spout surface. In smelt spout flow, the maximum surface velocity is about 1.25 times higher than average velocity (White 2011, 702). The width of smelt can be measured by knowing the dimensions of spouts. Volume rate can be calculated by knowing width and velocity of smelt, and the dimensions of spouts. Visual analysis system can also detect dirtiness of smelt, frozen smelt, which can plug the spout, and smelt flash that occurs from time to time. Smelt flash is small kind flare-up that do not significantly dirt the smelt spout surroundings, but can cause danger situation to people near the spout.

Five different situations that can be observed from smelt spout cameras are shown in Figures 37 - 41. Figure 37 shows clean smelt flow. This kind smelt flow is desired. Smelt does not contain impurities and flow is smooth. Figure 38 shows smelt flow, which has impurities with it. Those impurities are mostly char particles. Carbon should be involved in reduction reaction and burn in the boiler. It should not come out with the smelt. If a smelt sample contains a lot of carbon, it indicates that reduction rate can be high. This is not desirable because carbon should burn in the boiler and release heat energy much as possible.

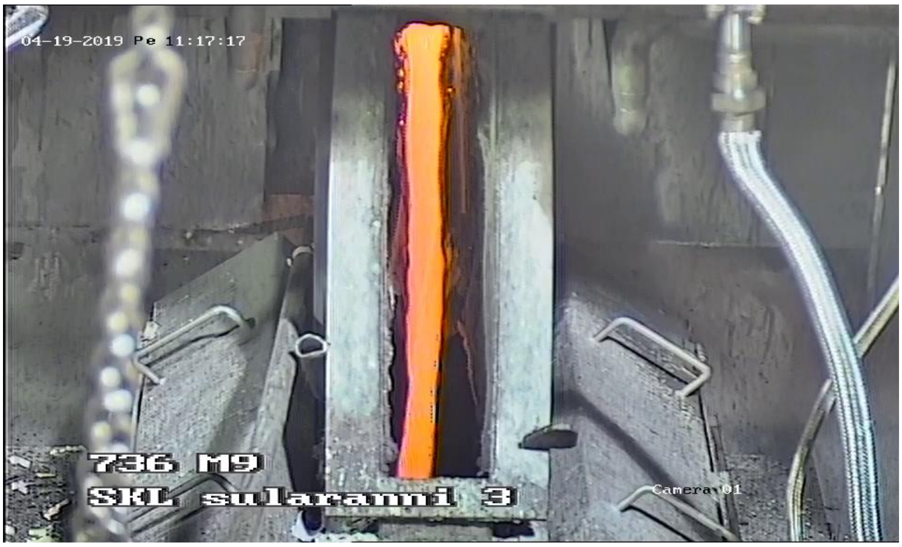

Figure 37. Clean smelt flow.

Figure 38. Dirty smelt flow.

Figure 39 shows how frozen smelt and char accumulate above the smelt flow. Smelt still flows under the layer of solidified stuff. This solidified stuff can accumulate more and cause plugging of the spout. Sometimes smelt splash to solidified layer and leave burning spot on the spout. That has potential to overload the spout cooling system and that is why spout is frequently cleaned. Figure 40 shows a plugged spout. This particular image is taken when all other spout works normally, but this one is for some reason plugged. The plugged spout should be opened immediately, because smelt can accumulate behind it and burst out at once.

Figure 39. Frozen smelt layer above smelt flow.

Figure 40. Plugged smelt spout.

Figure 41 shows smelt flash that occurs from time to time. Flash lasts from a couple of seconds to ten seconds. Usually something like slag falls from an upper furnace to char bed and causes smelt flash. Depending where falling happen and how big it is, flashing can be seen from either one or multiple spout.

Figure 41. Smelt flash.

These things offer new possibilities to study a boiler and smelt spout conditions. Flow rate measurements can offer some new way to calculate the energy balance of recovery boiler. Boiler conditions may be unbalanced if smelt flow is higher on one side of the boiler. So far total smelt flow rate has been possible to measure from dissolving tank, but with visual analysis, it could be possible to measure it faster and separately for each smelt spout. The quality of the smelt could also be monitored. Smelt should not contain unburned particles like in Figure 38 can be seen. The visual analysis system could calculate the number of impurities per minute and form a graph from that data. In this application, the graph could also be formed for each smelt spout. That could help to see if there are some operating states, which causes dirty smelt.

