OULUN AMMATTIKORKEAKOULU

DEVELOPMENT OF AN INDUSTRIAL HMI SYSTEM FOR SMELT SPOUT ROBOT

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Sularännit ovat keskeinen osa soodakattilan toimintaa, jossa epäorgaaniset kemikaalit kierrätetään ja samalla tuotetaan sähköä. Soodakattilan reaktioiden tuloksena syntyvä sula virtaa tulipesän alueelta sulanrännien kautta liuotussäiliöön. Jatkuva sulavirtaus aiheuttaa kovettuneen sulan kertymistä rännien seinämiin, minkä vuoksi sularännit on puhdistettava säännöllisesti. Tämä työ on perinteisesti tehty käsin, mikä altistaa operaattorit merkittäville fysikaalisille ja kemiallisille riskeille.

Näiden vaarojen vähentämiseksi Valmet Technologies on kehittänyt sularännien puhdistukseen tarkoitetun robotin. Robotti perustuu kuusiakseliseen teollisuusmanipulaattoriin, joka voi tarvittaessa liikkua lineaariradalla. Vaikka puhdistusprosessi on pitkälti automatisoitu, robotin häiriötilanteet edellyttävät toisinaan manuaalista ajoa. Manuaalinen ajo suoritetaan opetusyksiköllä, jonka käyttöliittymä on monimutkainen ja harvoin käytetty, mikä tekee sen käytöstä haastavaa ja virhealtista. Lisäksi manuaalinen ajo altistaa operaattorit suuremmille turvallisuusriskeille, sillä sula voi roiskua rännien ulkopuolelle.

Tämä opinnäytetyö tutkii mahdollisuuksia parantaa robotin ohjausjärjestelmää. Tapaustutkimuksena toteutettu työ keskittyy käytettävyyden ja turvallisuuden parantamiseen toteuttamalla robotille kosketusnäyttöön perustuva käyttöliittymä.

ABSTRACT

Oulu University of Applied Sciences
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Smelt spouts are an essential part of recovery boiler operation, where inorganic chemicals are recycled and electricity is simultaneously produced. Molten smelt, formed in the furnace, flows through the smelt spouts into the dissolving tank. The continuous flow causes smelt to accumulate on the spout surfaces, requiring regular cleaning tasks traditionally performed manually by operators.

Because this work is physically demanding and particularly hazardous, Valmet Technologies has developed a smelt spout cleaning robot to automate the process. The robot is based on a six-axis industrial manipulator that can travel along a linear track when required.

Despite the high level of automation, issues or malfunctions occasionally require operators to manually jog the robot using the teach pendant. The teach pendant interface is complex and rarely used, making manual operation challenging, time-consuming, and prone to errors. During normal recovery boiler operation, manual jogging also exposes operators to significant safety risks, as molten chemicals may splash onto the smelt spout deck.

This master’s thesis investigates potential improvements to the robot’s control system. Conducted as a case study, the research focuses on enhancing usability and operational safety through the implementation of a touchscreen-based human–machine interface.

SISÄLLYS

LIST OF SYMBOLS AND ABBREVIATIONS

NaOH	Sodium hydroxide
Na_2S	Sodium sulfide
Na_2CO_3	Sodium carbonite
$CaOH_2$	Calcium hydroxide
Na_2SO_4	Sodium sulfate
O_2	Oxygen
CO_2	Carbon dioxide
CO	Carbon monoxide
C	Carbon
NO_x	Nitrogen oxide
$Na_2S_2O_3$	sodium thiosulfate
mol	Amount of substance
IIot	Industrial internet of things
tds/d	Total dissolved solids per day
TP-program	Teach-playback program
TCP	Tool center point
HMI	Human machine interface
SAW	Surface acoustic wave
PSD	Planar scatter detection
FTIR	Frustrated total internal reflection

SCADA	Supervisory Control And Data Acquisition
PLC	Programmable logic controller
HIMA	Boiler safety logic system
MCR	Maximum Continuous Rating
ms	millisecond
DCS	Distributed Control System
CCTV	Closed-Circuit Television

1 INTRODUCTION

Operating a recovery boiler demands continuous cleaning of the smelt spouts. Smelt, a hot molten by-product, flows through smelt spouts. Traditionally, this cleaning process has been manually performed by operators, but environment is both chemically and physically hazardous. To enhance operator safety, Valmet has developed a smelt spout robot for automated cleaning operations. This robot, equipped with a rodding tool, cleans the smelt spouts in predetermined sequence. The cleaning process can be monitored and controlled from the control room's Distributed Control System (DCS).

The operating conditions for the smelt spout robot are extremely challenging and ever-changing. Since the position of the smelt spouts is constantly shifting, it is essential to accurately measure their location. Occasionally, the robot must be manually operated, a task that can be challenging and time-consuming due to the infrequent situations and the complexity of the control system.

As manual operation remains necessary in certain situations, improving the robot's control interface has become increasingly important for both safety and operational efficiency.

Since the smelt spout area ranks among the pulp mill's most dangerous zones, minimizing time in that area is crucial. Consequently, this thesis is dedicated to implementing touchscreen control for the robot to enhance workplace safety and efficiency.

1.1 Aim of thesis

This thesis seeks to enhance the smelt spout robot by meeting the following criteria:

- **Develop and integrate:** Desing and implement an intuitive touchscreen interface that is seamlessly integrated into existing robot control system.

- **Extended functionality:** Enhance robot's operational capabilities by introducing new functionalities through the touchscreen, allowing for smoother execution of complex tasks.
- **Improve safety:** Minimize personnel exposure to hazardous work environments (e.g., the smelt spout area) by reducing the time spent there through a control interface that supports rapid and safe operation.
- **Optimize user-friendliness:** Evaluate and test the performance and ergonomics of touchscreen control under real working conditions to ensure ease of use and reliable operation.
- **Provide recommendations for future development:** Analyze challenges encountered during usage and develop recommendations for further system improvements and broader application of the technology in industrial robotics.

1.2 Research questions

The development of a touchscreen-based control interface for the smelt spout robot raises several questions related to usability, safety, and system integration. Based on the aims of this thesis, the primary research question is:

How can a touchscreen interface be designed and integrated into an existing smelt spout robot system in a way that improves usability, operational safety, and daily functionality without compromising system reliability?

To support this main question, the following secondary questions are examined:

How effectively can the touchscreen extend the robot's operational capabilities and support smoother execution of complex tasks?

In what ways does the touchscreen interface reduce operator exposure to hazardous environments compared to previous control methods?

How user-friendly and intuitive is the touchscreen during real operating conditions, and how does it influence operator workflow?

What challenges arise during implementation and commissioning, and how can these inform recommendations for future development?

These questions guide the structure of the thesis and form the basis for the analysis presented in the Results, Conclusions, and Reflections chapters.

1.3 Restrictions and limitations

This section outlines the intentional boundaries of the study as well as the practical factors that influenced the research process.

1.3.1 Restrictions

The scope of this thesis is intentionally limited to the design, implementation, and evaluation of a touchscreen interface integrated into an existing smelt spout robot system. The work focuses on:

- touchscreen functionality, usability, and safety-related aspects
- integration with the robot's existing PLC and control logic
- operator interaction and commissioning-phase performance
- qualitative evaluation based on observations and user feedback

The thesis does **not** include:

- redesign of robot hardware or mechanical components
- development of new robot movement algorithms
- long-term performance monitoring beyond commissioning
- quantitative comparison between manual and automated rodding
- economic or lifecycle analysis of the system

These restrictions ensure that the study remains focused on the touchscreen interface and its role within the existing robot system.

1.3.2 Limitations

Several practical factors limited the depth and scope of the analysis:

- **Lack of quantitative data:** No reliable measurements existed for manual rodding time, operator presence on the spout deck, or previous robot operation without the touchscreen.
- **Simultaneous installation:** The robot and touchscreen were installed at the same time, preventing controlled comparison with earlier control methods.
- **Language barrier:** Limited shared language between operators and the commissioning team affected the depth of some feedback.
- **Limited pre-testing possibilities:** The touchscreen logic could not be fully tested before arriving on site, creating schedule pressure.
- **Site-specific environment:** Results reflect the conditions of a single recovery boiler and may not be directly generalized.

These limitations help explain the methodological choices made in the study and frame the interpretation of the results.

2 RECOVERY BOILER

A recovery boiler is a type of boiler designed for burning black liquor, a by-product of chemical wood processing. Black liquor mainly contains the wood binding agents remaining after the pulping process and the chemicals used during cooking. The recovery boiler has two primary functions: to recover the cooking chemicals contained in the caustic liquor and to combust the organic material in the black liquor, thereby generating renewable energy that is utilized as steam for the pulp mill and for electricity generation via turbines. (Finnish recovery boiler committee 2021.)

2.1 Recovery boiler operation

The primary fuel used in the recovery boiler is concentrated liquor, which in modern recovery boilers have a dry matter content of 80 %-85 %. The concentrated liquor is preheated to an appropriate temperature before being fed into the recovery boiler and is introduced into the furnace using liquor gun nozzles.

The operation of the recovery boiler can be divided into two primary process events:

- Regeneration of the chemicals contained in the concentrated liquor through the combustion process.
- Conversion of the feedwater supplied to the boiler into flashed high-pressure steam using the heat generated in the combustion process.

In addition to the primary process events, the recovery boiler is also associated with secondary process events which are:

- Combustion of both concentrated and diluted-off gases and recovery of the sulfur compounds they contain.

- Recovery of the ash salt produced by the combustion of concentrated liquor.
- Combustion of auxiliary fuel to meet the plant's steam demand.
- Conversion of the smelt into green liquor in a dissolving tank.

2.2 Kraft pulping

In the kraft pulping process, wood chips are immersed in a highly alkaline solution and exposed to high temperatures and pressures. During this digestion phase, the bonds formed by the organic lignin, which binds the fibers together, are broken down. As a result, the fibers separate while most of the lignin dissolves into a liquid stream, known as weak black liquor, which is illustrated in (Figure 1). This alkaline solution, known as white liquor, is composed of sodium hydroxide (NaOH) and sodium sulphate (Na_2S). (Tran & Vakkilainen, 2016.)

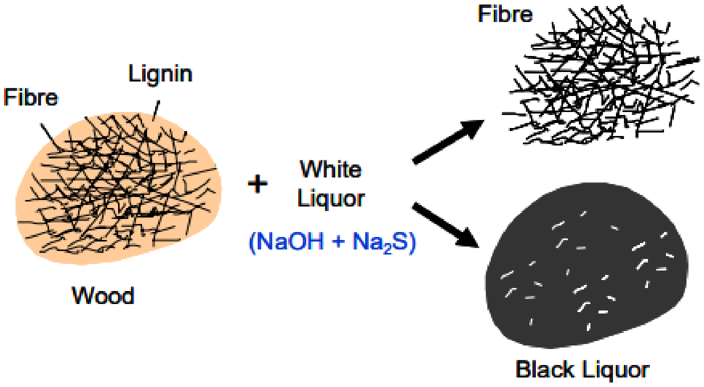


FIGURE 1. Kraft pulping process (Tran & Vakkilainen, 2016).

Once cooking is complete, the resulting mixture-referred to as black liquor, holds both the used cooking chemicals and the dissolved organic compounds. The pulp can then be separated from the black liquor through a washing process, and the liquor is subsequently reused for chemical recovery (Figure 2).

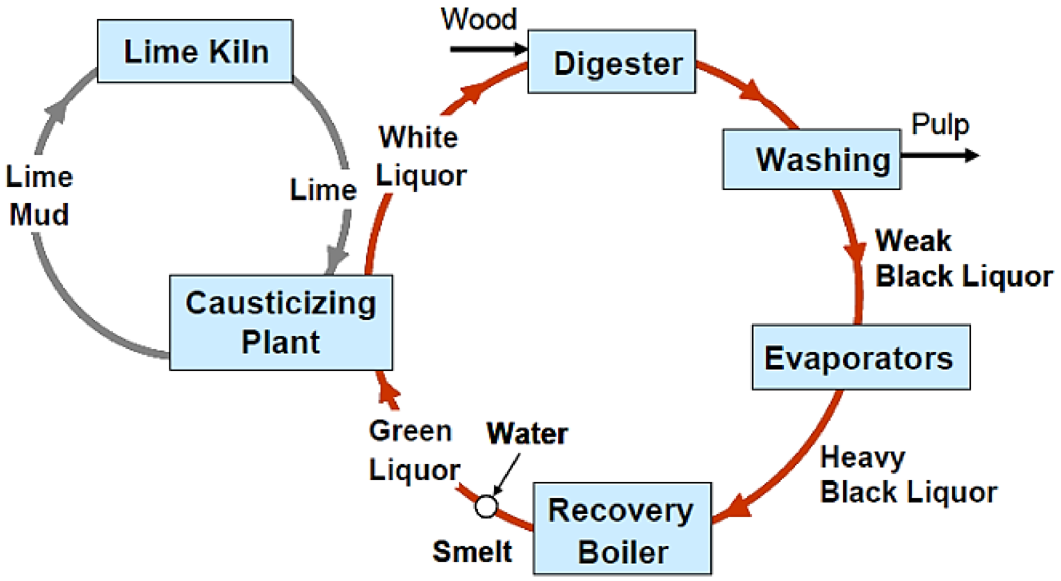


FIGURE 2. Simplified flowsheet of kraft recovery process (Tran & Vakkilainen, 2016)

After washing, the pulp is separated from the black liquor. The isolated pulp can then be bleached and converted into paper or board products. To make weak black liquor suitable for reuse in future digestion, it must undergo additional processing. The first step in this process is evaporation, where heat and flashing increase the concentration of solids by removing water. The resulting product, known as heavy black liquor or concentrated black liquor, exhibits a significantly higher dry-solids matter. (Tran & Vakkilainen, 2016.)

The organic fraction of evaporated black liquor is combusted in the recovery boiler to generate heat, while its inorganic portion is recovered as a molten smelt. This smelt flows into a dissolving tank, where it is dispersed by steam jet, leading to the formation of the green liquor. Next, the green liquor is transferred to the causticizing plant, where it reacts with lime to produce slaked lime. During the causticization process- with sodium carbonate (Na_2CO_3) reacting with calcium hydroxide ($CaOH_2$) and lime mud, white liquor is formed. Once the lime mud is removed, the white liquor is ready to be reused in the digesting process. (Ek, Gellerstedt & Henriksson, 2009.)

2.3 Recovery of the cooking chemicals

In the recovery boiler, sulfur and sodium contained in the cooking chemicals are recovered and regenerated into a reusable form in the high-temperature conditions of the furnace. Additionally, energy is produced by capturing the heat released during the combustion of organic matter in black liquor, which consists mainly of lignin, although hemicellulose also dissolves into the liquor during cooking (Raiko et al., 2002).

2.3.1 Reduction reactions in the furnace

The reactions of sulfur and sodium compounds in the black liquor are based on the reduction of sulfur, in which sodium sulfate contained in the black liquor is reduced to sodium sulfide in the smelt bed. The reduction of sulfur occurs through the following reactions. (Vakkilainen 2005. 4-6).

$$Na_2S + 2\ O_2 \rightarrow Na_2SO_4 \qquad (1)$$

$$Na_2SO_4 + 2\ C \rightarrow Na_2S + 2\ CO_2 \qquad (2)$$

$$Na_2SO_4 + 4\ C \rightarrow Na_2S + 2\ CO \qquad (3)$$

At the bottom of the recovery boiler, a smelt bed forms as shown in Figure 3, containing inorganic residues. According to equations 2 and 3, sodium sulfate reacts with free carbon under low-oxygen conditions in the smelt bed, producing carbon monoxide (CO), carbon dioxide (CO_2), and the reactive cooking chemical sodium sulfide (KnowPulp 2015 & Vakkilainen 2005, 4-6).

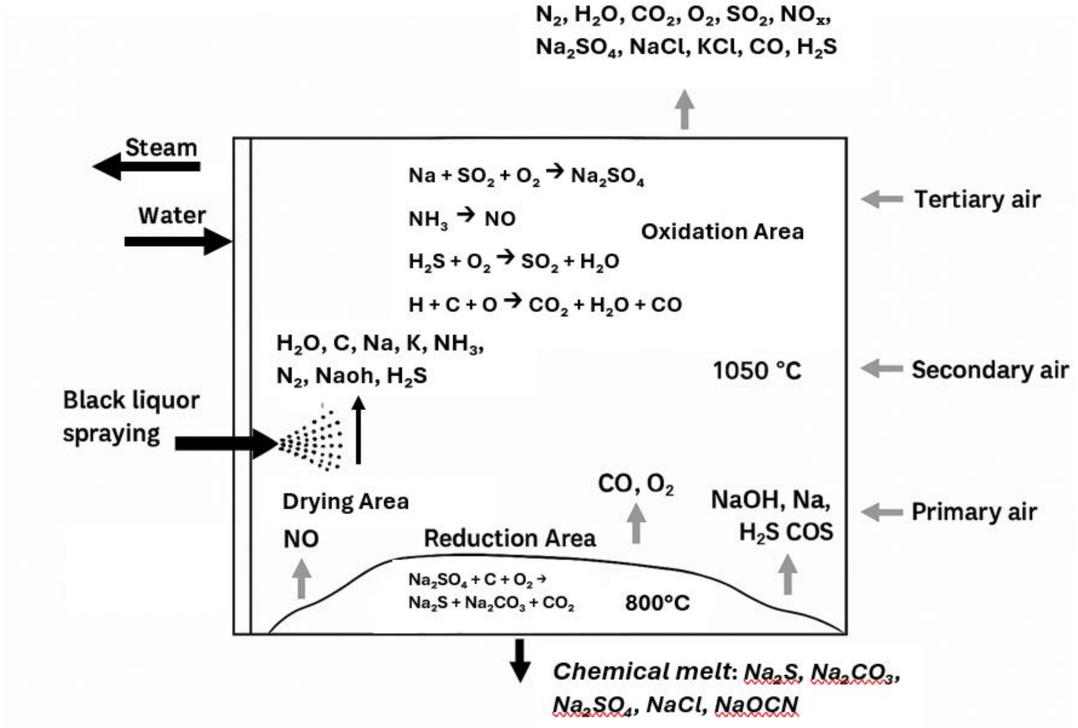


FIGURE 3. Reactions in the recovery boiler furnace (modified from source Suhr et al., 2015)

In complete reduction, all sodium sulfate is assumed to react into sodium sulfide within the chemical smelt. However, in practice, a portion of the sodium sulfate always remains unreacted. The success of sulfur reduction is described by the reduction efficiency, which typically ranges between 90-95 %. Sulfur reduction indicates the ratio between sodium sulfide and sulfur, and it is calculated using the following equation (Hupa, 2012).

$$\text{Degree of reduction} = \frac{n_{Na2S}}{n_{S,tot}} * 100\% = \frac{n_{Na2S}}{n_{Na2S}+n_{Na2SO4}} * 100\% \quad (4)$$

Following described in formula

nNa_2S = amount of substance of sodium sulfide [mol]

nS,tot = total amount of sulfur in the melt [mol]

nNa_2SO_4 = amount of substance of sodium sulfate [mol]

A high reduction rate is achieved when the smelt bed contains sufficient solid carbon to ensure that sodium sulfate reacts with carbon, rather than being re-oxidized by free oxygen above the bed into sodium sulfate, as described in Equation 1. In addition, successful reduction requires a high temperature, as the reduction rate is believed to double when the bed temperature is increased by 50-60 ºC. Therefore, low-oxygen and high-temperature conditions are essential in the reduction zone. (Hupa 2012, 3-4.)

Figure 4 illustrates the effects of air flow rate and smelt bed temperature on sulfur reduction. According to the figure, sodium sulfide and sodium carbonate are theoretically the dominant compounds in the smelt bed when the air-to-fuel ratio exceeds 20 % and the temperature is above 800 ºC. The smelt bed begins to solidify when the temperature drops below 800 ºC. Variations in black liquor composition solids content spraying conditions, and staged air supply influence combustion, resulting in significant fluctuations in the actual composition of the smelt bed. Furthermore, the limited reaction rate of chemical processes restricts the extent of sulfur reduction in the practice.

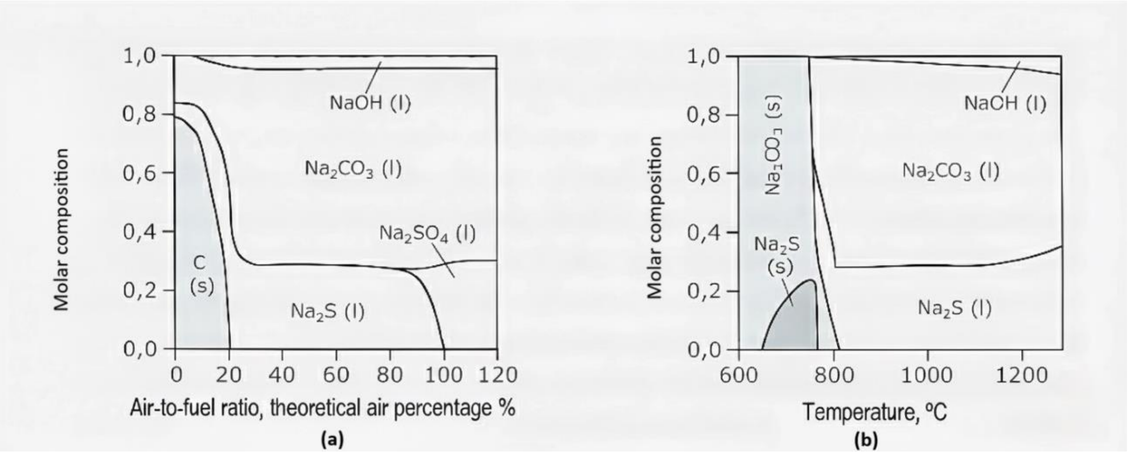


FIGURE 4. Effect of combustion air (a) and smelt bed temperature (b) on smelt bed composition and sulfur reduction (modified from source Hupa 2012)

2.3.2 Circulation of sodium and sulfur in the recovery process

The circulation of sodium and sulfur is often described using the S/Na_2 ration of black liquor or the sulfidity of white liquor. The S/Na_2 ratio is a more accurate indicator of the mill's sodium and sulfur cycle, as sulfidity also depends on causticity and reduction efficiency. Typically, the S/Na_2 ratio ranges between 0.35 and 0.5 in Nordic pulp mills. Figure 5 presents the chemical balances of an ideal recovery boiler process, in which sodium and sulfur compounds have been completely converted into sodium sulfide and sodium carbonate – although the process always involves some losses. (Hupa 2012, 2.)

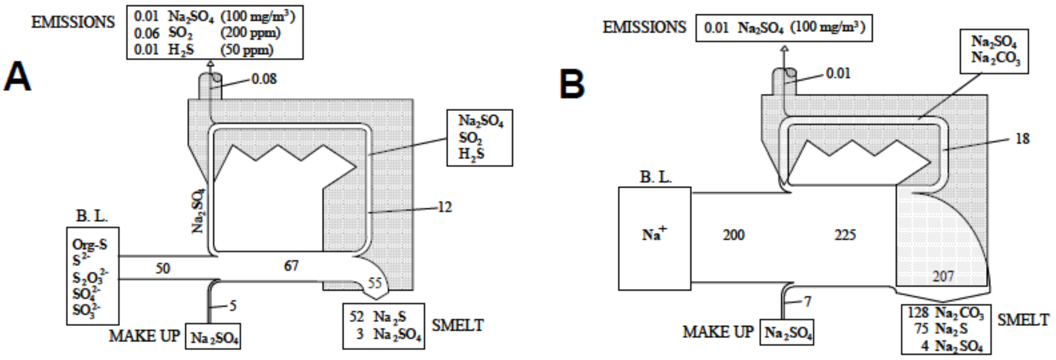


FIGURE 5.Sulfur (A) and sodium (B) chemical balances in the recovery boiler (Hupa 2012).

Sulfur and sodium are released into the flue gases as sodium sulfate and sulfur containing gases. Fly ash is collected from the flue gases using electrostatic precipitators and returned to the process cycle, and roughly 10 % of the sodium in black liquor originates from this recycled sodium. Depending on operating conditions, approximately 20-40 % of the total sulfur escapes into the environment through various emissions, such as sodium sulfate, sulfur dioxide, TRS compounds, and hydrogen sulfide – along with which a small amount of sodium is lost.

The sodium – sulfur cycle can also be examined using sulfidity, which is defined as the ratio between sodium sulfide and effective alkali. Sulfidity can be calculated using the following equation.

$$S - \% = \frac{n_{Na2S}}{n_{NaOH} + n_{Na2S}} * 100\% \qquad (2.5)$$

Following described in formula

n_{NaOH} = molar quantity of NaOH [mol]

In kraft pulp mills, sulfidity typically ranges between 35-45 %. In mills producing softwood pulp, increased sulfidity can improve yield up to 40 %, whereas in hardwood pulp production, the yield does not improve beyond a sulfidity level of 15%. Sulfidity also plays a key role in the operability of the recovery boiler, as it affects the fluidity of the smelt and the formation of acidic sulfates and sulfur emissions. High sulfidity promotes the formation of sulfur dioxide in the furnace, which contributes to plugging caused by acidic sulfates. Therefore, sulfidity must be effectively controlled through fly ash removal and the addition of make-up chemicals. (KnowPulp 2015.)

Sulfidity also affects the fluidity of the smelt, which is optimal at around 40-41 %. Figure 6 illustrates the influence of sulfidity on smelt fluidity. If the smelt bed temperature drops too low and sulfidity falls significantly below or rises above 40 %, this may cause flow issues in the smelt. Such conditions can lead to plugging of the spouts and uneven smelt flow from the spouts to the dissolving tank, thereby increasing the thermal load on the spouts. (Tran et al., 2006.)

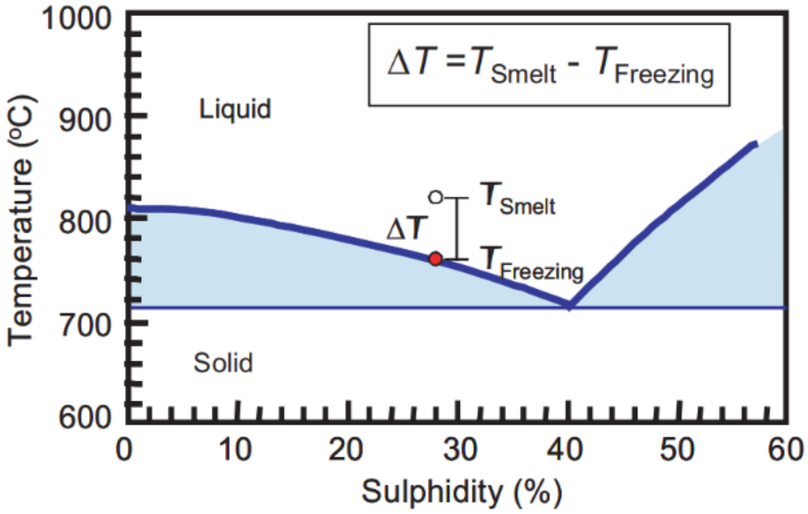


FIGURE 6. Dependence of smelt fluidity on sulfidity (Tran et al., 2006)

2.4 History of recovery boilers

Recovery boiler technology originates from the process development in the late 1800s by French chemist Nicholas LeBlanc, see (Figure 7): Early flame oven from late 1800s. During that period, soda was produced in a reducing furnace that was manually filled with black liquor. Wood-burning flue gases were used to dry the black liquor, which was then scraped off the oven floor and collected into a separate smelt pot, see (Figure 8): Smelt pot. In the smelt pot, the remaining organics underwent reduction and combustion. However, this system achieved a very inefficient chemical recovery, rarely exceeding 60 %. (Vakkilainen, 2005.)

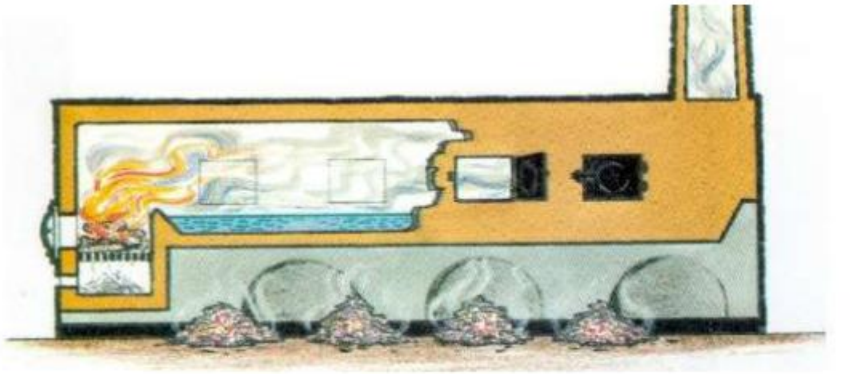


FIGURE 7. Early flame oven from the 1800's (Vakkilainen, 2005)

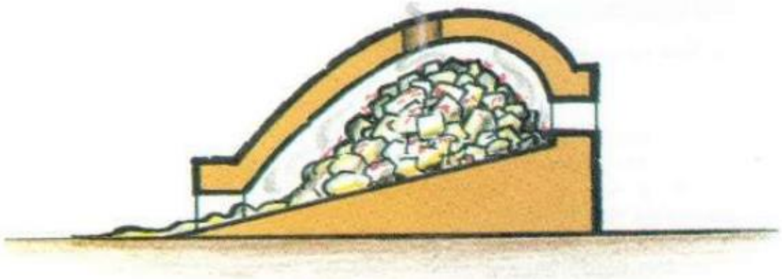


FIGURE 8. Smelt pot (Vakkilainen, 2005)

The kraft recovery boiler was invented by G.H. Tomlinson in the 1930s, marking a major milestone in the evolution of the kraft process. This breakthrough allowed the recovery reuse of inorganic pulping chemicals, thereby nearly completing the chemical cycle. The Tomlinson-type recovery boiler laid the foundation for the modern systems used today. (Salmenoja, 2019.)