Possible application for the visual analysis of the smelt spout could be a smelt surge warning device. A smelt surge happens when something block smelt flow in the furnace. It can be seen as totally stop or calmly flow on spouts. Something blocks the smelt for flowing until eventually it broke and cause surge of smelt coming from smelt spout by force. The visual analysis system could warn operators about an unusual event and they would have time to prevent or minimize the damage caused by the surge.

In his Master's thesis Rantanen (2017) suggest that spout conditions could be possible to know by smelt flow changes and temperature change of spouts cooling water. He proposed the idea that heat fluxes, which change often, and smelt blockages cause more fractures to spouts than evenly flowing smelt. By smelt spout visual analysis system, it could be possible to study these things more precise and develop more understanding about spouts. Spouts are things that have to be change once a year and it would be huge evolutionary step to promise a longer lifetime for them.

5.3.1 Smelt spout example

In the next example is calculated volume flow of smelt to three different smelt spouts in three different operating states. Data for calculations are video footages from smelt spouts and technical drawing of spout. From video footages was measured width and velocity of smelt. Technical drawings help to scale things seen from video to right size. Width of the smelt is needed to calculate the cross section area of the smelt flow. The volume flow of the smelt can be calculated by multiplying the velocity of the flow to cross section area of the flow.

The real width of the smelt can be calculated by knowing the real width of spout and width ratio of smelt to spout from video footage. The ratio of width can be measured by taking screenshot from video footage and using photo editor's measuring tool, which tells how many pixels are between two points. The real width of the spout can be measured from technical drawing. For example, the width of smelt and spout from image are 45 and 83 pixels and their ratio is 0.54. The real width of the spout is 95 mm and multiplying it with the ratio gives the real width of the smelt, which is 51.5 mm. By knowing the width of the smelt and dimensions of the spout, it is possible to calculate the cross section area of the smelt flow.

Velocity of smelt can be measured by calculating how long one char particles take time to travel from spout opening to the end of the spout. The smelt is fast so time cannot be measured with a stopwatch. Instead, by knowing the frame rate of the video and counting the number of frames that particle takes time to travel, it is possible to calculate the real time. For example, the video footages frame rate per second is 25 and travel time of particle is seven frame. Char particles travel time is $\frac{7\, frame}{25\, \frac{frame}{s}} = 0.28\, s$. Distance that char traveled in that time is measured from technical drawing. If travelled distance is 380 mm and takes 0.28 seconds to travel it, the velocity is 1.36 m/s. In an open channel flow the fluid surface velocity is not the same as average velocity of flow. In this example, the correction factor was estimated to be about 1.25. Surface velocity is divided by the correction factor to give an average velocity of 1.09 m/s.

In Table 4 is listed calculated values. At the top is operating situation where dry solid content to the recovery boiler is 2.72 kg/s and main steam production is 19.42 kg/s. Total smelt flow is then 1.02 l/s. The density of a smelt is approximately 2000 kg/m^3 (Vakkilainen 2005, 5-10), which means that total smelt mass flow is about 2.04 kg/s. Typical smelt mass flow is about 0,4 – 0,48 kg per kilogram of incoming black liquor dry solids flow. In the first situation smelt flow mass per incoming dry solid content is about 0.75 kg/kg$_{DSC}$, which means that smelt mass flow compared with incoming dry solid content is higher than it would be in normal operation situation. First situation was the day when the recovery boiler was temporarily run at half power. Probably smelt would run out or solidified on the furnace floor at some point. It did not happen because later of the day, recovery boiler was run up. Part of the main steam is produced with the help of startup burners, which also helps decreasing the amount of the smelt in the furnace. The second and third situations in the table are normal operational states. This recovery boiler is operated with dry solid content from 10 kg/s to 13 kg/s. As can be expect, the total volume flow of smelt increase when the mass flow of the dry solid increase. Smelt velocity is almost the same in both normal operational situations. Smelt mass flows per black liquor dry solid contents in situations two and three are 0.44 kg/kg_{DSC} and 0.54 kg/kg_{DSC}.

Table 4. Calculated volume flows to three different smelt spout in three different operating state.

Dry-solid 2.72 kg/s Main steam 19.42 kg/s				
	Spout 1	Spout 2	Spout 3	Total
Width [mm]	38.8	40.2	38.3	
Velocity [m/s]	0.87	0.87	0.87	
Volume flow [l/s]	0.33	0.37	0.32	**1.02**
Dry-solid 11.11 kg/s Main steam 33.15 kg/s				
	Spout 1	Spout 2	Spout 3	Total
Width [mm]	54.7	51.5	47.5	
Velocity [m/s]	1.00	1.09	1.09	
Volume flow [l/s]	0.89	0.85	0.70	**2.44**
Dry-solid 12.47 kg/s Main steam 39.57 kg/s				
	Spout 1	Spout 2	Spout 3	Total
Width [mm]	57.3	60.6	58.6	
Velocity [m/s]	1.00	1.09	1.09	
Volume flow [l/s]	0.99	1.22	1.14	**3.36**

The results of the calculated smelt flows seem to be near the possible results. This measurement technique would require more fine-tuning and verification of results several times. The visual analysis system could use the same measurement technique with smelt spout cameras. Results that are more accurate could be obtained with a better camera, which has more pixels to determine the width of smelt and higher frame rate for velocity measurements.

5.4 Carryover

There are a couple way to detect carryover. Burning liquor droplet can be detected at the upper furnace with the infrared camera. Those droplets are hotter than surrounding flue gases and thus more easily detectable. All the carryover particles are not burning so infrared camera cannot be trusted at all situations. Other method is to use sample probe. Probe can be a couple meter long and it is putted to upper furnace temporarily. Usually the sampling time is roughly a minute and probe is either cooled or uncooled. Cooled probe has better durability and flue gas and carryover stick much better to it. After sampling time, the probe is pulled out of the furnace. In Figure 42 is shown what surface of the probe looks like after the sampling. Black staff is unburned black liquor and it is least desirable thing that can foul the superheaters. Light red or red areas are burned black liquor and contain much sodium sulfide. This stuff should be in the char bed and not on the way to superheaters. An ideal situations is when carryover sample contains only grey material.

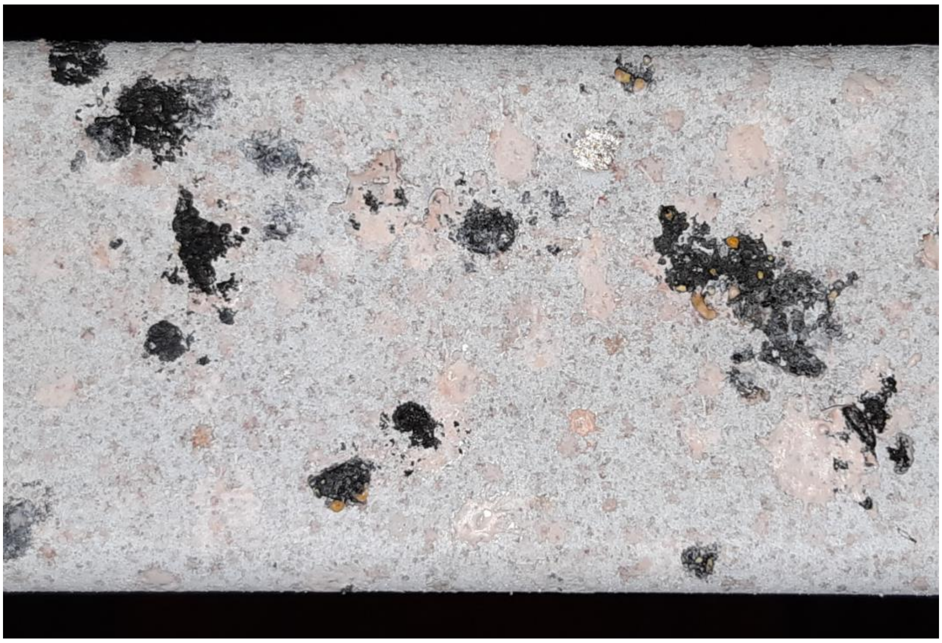

Figure 42. Carryover sample.