Recent improvements in recovery boilers have focused on enhancing safety, lowering emissions, extending operating periods with less frequent maintenance, increasing capacity and power production, and integrating digital technologies. Safety has been boosted by employing interlock systems, emergency shutdown protocols, and rapid drainage, while overall emissions from recovery boilers have decreased, reducing Nox emissions remains challenging- likely due to high dry solids content. Additionally, boilers can now run for up to 24 months continuously while reduced maintenance, and their improved power output makes them selfsufficient, even generating excess electricity for sale. Pulp mills are no longer limited in capacity by their recovery systems, and the grooving adoption of digital solutions, including extensive data analysis and IIot (Industrial Internet of Things) applications, is further modernizing these operations. (Salmenoja, 2019.)

Bracell`s project Star, located in Lençóis Paulista, Brazil, features one of the largest recovery boilers ever built. Engineered by Andritz, recovery boiler processes up to 13 000 tons of black liquor dry solids per day (tds/d) – surpassing global benchmarks. The unit provides more than double the energy required to power the entire mill, with potential to supply electricity equivalent to a city of one million people. (ANDRITZ, n.d.)

2.5 Recovery boiler design

Key design choices for recovery boilers include whether to use a screen or screenless superheater area, opting for a single-drum or a two drum configuration, selecting the appropriate tube materials for the lower furnace walls, choosing between a vertical or horizontal boiler bank layout, and determining the arrangement of the economizer as well as the type and number of air levels. Main parts of the recovery boiler are presented in Figure 9.

Critical design parameters for sizing a recovery boiler encompass the dry solids capacity, the heat value and elemental composition of black liquor, the percentage of the dry solids obtained from evaporation, the target conditions for main steam, the feed water’s inlet temperature and the economizer’s flue gas outlet temperature. Notably, the black liquor dry solids flow is the decisive factor in establishing the correct boiler dimensions. (Vakkilainen, 2005.)

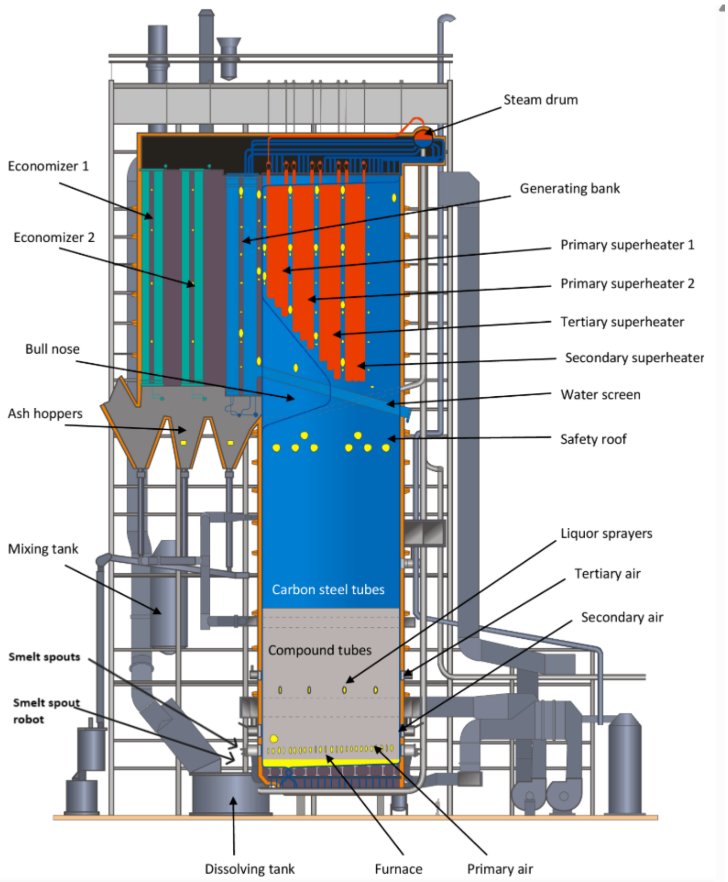


FIGURE 9. Recovery boiler design, modified from source (Praszkier, 2011)

Modern recovery boilers are designed with a single steam drum, a vertical steam generating bank, and widely spaced superheaters. The single-drum configuration has replaced the traditional two-drum design due to its enhanced safety and higher availability. Positioning the steam drum outside the furnace, with fewer openings in its wall, significantly reduces the risk of water leakage and allows the systems to withstand higher pressures and greater capacity. Moreover, the vertical arrangements of the steam generating bank facilitate easier cleaning, as the upward flue gas flow improves ash removal even under heavy dust loads. Additionally, generous side spacing for the generating bank and economizers minimize plugging and optimizes cleaning while the wide spacing in the superheater area helps to reduce fouling. (Tikka, 2008.)

2.6 Combustion liquor system

The combustion liquor system is designed to transfer concentrated black liquor from the evaporation plant, blend it with ash, and deliver it to the recovery boiler furnace for combustion. The recovery boiler´s combustion liquor system consists of combustion liquor tanks, a mixing tank, combustion liquor pumps, a preheater, and liquor spray guns. The system can be implemented either pressurized or non-pressurized setup. However, pressurized systems have become more common as the dry solids content of the combustion liquor has increased from 70 % to over 80 %. A pressurized system is normally used for liquor with higher dry solids content than 75 %. In a non-pressurized system, the concentrated black liquor is directed from the mixing tank, after being blended with ash, straight through the combustion liquor pumps to the preheater, and from there sprayed into furnace. (Valmet, 2025; KnowPulp, 2015.)

In a pressurized system which is illustrated in Figure 10, concentrated black liquor is transferred from the evaporation plant´s storage tank to the recovery boiler´s mixing tank, where it is blended with fly ash collected from the boiler tubes, economizers, and electrostatic precipitators. After mixing, the liquor is returned to the evaporation plant for final concentration. Once this final evaporation step is completed, the liquor is referred to as firing liquor and stored in a pressurized tank. From there, the firing liquor is fed by specialized pumps through a direct liquor preheater and sprayed via liquor guns located on the furnace walls, which evenly distribute the liquor into the lower furnace chamber for combustion. (Valmet, 2025; KnowPulp, 2015.)

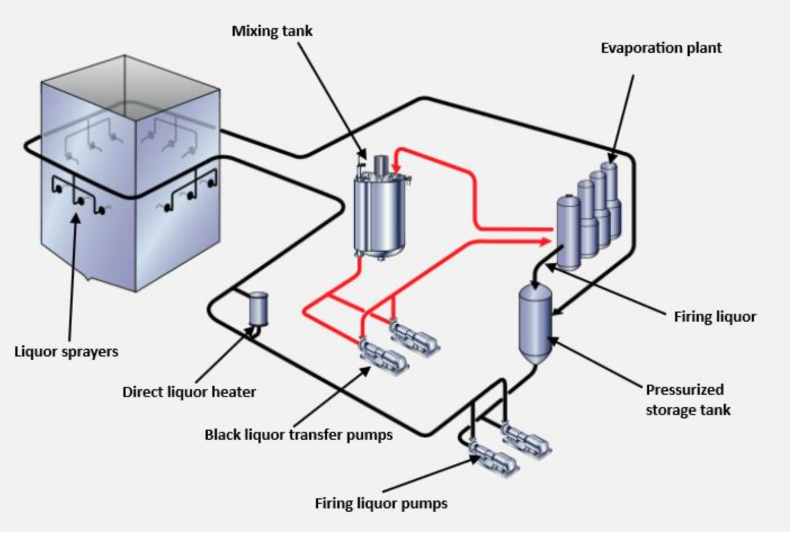


FIGURE 10. Pressurized combustion liquor system, modified from source, (Valmet, 2025)

2.6.1 Mixing tank

Black liquor with a dry solids content of 40-70 % is pumped from the evaporation plant to a dedicated mixing tank (see Figure 11), where it is blended with fly ash collected from the recovery boiler and electrostatic precipitators. The mixing tank is equipped with a rotating agitator and a perforated plate that separates the suction and mixing zones. This perforated plate ensures a uniform composition of black liquor and fly ash before liquor is directed from the suction side either back to the evaporation plant for further concentration or to the combustion liquor pumps.

The level inside the mixing tank is regulated by adjusting the flow rate of incoming liquor, typically controlled via speed of transfer pumps. To prevent overflow, the tank is fitted with both a drainage system and an overflow outlet. This setup ensures stable operation and consistent liquor quality for downstream processing. (Valmet, 2025; KnowPulp, 2015.)

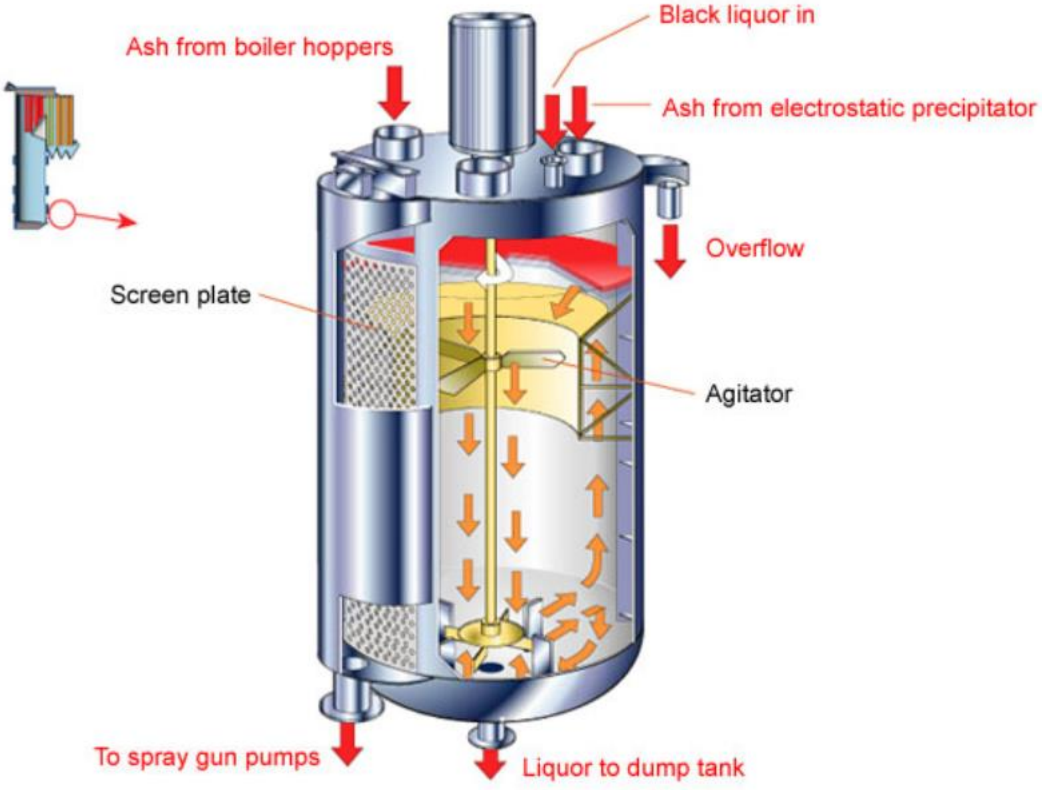


FIGURE 11. Structure of the mixing tank (KnowPulp, 2015)

2.6.2 Combustion liquor tank

After final evaporation, the black liquor is transferred at its final concentration to the firing tank. The purpose of this tank is to store the black liquor intended for combustion, referred to as firing liquor, and to regulate its viscosity and spraying temperature by adjusting the internal pressure. The firing temperature of the liquor is increased by raising the tank pressure through the injection of process steam. Conversely, the pressure, and thus the firing temperature is lowered by releasing tank gases into the non-condensable gas stream. (Valmet, 2025; KnowPulp, 2015.)

2.6.3 Combustion liquor pumps and preheating

Combustion liquor is typically pumped using two specially designed centrifugal pumps, one of which serves as a backup. From the pumps, the liquor is directed toward the spray guns, but before spraying, the final firing temperature – and the droplet size, is adjusted using either a direct or indirect preheater. In direct heating, medium-pressure steam is injected directly into the liquor. Alternatively, indirect heating uses a separate heat exchanger, where the liquor is heated with low-pressure steam without mixing steam into the liquor itself (KnowPulp, 2015).

2.6.4 Firing liquor guns and nozzles

Selecting the appropriate nozzle type is particularly important when aiming to control spray quality, droplet dispersion, smelt bed management, and the formation of carryover. Nozzle typer differ significantly from one another, resulting in notable variations in spray patterns. Figure 12 presents four typical nozzle designs, of which the spoon nozzle is the most used. In a nozzle, the combustion liquor flow is dispersed into a fan-shaped spray within the spoon structure, ensuring even distribution of liquor into the furnace. In swirl cone and V-type nozzles, the internal geometry constricts the flow and thereby influences the spray pattern- as illustrated in Figure 12. (Adams, 1997.)

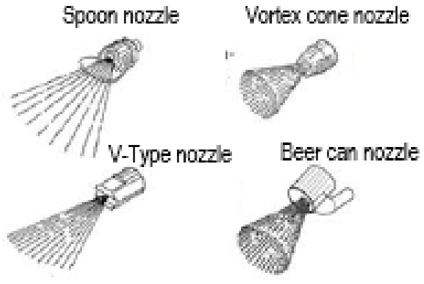


FIGURE 12. Various types of liquor nozzles (Engblom 2017, 18)

2.7 Green liquor system

The green liquor system consists of the dissolving tank with its associated equipment, green liquor pumps, and interconnected piping. Smelt discharged from the recovery boiler flows down through smelt spouts into the dissolving tank, where it is dissolved using weak white liquor. The tank itself is typically cylindrical, oval , or figure-eight shaped, constructed from carbon steel plates and lined internally with waterproof concrete or acid proof steel. In addition to protecting against corrosion, the concrete lining also serves as sound insulation, as smelt impacting the liquid surface at the bottom of the tank can produce small explosive reactions. Powerful agitators together with pump rotation help prevent the solidification of salts. (Valmet, 2025; KnowPulp, 2015.)