Potential visual analysis application for carryover sample is to measure the areas of unburned and burned carryover particles from the probe. Visual analysis system can find specific colors and calculate how much image contains that color. In Figure 43 is shown example how visual analysis system could find and calculate how much specific stuff is on the surface of the probe. Blue areas are detected unburned and red areas are burned black liquor. System also could record the results for later review. Carryover sample can be taken from different places from upper furnace. With visual analysis system could be possible to compare results from different points of the boiler. With regular measurements, could be possible to create chart that show development of carryover over the time and in different points of the boiler.

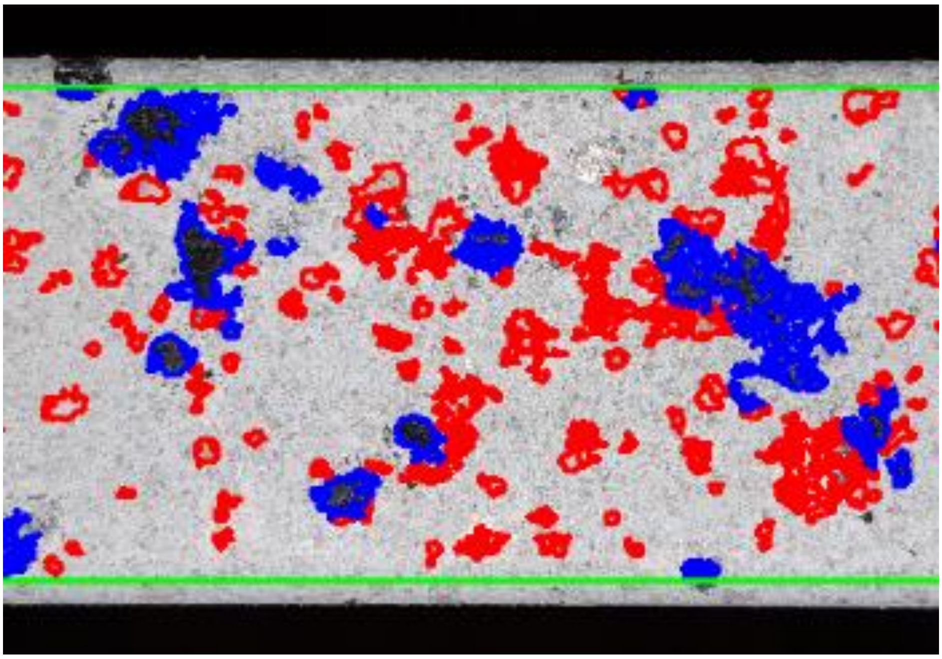

Figure 43. Analyzed carryover sample.

Carryover is one of the most unwanted phenomena in the recovery boiler. Visual analysis could provide a way to study it more. The reasons for carryover could be found by measuring it at intervals. Visual analysis system could offer excellent tool for analyzing the samples and recording them for later review.

6 CONCLUSION

Visual analysis in a recovery boiler offers many new ways to measure boiler performance. Many things cannot be measured in a traditional way. Operators have analyzed performance of the recovery boiler by looking footages from char beds or smelt spouts. What if these visually analysis objects were combined with computer-based visual analysis software? It would be more precise than a human eye, it would analyze things the same way every time and it would record the results for later review. In the beginning, visual analysis system would be the help of operators. Later when there are more experiences with the system, it could be connected with an automation system to control some operating parameters.

Possible visual analysis objects are shown in Figure 44. It contains familiar objects like carryover, char bed cameras, liquor gun cameras and smelt spout cameras. Heat exchangers cameras and reduction sample analysis are left for less attention in this thesis. Conditions of the heat exchanger have been researched most often during the maintenance break by cameras. That way can be seen where a fouling is thick or is there any structural failures. During the boiler operation, flue gases could work as a visual barrier and hinder the operation of the cameras.