To assist smelt dissolution, steam jets are commonly directed at the incoming smelt stream. The process generates vent gases that are transferred to a washer unit, where dust and sulfur compounds are removed. In modern mill systems, these gases are subsequently incinerated in the recovery boiler to mitigate emissions (Valmet, 2025; KnowPulp, 2015).

The green liquor circuit (illustrated in Figure 13) typically includes two pipelines: one supplying weak white liquor to the dissolving tank, and the other transporting green liquor to the causticizing stage. These lines are occasionally switched to reduce the risk of blockage caused by green liquor precipitation. Each line is equipped with its own pump. Liquor flows within the system are controlled either by monitoring tank levels or analyzing liquor concentrations. The circulation pump and associated equipment are made of acid – resistant stainless steel to withstand the corrosive nature of green liquor. (Valmet, 2025; KnowPulp, 2015.)

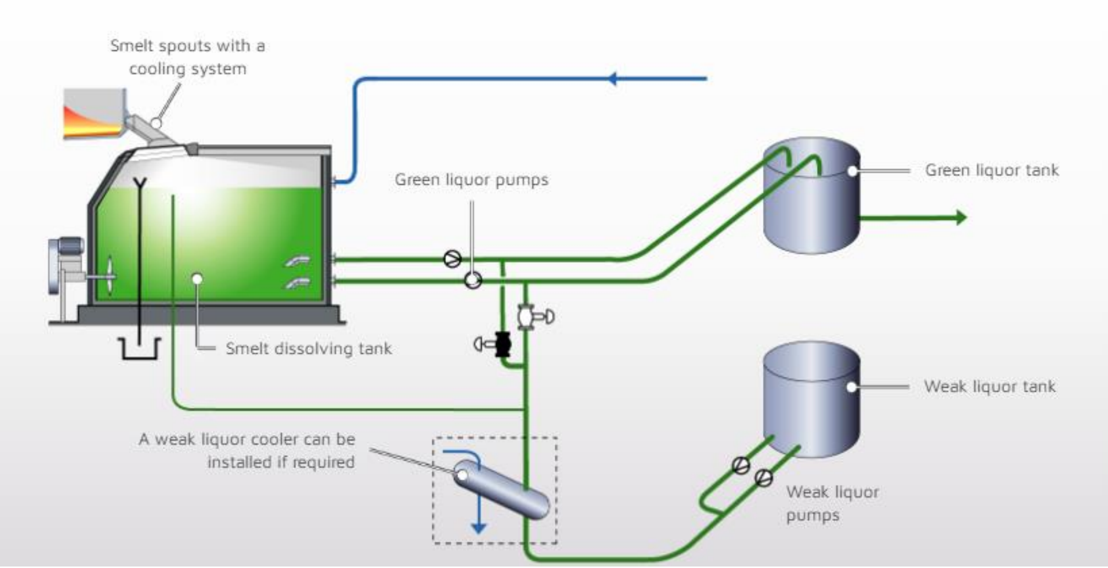


FIGURE 13. Main components of green liquor system (Valmet, 2025)

2.8 Combustion air system

The combustion air system regulates both the quantity and distribution of oxygen required to ensure complete and controlled reactions within the furnace. Air must be supplied in a manner that promotes even dispersion across the entire smelt bed and reaches as low as possible into the furnace to support optimal combustion. In modern recovery boilers, the combustion air system typically consists of combustion air fans, air preheating units, and multiple air staging levels. The purpose of this system is to deliver the precise amount of air needed to achieve efficient and stable combustion of black liquor. (Valmet, 2025; KnowPulp, 2015.)

Combustion air is introduced into the furnace through air nozzles, as illustrated in Figure 14. The air enters the furnace at approximately 16 °, promoting mixing with surrounding gases. In the central region of the furnace, the airflow begins to curve upward due to lower gas flows beneath and the weakening momentum of air jets. Typically, the amount of combustion air supplied to the recovery boiler ranges between 3.6 and 4.0 m³n/kg dry solids. In addition to the theoretical air requirement, an excess air margin of approximately 10-20 % is added to ensure complete combustion. (Vakkilainen 2005, 7-4.)

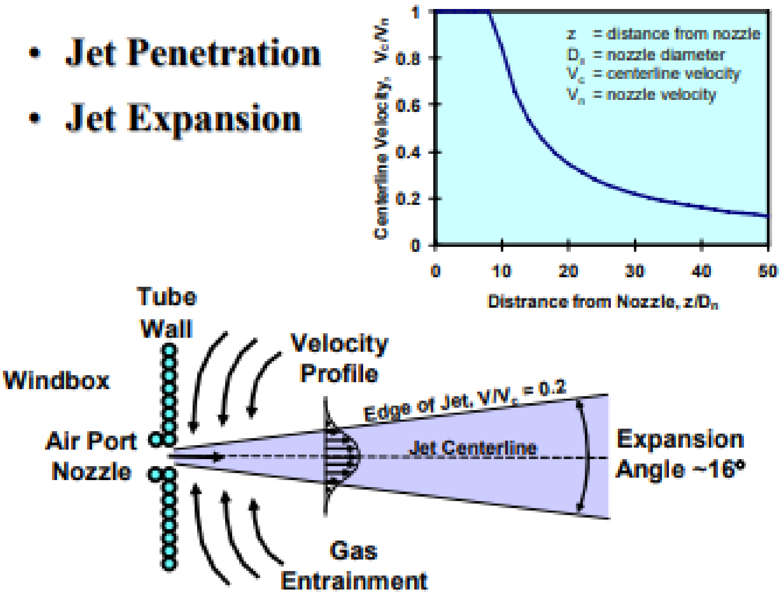


FIGURE 14. Air supply to the furnace (Wessel 2015, 3)

2.8.1 Combustion air fans

Combustion air is typically drawn from the upper sections of the boiler building or, in some cases, partially from outside air. Due to the high cost of axial fans at industrial scale, combustion air rans are most commonly large dial radial fans. In a radial fan, air enters through the inlet in the direction of the shaft and is guided by the impeller toward the outer edge of the casing where it flows into the spiral housing and into the air duct. These fans are often equipped with impellers featuring backward-curved blades, which help achieve optimal efficiency. (Huhtinen et al., 2000.)

Fan selection is based on the required volumetric flow rate and pressure difference, using performance curves provided by equipment manufacturers. In addition to these parameters, fan efficiency and the shape of the performance curve also influence the choice. Energy-efficient air fans are often equipped with inverters allowing the desired duct pressure to be achieved by adjusting the fan´s rotational speed. For fault conditions, fans are also fitted with guide vane control, where the airflow is redirected in the direction of the impeller´s rotation within the guide vane assembly, thereby reducing the flow rate. (Huhtinen et al., 2000.)

2.8.2 Combustion air preheating

In recovery boilers, steam preheaters are used for combustion air heating instead of flue gas heat exchangers. This is since the flue gas ducts in recovery boilers are significantly dirtier and structurally different compared to conventional steam boilers. As a result, combustion air is not heated using flue gases (Vakkilainen, 2010 & Huhtinen et al., 2013).

Steam preheating typically utilizes low- or medium-pressure steam at 3-10 bar and the combustion air is heated to approximately 120-150 °C. Steam-air heat exchangers are commonly constructed with finned tubes to ensure optimal heat transfer, as condensing steam transfers heat more effectively than air. Additionally, preheating the combustion air with steam prevents excessive cooling of flue gases and helps avoid falling below the acid dew point. (Huhtinen et al., 2000, 201.)

2.8.3 Air levels

Air supply to the furnace is divided into several combustion air levels, consisting of primary, secondary, tertiary and in some cases, quaternary air stages. Figure 15 illustrates a typical multi-level air distribution system used in recovery boiler furnaces. A combustion air system in which secondary and tertiary air is introduced at multiple levels so stage the combustion process is referred to as multi-level system. This configuration reduces flue gas velocities in the lower furnace, thereby minimizing carryover and maximizing air penetration into the smelt bed. In some cases, air supply is implemented using a so-called vertical system, where secondary and tertiary air is introduced into the furnace at 4 to 6 different elevations.

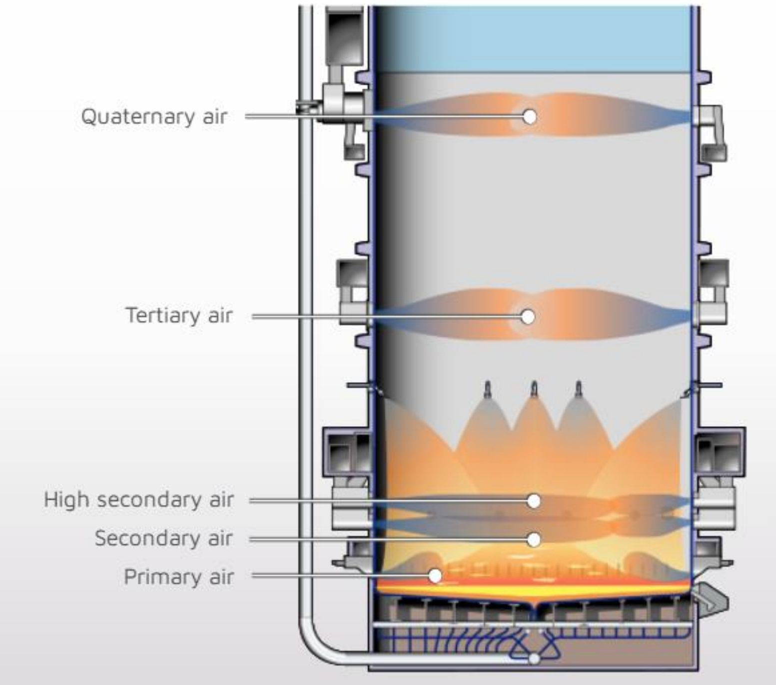


FIGURE 15. Example structure of combustion air levels (Valmet, 2025)

Primary air supply

Primary air is preheated to a temperature of approximately 120-150 °C before being evenly distributed into the recovery boiler furnace through primary air nozzles located on each wall, as shown in Figure 16. Modern HI-power recovery boilers can have temperatures up to 200 °C. These nozzles are positioned about 1-1.5 meters above the furnace floor. The primary air delivers oxygen to the edges of the smelt bed, and its flow rate is used to regulate the height and shape of the bed (KnowPulp 2015). The primary function of the primary air is to control the combustion of the smelt bed near the airports, prevent molten smelt from entering the ports, and maintain the bed at a sufficiently high temperature and fluidity.

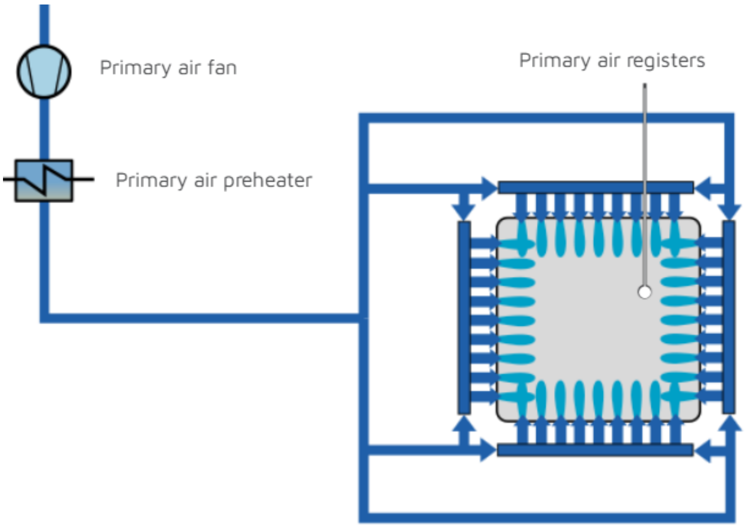
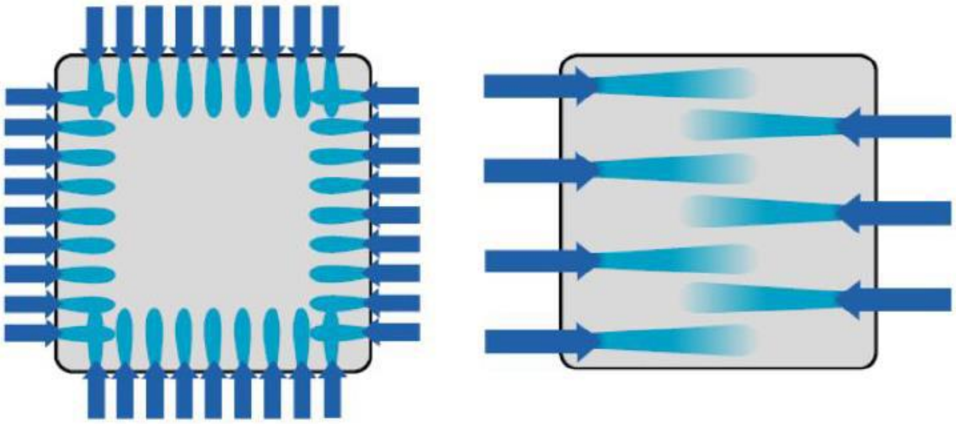


FIGURE 16. Primary air supply and equipment (Valmet 2025)

The proportion of primary air relative to the total combustion air varies between approximately 25-60 % depending on the design and operation of the recovery boiler. In high dry solids boilers, the typical share of primary air is around 30 % of the total air supply. The pressure in the “air box” generally ranges between 0.8 and 1.5 kPa. (Vakkilainen 2005, 7-3, 9-9.) The primary air flow must be optimized to prevent the formation of vertical cortices in the lower furnace caused by excessive pressure or air volume. These vortices affect the trajectory of black liquor droplets, resulting in uneven distribution onto the smelt bed. Conversely, insufficient primary air flow cools the furnace, which may cause molten smelt to enter the primary air port and block nozzles. (KnowPulp 2015.)

Secondary air supply

Secondary air is introduced into the furnace at multiple levels, approximately 1-3 meters above the primary air level, at a temperature of around 120 °C. The supply of secondary air can be implemented in the ways shown in Figure 17. The lower secondary air level may be distributed evenly from all four walls, or alternatively, like the upper secondary air level, from two opposite walls in an interlaced pattern (Wessel 2015,4). The pressure of secondary air in the “air box” typically ranges between 3 and 5 kPa. However, due to pressure fluctuations within the furnace, the pressure at the nozzle may be 0.2-0.4 kPa higher (Vakkilainen 2005, 7-4).