Measuring a reduction rate from a smelt sample is another thing left for a less attention. An experienced operator can estimate the reduction rate by looking at the sample. There are some indicators in colors and in the composition of the sample surface that operators use to estimate the reduction rate (Nurmi 2019, 32). Maybe there are a way to copy this skill and make computer-based visual analyze software for that. An accurate measurement method is chemical-based and it needs a couple hours to get the results. With visual analysis system measuring the reduction rate would be fast, but probably not so accurate. It could tell the reduction rate difference between spouts and if there have been major changes.

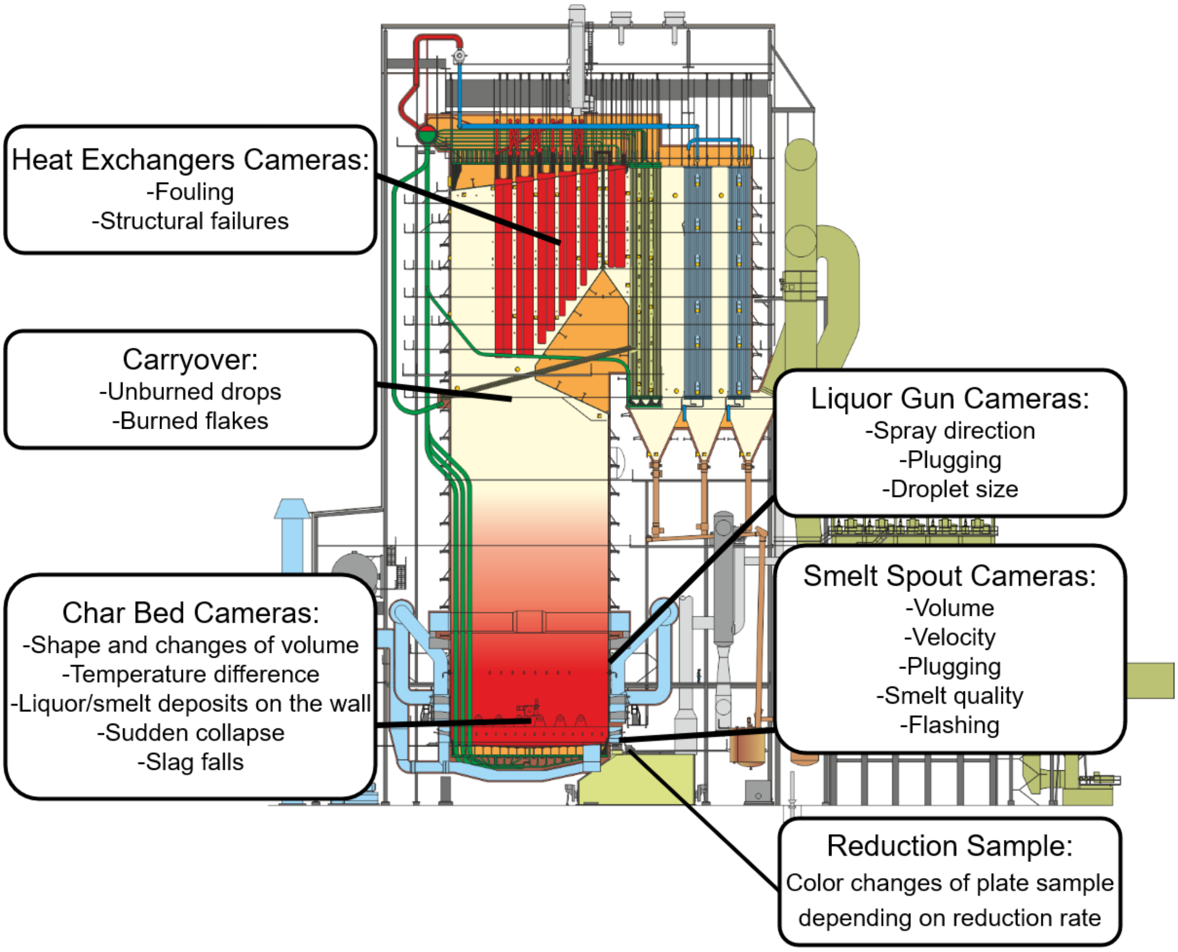

Figure 44: Possible objects for visual analysis.