(a) (b)

FIGURE 17. Alternative secondary air supply methods: Four-wall distribution (a) or interlaced two-wall distribution (b) (modified from source Valmet 2025)

Secondary air is used to control the height of the smelt bed and to facilitate the combustion of volatile compounds and char within the furnace. It also plays a key role in regulating air mixing. Excessive secondary air may cause the black liquor spray to rise into the upper regions of the furnace. Therefore, the pressure of the secondary air must be sufficiently high to ensure adequate penetration and maintain effective control of smelt bed. To improve penetration, an additional upper secondary air level has been introduced in the recovery boiler (Wessel 2015, 3 & KnowPulp 2015). High secondary air may include vent gases originating from the dissolving tank vent gas scrubber, as well as diluted non-condensable gases from the mill (Valmet 2025).

Furnace behavior can be effectively predicted by monitoring temperature profiles and examining the amount of carryover in the upper furnace. Figure 18 illustrates the temperature distribution within the furnace, showing that the highest temperatures are typically located near the secondary air levels. As a result, increasing the temperature of combustion air can enhance the combustion process and improve heat transfer. (KnowPulp 2015 & Vakkilainen 2005, 9-11.)

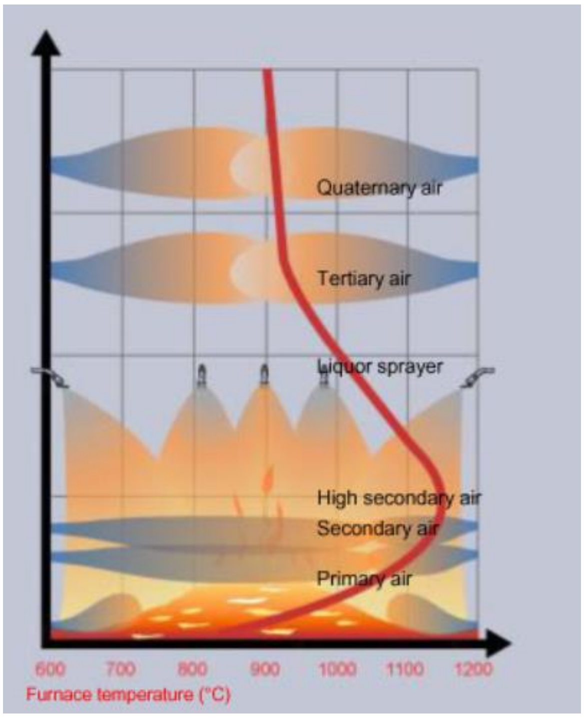


FIGURE 18. Furnace temperature profile (KnowPulp 2015)

Tertiary- and quaternary air supply

Tertiary air is introduced into the recovery boiler at high velocity without preheating, typically 3-6 meters above the liquor spray level. Its primary function is to complete the combustion of unburned gases and to help equalize airflow before the upper section of the furnace (Vakkilainen 2005, 7-5, 9-9 & KnowPulp 2015). Tertiary air can also be staged across multiple levels to facilitate complete combustion, which helps partially reduce nitrogen oxide (NO_x) emissions.

Additionally, air can be supplied from the quaternary level, located significantly higher than the other air stages. Like tertiary air, quaternary air is intended to reduce NO_x emissions formation and flue gas flow. (KnowPulp 2015 & Valmet 2025.)

If required, quaternary air is drawn from the tertiary air duct and supplied to the furnace through air registers located on the front and rear walls. Tertiary and quaternary air supply can be implemented using configurations such as the 4-3 or 3-2 system, as illustrated in Figure 19. In modern boilers, the air ports are arranged in an interlaced pattern, made possible by adding one extra air nozzle to the front wall. It is also common practice to introduce diluted malodorous gases into the furnace from tertiary air level. These gases are cleaned and heated prior to being fed into the recovery boiler. Additionally, if issues arise in the distribution of malodorous gases, supplementary air may be injected into the duct to stabilize the flow. (Valmet 2025.)

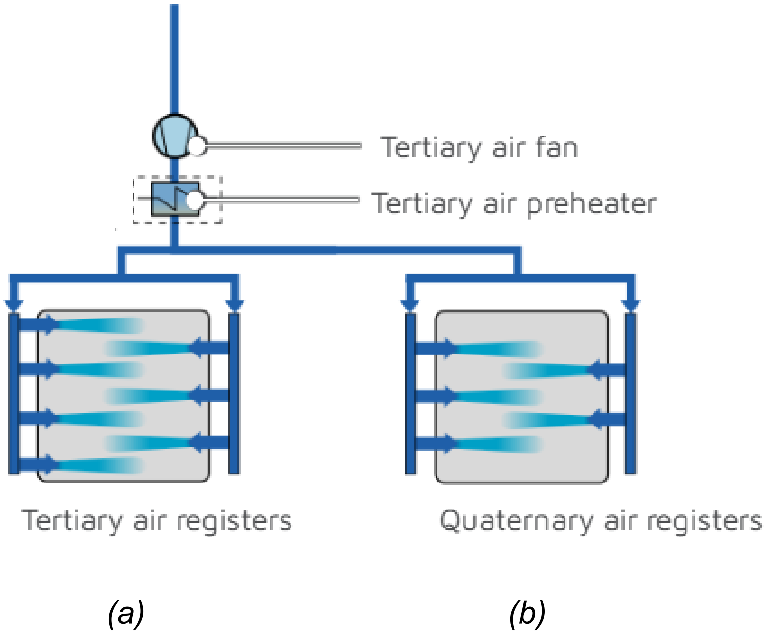


FIGURE 19. Interlaced 4-3 (a) and 3-2 (b) Configurations for Tertiary and Quaternary Air Supply Systems (Valmet 2025)

2.9 Water-steam circulation of the recovery boiler

The water-steam system of the recovery boiler consists of a feedwater tank, feedwater pumps, economizers, a steam drum, an evaporator, a circulation piping system, and superheaters, as illustrated in Figure 20. The water-steam circulation in a recovery boiler follows the same basic principles as in other natural circulation boilers, although the recovery boiler includes some structural differences. Feedwater is pumped from the feedwater tank to the economizers, where temperature is raised close to the boiling point before being directed to the steam drum. From the drum saturated water descends to the lower part of the evaporator due to density differences and returns to the drum after evaporating. The generated steam is then routed from the drum to the superheaters and finally to the turbine for process steam and energy production. (KnowPulp 2015.)

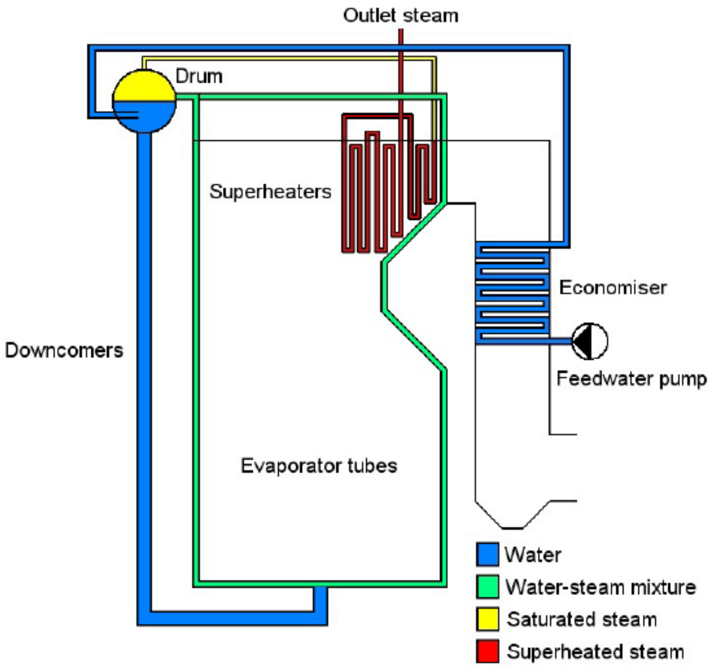


FIGURE 20. Recovery boiler feedwater circulation (Valmet internal archive 2025)

2.9.1 Feedwater tanks and pumps

Ion-exchanged and purified make-up water is supplied to the recovery boiler´s feedwater tank via a deaerator, non-condensable gases are removed from the make-up water by stripping with low-pressure steam, after which the water is directed to the tank for storage at a temperature of approximately 110-140 °C. Due to load fluctuations and disturbances in the recovery boiler, water is stored in the feedwater tank according to process requirements, and the tank level is regulated by adjusting the flow of make-up water and condensate. (Valmet 2025.)

Feedwater is pumped and pressurized by feedwater pumps from the feedwater tank to the preheating stage. For this purpose, the recovery boiler is equipped with two multistage centrifugal pumps driven by electric motors, each capable of raising the feedwater pressure to at least 20 % above the boiler’s design pressure. Additionally, a turbine-driven feedwater pump is installed for backup during disturbance conditions. Under normal operating conditions, the feedwater pressure is maintained at 5–10 % above the boiler’s operating pressure to compensate for pressure losses in the piping system. Typically, only one electric feedwater pump is used for pumping, while the others remain on standby.

2.9.2 Economizers

Feedwater is preheated in economizers using the thermal energy of flue gases, which transfer their heat and cool down in the process (Vakkilainen 3005, 7-8). Economizers, often composed of vertical tubes, typically operate as counterflow heat exchangers, feedwater enters at the bottom and flows upward, while flue gases descend through the duct as shown in Figure 21. Flue gases generally enter the economizer at temperatures between 350 ºC and 450 ºC. To prevent fouling in the downstream sections of the recovery boiler, the flue gas duct is designed with a bypass flow, which redirects the gas stream to the upper part of the economizer. (Huhtinen 2013, 74 & Vakkilainen 2005, 6-15.)

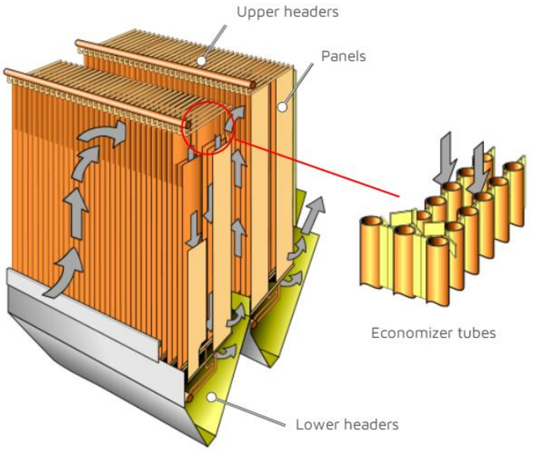


FIGURE 21. Structure of the economizer (Valmet 2025)

In modern boilers, the tubes of the economizers are typically spaced 110–180 mm apart, although minimum spacing can vary significantly. The free flow area of the flue gas duct in Economizer 2 is commonly between 0.13–0.17 m² per square meter of base area, while in Economizer 1, the free flow area typically ranges from 0.11–0.16 m²/m² base. (Vakkilainen 2005, 6-16.)

2.9.3 Steam drum and Dolezal

Feedwater is directed to the surface condenser, also known as Dolezal, where it condenses steam from the steam drum. The clean condensate obtained from the surface condenser is used to cool the superheaters, helping to maintain the purity of the superheated steam. Finally, the feedwater is routed to the steam drum, as shown in Figure 22, where the saturated water heated in the economizers is separated from the steam (KnowPulp 2015).

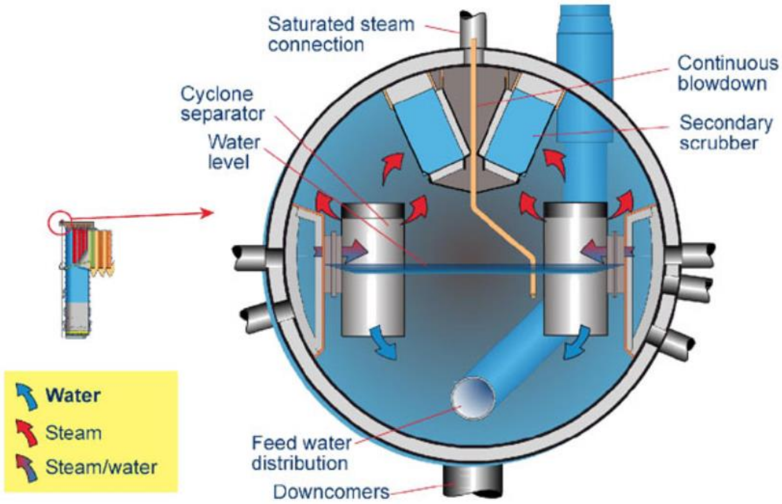


FIGURE 22. Operation and structure of the steam drum (KnowPulp 2015).

The steam drum is the most complex component of the recovery boiler. It serves to separate saturated water and steam for the purposes of evaporation and superheating. Partially vaporized water arriving from the evaporator enters the drum through riser tubes. Inside the drum, cyclone separators direct the water to the lower section, while the steam exits through demisters at the top and continues to the superheaters. The water separated from the steam then flows into the downcomers due to the difference in density. (Vakkilainen 2012, 21.)

2.9.4 Boiler tubes

In the recovery boiler, boiler water is heated in the furnace, screen tubes, and generating bank tubes through radiant heat and the hot flue gases produced by black liquor combustion. This process creates a mixture of saturated steam and water, which is then returned to the steam drum. From the steam drum, the saturated water typically descends through 4 to 6 downcomer tubes to the lower part of the evaporator section, into the main distribution header. From this header, the water is distributed to the sidewall tubes and bottom tubes, which also form the front and rear walls of the furnace. (Valmet 2025.)

Evaporation begins in the lower section of the evaporator tubes, and as steam is generated, the partial mixture rises back to the steam drum through the wall tubes due to changes in density. Although most of the evaporation occurs in the furnace's water wall tubes, a portion of the saturated water is directed to the boiler bank for further evaporation. (Vakkilainen 2005, 7-10.)

In modern recovery boilers, the furnace walls are built from vertical steel tubes arranged in parallel rows. These tubes are joined by flat steel fins (see Figure 23) that are fully welded along the contact line between tube and fin, forming a gas-tight enclosure. This design is known as the membrane wall structure, which improves thermal efficiency and prevents air leakage (Valmet 2025).