6.1 Potential for detecting unusual situations

Visual analysis system has great potential to detect unusual events in the recovery boiler. There are not a direct way to measure or observe things like black liquor spraying, char bed asymmetry or smelt flow. However, those are things that affect the operation of the recovery boiler or tell if there is something wrong. Operators may detect these issues while working around the recovery boiler, but surely some things go unseen or the situation is not addressed quickly enough. Also, operators' observations do not leave any markings on the system for further investigate the cause of the issue. By combining the visual analysis system with the above mentioned objects, problems would be detected quickly and the situations would be recorded in the system for further review.

There are many unusual situations that can be detected from char bed cameras. Char bed phenomena are too fast growing or shrinking of the bed, cold spots on the surface of the bed, and repeated asymmetric mound. Those things can affect a reduction rate, emissions and upper furnace conditions. Other things that can be seen from char bed cameras are possible stresses on wall pipes and primary airports. For optimal monitoring of the char bed, there should be at least four char bed cameras that could look at each wall and the char bed from every direction.

Unusual situations with smelt spout cameras could be plugging of spout, increased numbers of impurities or smelt flashes, and significant difference in smelt flow between spouts. Liquor gun cameras could detect changes in black liquor spraying. It could warn if spray direction is wrong or a nozzle is dirty. Spraying formation can change even though the black liquor volume flow and the temperature stay the same. A good way to detect it is to look what kind the spray formation is visually.

6.2 Other benefits

Visual analysis offers a new way to study the phenomena of the recovery boilers. Researchers could study how changes in the char bed affect other things in the recovery boiler. It has been hard to combine any visually seen things to process data. Visual analysis system that follows char bed size and shape could be huge help to develop and understand more the recovery boilers process. Other studies could be with smelt spout conditions and black liquor spraying in a real furnace conditions.

Visual analysis does not always have to be real-time analyze from the video footage. For the carryover measurements, it is possible to develop a system that analyzes image, which is taken from the carryover sample, by using the same method every time. Operator takes the normal carryover probe sample, takes a picture of it and uses the visual analysis system to analyze and record the results. So far processing of the results has been on the shoulder of operators.

In general using visual analysis with the operating the recovery boiler could improve the understanding of it. When there are system that shows what kind the char bed is currently, operators could learn what parameters to change to adjust the char bed to like it should be.

7 SUMMARY

The aim of this thesis was to research potential of the visual analysis in the recovery boiler. The purpose was to find out what things are possible to see from images or video footages and is there any way to integrate visual analysis to it. The research material was from a small Finnish recovery boiler, but the same kind material would have gotten from any recovery boiler.

Theory of recovery boiler components, black liquor and char bed were introduced in literature part of this thesis. In theory chapters, the goal was to introduce components and phenomena that happen and can be seen in recovery boilers. Properties of black liquor and formation of spraying are important things to know when image footage from liquor spray is researched. It is good to know that spraying is complex phenomenon and needs more research. For that visual analysis system could be a great help. Shape, size and temperature of the char bed affect many things in recovery boiler operation. Even though the importance of the char bed is well known in theory, monitoring and measuring its conditions has been pretty weak. The visual analysis system could offer for that a new way to see and understand what is happening and should happen inside the lower furnace.

In research part of this thesis, the basic theory of the visual analysis was introduced and what things are possible to detect from black liquor spray, char bed, smelt spouts and carryover samples. Observable phenomena were introduced separately and tried to bring out the reasons why those things should be monitored with the visual analysis system. Couple examples from char bed and smelt spouts were presented to prove that if something can be seen and analyzed by human eye, it is possible to combine with a computer-based visual analysis system.

As a result, it is possible to see things from the recovery boiler that have not been measured or monitored in more detail before. For monitoring those things, it could be possible to ensure more stable and safety recovery boiler. Systems with actual integrated visual analysis could be good next targets for further research.

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