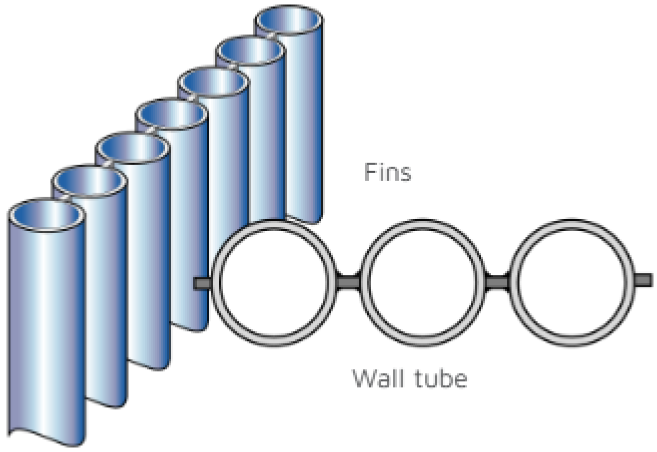


FIGURE 23. Boiler tube membrane design (Valmet 2025)

Composite tubes are essential in the lower furnace area, where exposure to molten smelt and aggressive gases is most intense. The stainless-steel cladding protects against corrosion and extends the service life of the pressure parts. These tubes typically continue upward beyond the tertiary and quaternary air levels, ensuring durability in elevated furnace sections. (Valmet 2025.)

2.9.5 Generating bank

The boiler bank tubes, or evaporative surface shown in Figure 24, form part of the evaporator section of the recovery boiler, where approximately 10–25 % of total evaporation occurs depending on the operating pressure. Structurally distinct from conventional steam boilers, the generating bank typically consists of vertical finned tube panels arranged in a long- or crossflow configuration. These panels are supplied with boiler water via downcomers from the steam drum and connected to upper headers. The steam/water mixture returns to the drum through riser tubes. The outer walls of the generating bank feature membrane-type construction and are integrated into the water circulation loop. Located in the flue gas duct downstream of the nose, and positioned between the superheaters and economizers, the generating bank also incorporates spacer pins between tube panels to prevent excessive vibration during operation. (Vakkilainen 2005 & 7-9, Valmet 2025.)

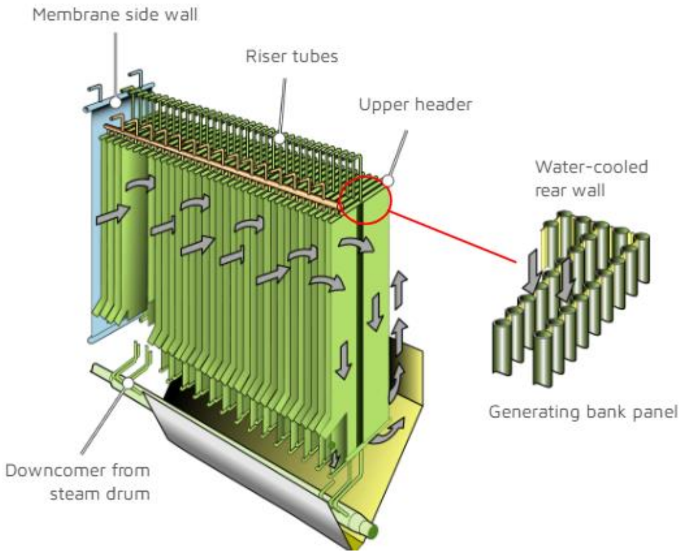


FIGURE 24. Generating bank structure (Valmet 2025)

2.9.6 Superheaters

Saturated steam from the steam drum is directed through a demister to the primary superheater, which is physically located closest to the boiler bank tubes, as shown in Figure 25. In the primary superheater, the steam is heated beyond the saturation point to make it suitable for turbine operation. From there, the superheated steam is routed via distribution headers to the secondary superheater, positioned nearest to the furnace, and then to the tertiary superheater, where it reaches its final superheat temperature. (Valmet 2025 & Vakkilainen 2005, 7-9.)

The fresh steam is then directed from the tertiary superheater to the main steam valve, which regulates the flow of steam to the turbine. To ensure durability and performance, the superheaters must be protected from radiant heat emitted by the lower furnace. The primary stage is located above the furnace nose, which provides shielding. Superheater stages positioned in front of the nose are protected by the screen tubes. Additionally, the outer loops of these superheaters may be constructed from stainless steel to withstand corrosive conditions. (Valmet 2025 & Vakkilainen 2005, 7-9.)

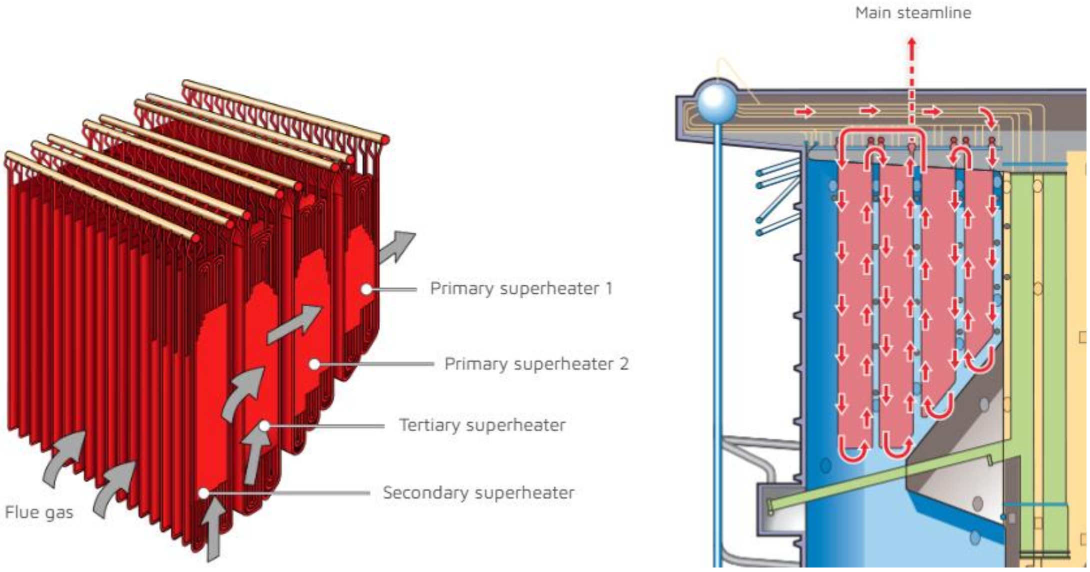


FIGURE 25. Structure of the superheaters and steam flow direction (Valmet 2025)

In modern recovery boilers, steam is superheated to temperatures exceeding 500 °C, with pressures typically ranging between 90 – 110 bar. To maintain optimal steam temperature, cooling water is injected into the superheated steam line through a dedicated spray chamber. This spray-type attemperator system enables precise temperature control before the steam reaches the turbine.

The cooling water used for this purpose is either condensate obtained from the surface condenser or, alternatively, feedwater sourced directly from the feedwater line (Vakkilainen 2005, 7-9).

Superheaters in recovery boilers are categorized based on their position within the furnace and their mode of heat transfer. The first superheater is typically exposed to direct radiant heat from the furnace and is therefore referred to as a radiant superheater. Subsequent superheaters receive heat primarily through convection from the flue gas stream and are thus called convective superheaters. The transition from radiant to convective heat surfaces plays a critical role in staged steam temperature elevation and energy efficiency optimization. (Vakkilainen 2005, 6-12.)

2.10 Sootblowing system

Sootblowing refers to the process of removing accumulated deposits from heat transfer surfaces using external force — typically by “blowing” with high-pressure steam, as illustrated in Figure 26. In recovery boilers, effective sootblowing is especially critical due to the high ash content of black liquor, which leads to extensive fouling of heat surfaces. The need for sootblowing is determined by the amount of ash generated during combustion and the melting behavior of the fly ash. Without a properly functioning sootblowing system, the boiler’s heat transfer efficiency deteriorates, and over time, the flue gas duct may become severely restricted or even plugged. (Tran et al. 2016.)

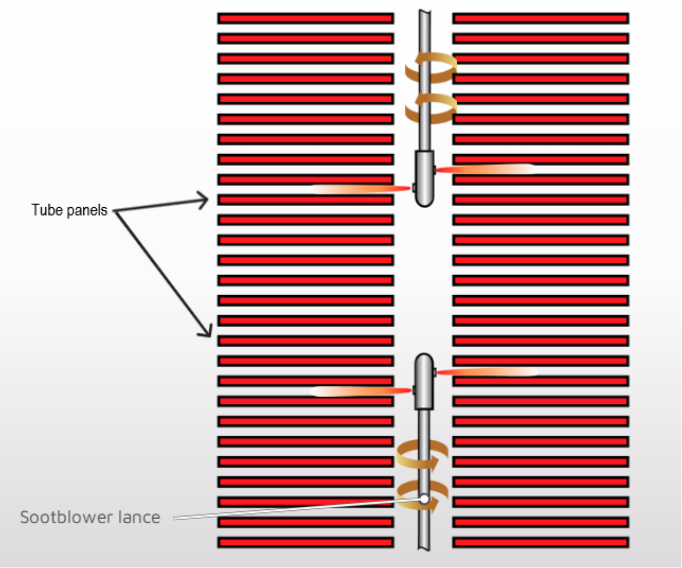


FIGURE 26. Sootblowing working principle, modified from source (Valmet 2025)

Typically, sootblowing in recovery boilers is carried out using retractable steam sootblowers, which direct high-pressure steam through a nozzle onto the heat transfer surfaces and into the spaces between them. The steam lance moves inside the furnace in a rotating motion, as illustrated in Figure 26, ensuring that the steam jet covers the widest possible area.

The cleaning efficiency of a sootblower depends on its blowing power and the structure of the deposit. Key factors influencing penetration and effectiveness include steam mass flow, pressure, temperature, nozzle size and shape, dispersion capability, distance to the deposit, and the sootblowing sequence. The deposit structure determines the removal mechanism: brittle deposits tend to disintegrate, while hard deposits are displaced from the surface. These mechanisms are illustrated in Figure 27 (Kaliazine et al. 1997).

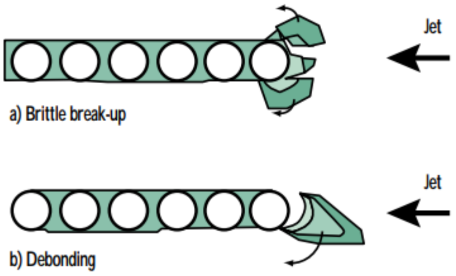


FIGURE 27. Deposit removal (Kaliazine et al. 1997)

2.10.1 Sootblower

The sootblower consists of a globe valve, steam pipe, motor, sootblower carriage, limit switches, and a sootblower lance. The movement of the sootblower is controlled by a motor, which may be located either at the end of the lance or mounted on the carriage above the gearbox, as shown in Figure 28. The lance tube’s rotational and reciprocating motion is driven by a primary gear mechanism, ensuring effective cleaning coverage across the heat transfer surfaces. (KnowPulp 2015.)

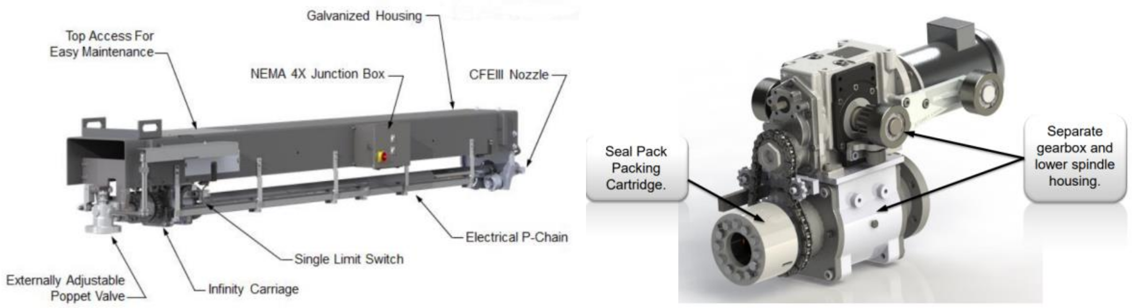


FIGURE 28. Steam sootblower structure (Clyde Bergemann 2014)

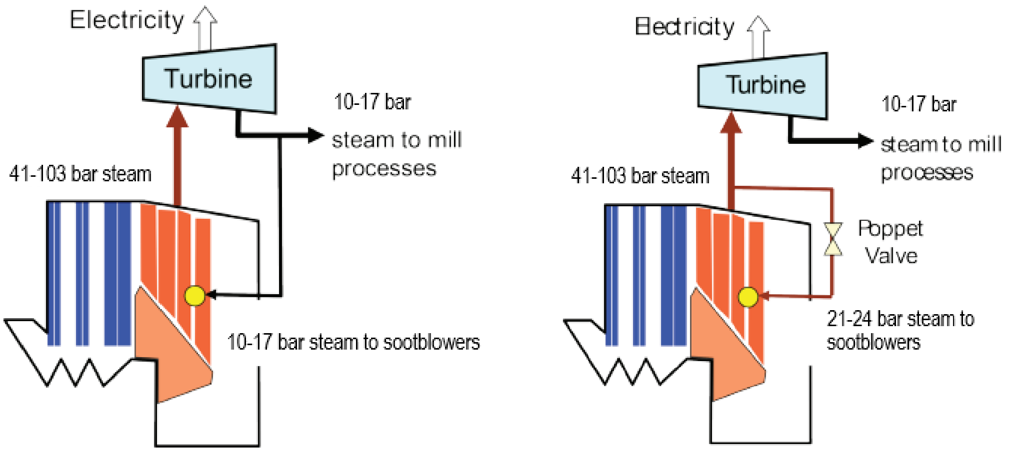
The globe valve is located at the rear end of the sootblower and regulates the steam flow mechanically via a cam mechanism, which adjusts the valve position based on the movement of the carriage. The cleaning pressure is controlled using the valve's adjustment ring, either by fully opening the globe valve and regulating pressure via the sootblower group's control valve, or by adjusting the pressure individually for each sootblower using its own globe valve.

Steam flows from the globe valve into a stainless-steel steam pipe, which is sealed using a gland packing. At the end of the pipe, there are two steam nozzles positioned on opposite sides, directing high-pressure steam jets onto the heat transfer surfaces. The steam pipe is housed inside the sootblower lance, ensuring targeted cleaning during operation (KnowPulp 2015).

2.10.2 Sootblowing steam

Sootblowing in the recovery boiler consumes approximately 3–12 % of the produced high-pressure steam, depending on the boiler's design and operational parameters. This steam, which could otherwise be utilized for power generation or process heating, is directed to sootblower systems to maintain clean heat transfer surfaces and ensure efficient boiler performance. (Tran et al. 2008, 2.)

Sootblowing steam is often extracted from the superheater's collection chamber, where its pressure is reduced to 21–24 bar using a sootblowing steam valve, as illustrated in Figure 29a. Alternatively, the steam can be taken from the first extraction stages of the turbine at a higher pressure, or as intermediate- or low-pressure steam in the range of 10–17 bar, as shown in Figure 29b. This approach helps reduce fresh steam consumption, since steam does not need to be drawn directly from the superheater steam line. (Tran et al 2008, 1.)



(a) (b)

FIGURE 29.Use of a high-pressure (a) and low-pressure (b) sootblowing steam (Tran et al 2008, 2)

When low-pressure steam is used for sootblowing, it is important to note that the dynamic pressure at the nozzle tip, known as Peak Impact Pressure (PIP) along with sootblowing effectiveness, will decrease. Naturally, lower steam pressure and temperature reduce jet penetration and cleaning power. Additionally, low-pressure steam often contains a small amount of condensate, which can further hinder performance. To compensate, a higher steam flow must be directed to the sootblowing system. This can be achieved using optimized, more efficient and larger nozzles. For example, increasing the steam flow by 15–20 % at a soot-blowing pressure of 14 bars can help achieve sufficient cleaning effectiveness. (Tran et al. 2008,1.)

2.10.3 Sootblowing nozzles

In addition to steam parameters, the type of nozzle used to direct steam onto heat transfer surfaces significantly affects sootblowing efficiency. Modern systems have transitioned to using fully expanded nozzles instead of under-expanded nozzles, as the former reduced disruptive shock waves that previously hindered cleaning performance. As a result, cleaning effectiveness has improved substantially. With the same steam consumption, fully expanded nozzles deliver multiple times higher cleaning efficiency compared to the previously used nozzle designs. (Tran et al. 2015a.)

The leading sootblower suppliers have continued to develop nozzle heads, further improving cleaning efficiency and thereby reducing steam consumption for sootblowing. Figure 30 presents the high-performance nozzles from Diamond Power and Clyde Bergemann, which are now the most used in modern recovery boilers.

Diamond Power's Gemini

Clyde Bergemann's CFE

FIGURE 30. High-performance sootblower nozzle from two suppliers (Tran et al 2015, 5)

2.11 Ash conveyers

The ash generated in the recovery boiler, consisting of predominantly of sodium sulfate (Na_2SO_4) and sodium carbonate (Na_2CO_3), is collected from the ash hoppers and electrostatic precipitators (ESP) and subsequently mixed with black liquor in the black liquor tank to enable chemical recovery, as shown in Figure 31. From the hoppers, the ash is discharged via rotary feeders onto eclosed, dustproof scraper conveyors located directly beneath. The rotary feeders serve a dual purpose: they regulate the ash flow and present both ambient air and vent gases from the mixing tank from entering the flue gas ducts. (Valmet 2025 & KnowPulp 2015.)

In the design and operation of the ash conveying system, it is critical to ensure that any potential leakage from heat transfer surfaces does not allow water to travel from the lower entry point of the scraper conveyor into the black liquor in the mixing tank, as such an occurrence could lead to hazardous reactions. The primary function of the ash handling system is to transport ash from the recovery boiler and ESP to the mixing tank, and, where applicable, to the ash leaching tank, while maintaining process safety and minimizing the risk of gas or liquid backflow. (Valmet 2025 & KnowPulp 2015.)

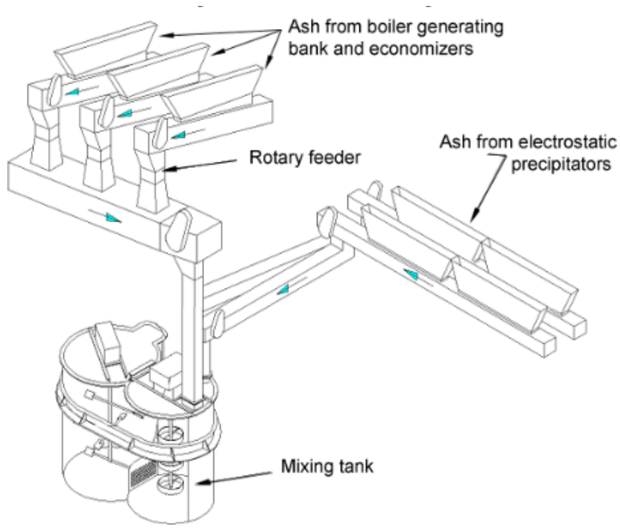


FIGURE 31. Ash conveyors (KnowPulp 2015)

2.12 Auxiliary fuel system

Heavy fuel oil is most employed as an auxiliary fuel, although some boilers may alternatively operate on natural gas or light fuel oil. The oil combustion system typically comprises a pumping unit with integrated preheaters, connecting pipelines, and burners.

In recovery boiler, two primary types of oil burners are used:

Load burners, which are engaged solely to increase the boiler´s steam output.

Start-up burners, which are utilized during boiler warm-up, to support black liquor combustion, to establish the char bed, and to continue to the final combustion stage.

These burners generally employ steam or air pressure atomization. Current regulations require that all newly installed or modernized recovery boiler oil burners be equipped with flame monitoring and control systems, which automatically shut off the oil supply if the flame is extinguished. Furthermore, one or two emergency shutdown valves with actuators are installed to isolate specific oil lines when necessary. (KnowPulp, 2015.)

3 BURNING PROCESS IN RECOVERY BOILER

Black liquor, also referred to as waste liquor, is a liquid fuel burned in the recovery boiler. Due to its high content of inorganic material, it presents significant combustion challenges, primarily because of its low heating value and high moisture and ash content. These characteristics give rise to specific considerations in its combustion process. This chapter examines the spraying of black liquor, the stages of its combustion, and the properties that influence these processes.

3.1 Black liquor

Black liquor is an intermediate product of the pulping process, composed of inorganic compounds such as various sodium and sulfur species. It is generated when the active alkalis in the cooking chemicals—namely sodium hydroxide (NaOH) and sodium sulfide (Na_2S)—dissolve the lignin that binds wood fibers into the cooking liquor. Black liquor is also separated during the pulp washing stages. (Raiko et al., 2002, p.522.)

In addition to inorganic constituents, black liquor contains organic compounds such as lignin, hemicellulose, and extractives, which combust in the recovery boiler and release substantial amounts of heat. Alongside the active alkalis, black liquor also contains sodium carbonate (Na_2CO_3), sodium sulfate (Na_2SO_4), and sodium thiosulfate ($Na_2S_2O_3$). Its composition changes during pulp washing and evaporation: in the washing stage, atmospheric oxygen oxidizes sodium sulfide into polysulfide or sodium thiosulfate, while during evaporation, hydrogen sulfide and methanol present in the liquor are volatilized. (KnowPulp 2015.) The typical composition of black liquor generated in softwood pulping is presented in Table 1. The values are expressed as percentages of the dry solids in the firing liquor.

	Typical composition [%]
Carbon, C	35
Hydrogen, H	3,6
Nitrogen, N	0,1
Oxygen, O	33,9
Natrium, Na	19,4
Kalium, K	1,8
Chlorine, Cl	0,5
Sulphur, S	5,5
Others	0,2
calorimetric heating value [MJ/kg]	14,2

Table 1. Compositions of softwood black liquor (Alakangas et al. 2016, 113)

Figure 32 presents the key process variables and physical properties that influence the combustion behavior of black liquor. Among the monitored parameters, solids content and chemical composition are essential, but temperature plays a particularly critical role. Temperature directly affects the density and viscosity of black liquor, which in turn governs its droplet formation during atomization. Since droplet formation is a decisive factor in combustion efficiency, temperature must be carefully controlled to ensure stable and effective burning conditions. (Alakangas et al. 2016, 115 & Adams et al. 1997, 61.)

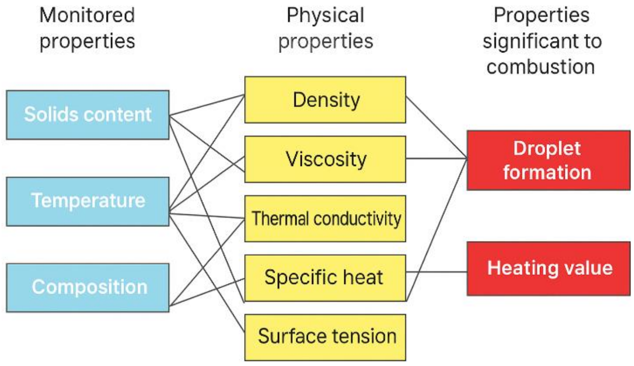


FIGURE 32. The spraying of black liquor is influenced by process variables and physical properties (Modified from source Alakangas et al. 2016, 115)

3.1.1 Effect of solids content on the properties of black liquor

The solids content of black liquor separated during the cooking and washing stages typically ranges between 14–18 %. Due to the high-water content, the liquor must be concentrated through evaporation. For combustion purposes, the solids content of black liquor is normally increased to 72–85 %, ensuring sufficient energy density and stable burning conditions. (Suhr et al. 2015, 205.)

The solids content of black liquor influences all its physical properties. Increasing the solids content raises both the density and viscosity of the liquor, while the reduction in moisture lowers its thermal conductivity and specific heat capacity. As these physical properties change, the boiling point rise (BPR) defined as the temperature difference between the boiling points of black liquor and pure water at equal pressure, is also affected. (KnowPulp 2015.)

3.1.2 Effect of residual alkali content on the properties of black liquor

Residual alkali refers to the amount of alkali remaining in black liquor after the cooking process. Its concentration depends on factors such as the number of cooking stages, the quality of the wood raw material, chip size, and the bleaching process. Due to this variability, no fixed guideline value exists. Insufficient alkali dosing may lead to lignin reprecipitation, whereas excessive residual alkali results in unnecessary consumption of costly chemicals. In industrial practice, residual alkali concentrations typically range between 5 and 10 g/l. (KnowPulp 2015.)

Residual alkali content influences the solubility of organic matter in black liquor and reduces its viscous properties. When the residual alkali level is higher than desired, organic compounds remain dissolved, resulting in lower overall viscosity. Conversely, at lower residual alkali concentrations, the viscosity of black liquor naturally increases due to reduced solubility of organic material. (Pulp and Paper Canada 2019.)

3.1.3 Effect of soap and tall oil content on the properties of black liquor

Black liquor typically contains approximately 1 % soap, but in mills without dedicated tall oil recovery, the soap content may reach up to 2.5 %. Variations in soap concentration affect the quality of black liquor, posing challenges for both its production and recovery boiler operation. Poor soap separation reduces black liquor throughput and increases fouling and TRS emissions, even at low concentrations. On the other hand, elevated soap levels enhance combustion, improve steam generation efficiency, and raise char bed temperature, as the heating value of soap is nearly twice that of black liquor. This contributes to a higher reduction efficiency and facilitates SO_2 emission control. (Allen et al. 2007.)

Soap has a higher viscosity than black liquor and does not fully dissolve into it, resulting in a broader droplet size distribution during spraying. This leads to the formation of both fine and coarse droplets, which in turn affects the combustion time of individual droplets. Elevated soap content shifts combustion toward suspension burning and increases the amount of carryover, contributing to fouling in the superheater area. At high soap and tall oil concentrations, the spray angle of black liquor burners should be reduced to direct droplets more effectively into the furnace and prevent them from escaping into the upper regions. However, at lower liquor temperatures and reduced spray angles, additional primary air must be supplied to maintain adequate char bed temperature.

3.2 Black liquor spraying

Black liquor is sprayed into the furnace of the recovery boiler as a droplet-form jet using liquor nozzles, as illustrated in Figure 33. The uniform distribution of droplets across the reduction zone depends on the atomization quality, which significantly influences combustion behavior, char bed performance, sulfur reduction, flue gas mixing, and carryover control. Based on char bed conditions and combustion dynamics, the liquor spray temperature is adjusted accordingly. For black liquor with 65–80 % solids content, typical spray temperatures range from 115 to 143 °C. (Karami et al. 2013.)

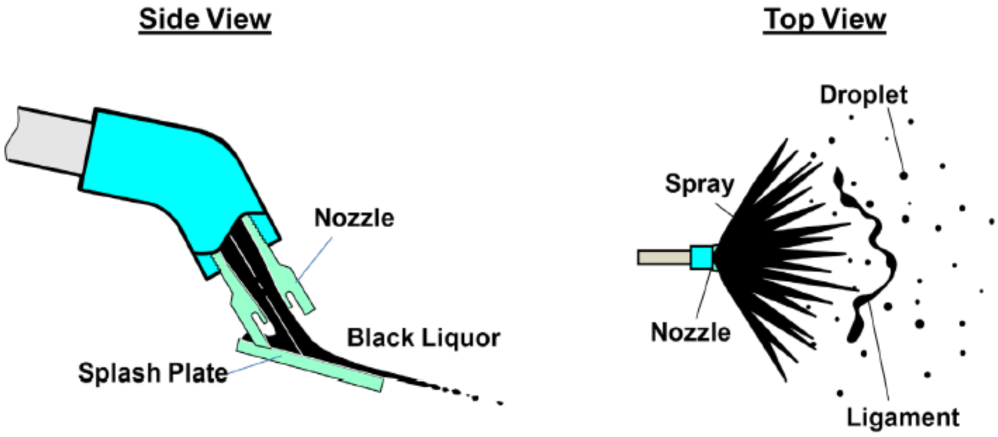


FIGURE 33. Spoon shaped liquor nozzle and spray pattern (Karami et al. 2013)

Optimal droplet sizing, typically between 2 and 4 mm, is crucial for efficient recovery boiler operation. Properly sized droplets dry before entering the furnace, minimizing the risk of upward drift and subsequent carryover. Achieving this requires consistent nozzle alignment, orientation, and spray stability. Moreover, droplet size affects the spatial dynamics of combustion: as droplets become smaller, combustion shifts toward the suspension phase, which decreases the amount of char settling on the furnace floor and consequently reduces the char bed height.

Uniform distribution of black liquor spray over the char bed area is essential for maintaining stable furnace operation and preventing harmful accumulation on the furnace walls. Indicators of well-controlled spraying include a symmetrical char bed, optimized heat transfer, and effective sulfur reduction. Spray characteristics are governed by several factors: liquor temperature, volumetric flow rate, nozzle design and dimensions, and the number of liquor guns employed. These variables directly affect the flow velocity and pressure at the nozzle. Notably, increasing the number of liquor guns lowers the pressure, which in turn leads to the formation of smaller droplets.

Raising the temperature of black liquor reduces its viscosity, which also leads to smaller droplet formation during spraying. A sufficiently high temperature ensures adequate fluidity and unobstructed flow through the liquor delivery system without significant pressure losses. Temperature control is critical for spray performance; if the temperature becomes too high, flashing, rapid vaporization of the liquor, can occur at the nozzle. This phenomenon may cause severe operational issues, including premature boiling inside the nozzle, ultimately preventing liquor from reaching the furnace. (Karami et al. 2013.)

Flashing occurs when the velocity of black liquor at the nozzle becomes too high, inducing vapor bubble formation that destabilizes the spray. This leads to poor dispersion, with droplets striking furnace walls and accumulating unevenly on the char bed. Operationally, many recovery boilers function within the flashing zone, which complicates spray dynamics and overall process stability. A notable example is found in Finnish mills, where black liquor is routinely introduced into the furnace at temperatures above its boiling point, increasing the risk of flashing-related disturbances.

3.3 Stages of black liquor firing

The combustion of black liquor resembles that of many solid fuels, such as coal and wood, proceeding through three primary stages: drying, pyrolysis, and char combustion. However, black liquor droplets expand significantly more during combustion compared to conventional fuels. The solid fraction of black liquor contains a high concentration of inorganic compounds with low melting points. As the organic matter burns, the water within the droplet evaporates, and the remaining material transitions into molten form, eventually settling into the char bed as smelt. The combustion of black liquor droplets is a rapid reaction, as illustrated in Figure 34. (Adams 1997, 132-133.)

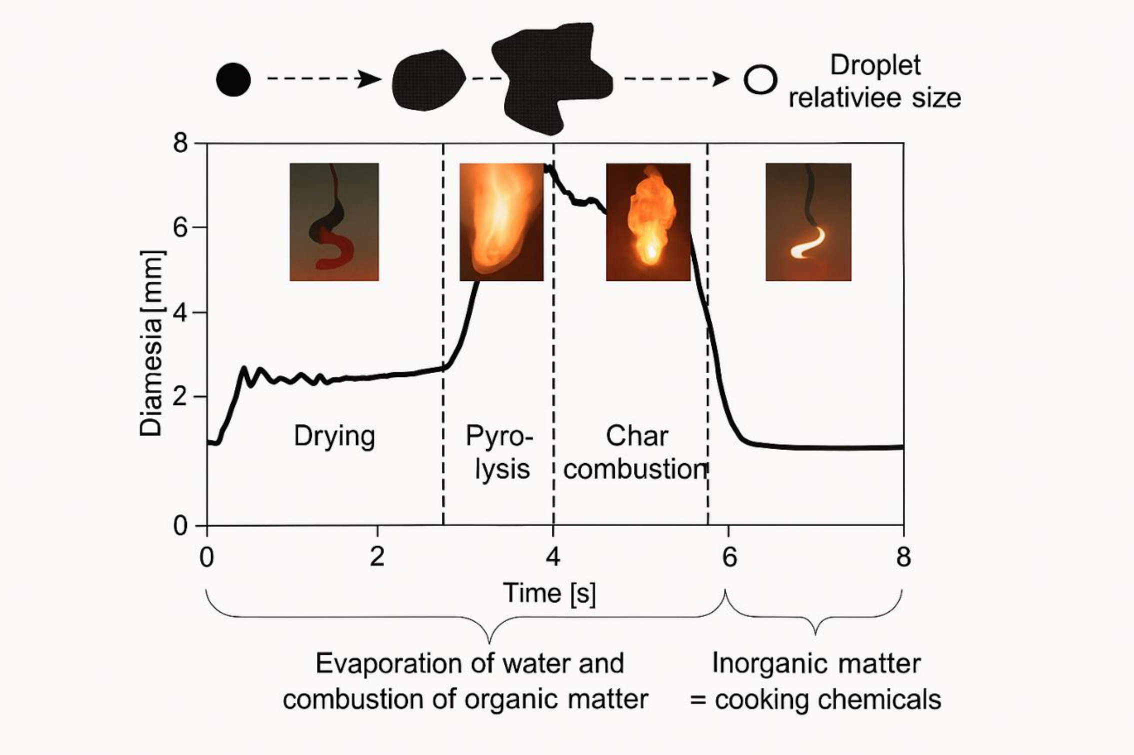


FIGURE 34. Stages of black liquor combustion (Modified from source Vakkilainen 2005, 4-1)

In the drying stage, water within the black liquor droplet evaporates over a period of roughly 0.5 to 3 seconds, influenced by both droplet diameter and furnace temperature. The process begins with heat transfer via radiation and convection, followed by internal conduction. As drying commences, the droplet swells to approximately 1.5 times its initial size, though its dimensions may fluctuate due to localized boiling. Because the furnace heat is primarily consumed by the phase change of water, the droplet’s temperature remains relatively stable throughout this phase. Importantly, drying does not eliminate all moisture—around 5 % of water typically remains in the droplet even after the drying phase concludes. (Raiko et al. 2002, 535 & Bajpai 2017, 80.)

Following the drying phase, the black liquor droplet releases volatile compounds and undergoes pyrolysis, resulting in an increase in droplet volume. If sufficient oxygen and high temperatures are present in the surrounding environment, the pyrolysis gases ignite, producing a visible flame. In some cases, the release of volatiles is so intense that the droplet becomes isolated from oxygen, and the conditions within the droplet resemble pyrolysis or heating in an inert atmosphere. (Vakkilainen 2005, 4-3.)

The release of volatiles and the pyrolysis of black liquor droplets are exceptionally rapid reactions. During this stage, volatile gases are emitted primarily from the droplet's outer surface, leaving a portion of un pyrolyzed material within (Vakkilainen 2005, 4-3). As the droplet has already lost most of its moisture, the heat transferred from the furnace is no longer consumed by water evaporation, allowing the droplet temperature to rise significantly. The droplet expands to several times its original size, but this growth eventually stabilizes, and the surrounding flame extinguishes. At this point, only porous solid char remains, as all volatile compounds have been released. (Raiko et al. 2002, 535.)

Char combustion occurs without a visible flame and proceeds from the outer surface of the droplet as oxygen from the combustion air reacts with the carbon. As the carbon burns away, the droplet gradually shrinks. The duration of char combustion is influenced by several factors: furnace oxygen concentration and temperature, droplet size, and the extent of swelling during pyrolysis. For medium-sized droplets, typical combustion times range from 2 to 5 seconds. However, under low oxygen conditions—such as at 5 % O_2—the combustion time may extend to several tens of seconds. (Adams 1997, p. 152; Raiko et al. 2002, 537.)

As char combustion proceeds, solid carbon is consumed, leaving behind molten inorganic smelt, the composition of which is shown in Figure 34. In a complete combustion process, sodium sulfate in the black liquor is reduced to sodium sulfide. Due to the high sodium content, not all sodium binds with sulfur; some react with carbon to form sodium carbonate. As previously discussed, in oxygen-rich conditions, sodium sulfide may oxidize back into sodium sulfate according to Equation 1. Therefore, in a successful combustion process, the burning char must reach the char bed surface while still actively combusting. This ensures that the molten smelt is released from the char without re-oxidizing sulfide into sulfate. (Raiko et al. 2002, 538.)

4 CLEANING OF SMELT SPOUTS

Smelt is the inorganic residue produced during the chemical reactions occurring in the furnace of a recovery boiler. It serves as the primary medium through which valuable cooking chemicals are recovered. Typically, smelt consists of approximately 60–70 % sodium carbonate (Na_2CO_3) and 20–30 % sodium sulfide (Na_2S). Minor constituents include sodium sulfate, sodium chloride, potassium salts, and residual char bed material.

Smelt begins to solidify at temperatures between 740 °C and 780 °C. However, in modern recovery boiler operations, the smelt temperature is maintained between 800 °C and 850 °C, ensuring that it remains fully molten. In this state, the smelt flows continuously from the furnace into a dissolving tank via designated smelt spouts, enabling efficient chemical recovery and downstream processing, as illustrated in Figure 35. (Vakkilainen 2005, 65.)

FIGURE 35. Smelt media flowing through smelt spout

In the dissolving tank, molten smelt is mixed with weak white liquor from the causticizing plant, resulting in the formation of green liquor (see Figure 36). The dissolution process is highly vigorous, as the smelt stream is broken into fine droplets by high-pressure steam shatter jets immediately upon exiting the smelt spouts. This fragmentation serves a dual purpose: it reduces the intense noise generated during dissolution and mitigates the risk of smelt–water explosions within the tank. The interaction between molten smelt and white liquor creates a highly turbulent environment, characterized by loud acoustic emissions and strong mechanical vibrations, making the vicinity of the dissolving tank a particularly challenging and uncomfortable workspace for operating personnel. (Tran et al. 2015b & Valmet, 2025)

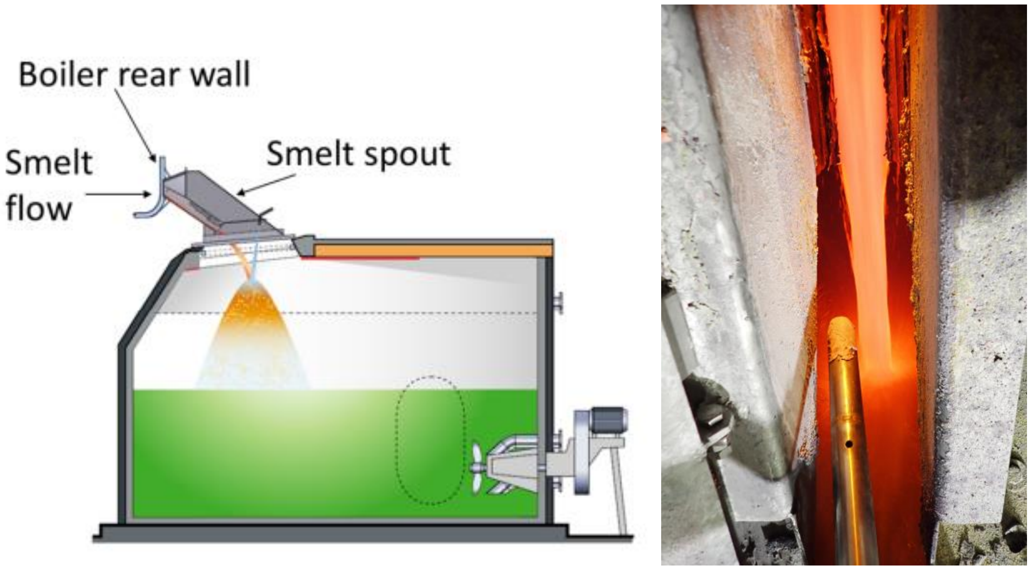


FIGURE 36. Smelt stream being dissolved by steam shatter jet nozzle (Valmet, 2025)

4.1 Smelt spouts

The primary function of the smelt spout is to channel molten smelt from the bottom of the recovery boiler into the dissolving tank. In a modern system, smelt spouts are typically water-cooled to withstand the extreme thermal conditions and ensure operational safety. Nevertheless, uncooled designs also exist and are occasionally employed, although they are less common due to higher thermal stress and reduced durability. In Figure 37 water cooled smelt spout is illustrated.

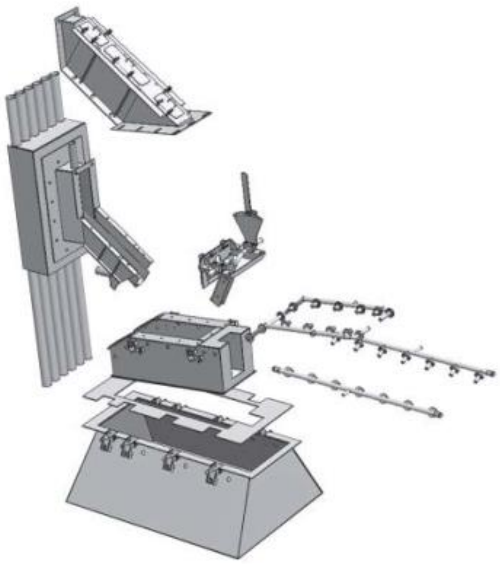


FIGURE 37. Water cooled smelt spout (Valmet 2025)

The number of spouts varies according to boiler size and design. Figure 38 provides a schematic overview of the different structural areas. The lower section of the spout is commonly referred to as the doghouse, whereas the elongated, sloped portion is simply called the spout. The interface connecting the spout to the furnace rear wall is designated as the opening.

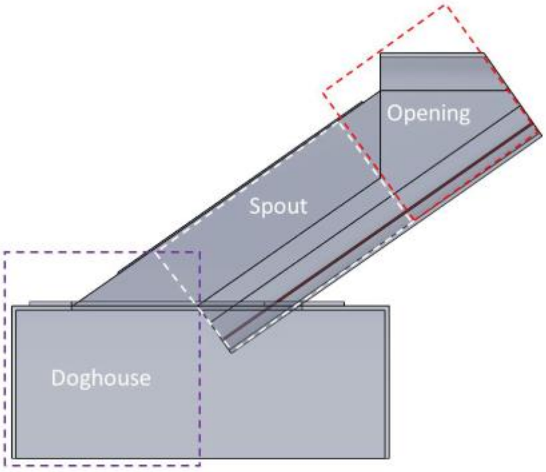


FIGURE 38. A schematic side view provides an illustrative representation of a smelt spout (Lavonen 2020)

The molten smelt exits the furnace through the opening and is directed toward the doghouse via the inclined spout. In cross-section, the spout resembles an elliptical shape, guiding the flow efficiently. The actual dissolution of smelt occurs within the doghouse, which is characterized by its rectangular geometry.

4.2 Challenges in smelt spout cleaning

Routine cleaning of smelt spouts is essential for safe and reliable boiler operation. If cleaning is neglected, the spouts may become blocked, leading to severe safety risks such as uncontrolled smelt run-off. During such events, the smelt discharge can reach peak flow rates that are typically three to five times higher than normal, and I extreme cases even greater (Tran et al. 2015b).

To avoid blockages and the associated safety risks, smelt spouts should be inspected and cleaned by field operators at regular intervals, typically every one to two hours. Traditionally, this work is carried out using long iron rods. To reduce mechanical wear on the spout, proper cleaning technique is essential, and the tool should be designed with a rounded tip to minimize damage during use. (Finnish Recovery Boiler Committee 2018)

Working in the vicinity of smelt spouts involves inherent safety hazards due to the extremely high temperature of the molten smelt. Occasional splashing can result in burns to operators, while more severe disturbances pose even greater risks. The most critical scenarios include smelt–water explosions, uncontrolled smelt run-off, and dissolving tank explosions. A further challenge is that these events often occur without clear warning signs, making preventive measures and cautious operating practices essential (Finnish Recovery Boiler Committee 2018).

4.3 Methods of smelt spout cleaning

The most common and still widely used method for smelt spout cleaning is manual work performed by an operator. A long metal rod is employed to remove solidified smelt from the runner. According to ANDRITZ (2020) this task is physically demanding and hazardous, as the spout deck is considered one of the most dangerous areas in a pulp mill. To make the work slightly more manageable, a support structure can be installed in front of the runner, allowing the operator to rest the cleaning tool and thereby avoid carrying its full weight throughout the process.

The increasing emphasis on reducing operator exposure to molten smelt has accelerated the development of automated cleaning technologies that eliminate the need for direct human presence at the spout deck. One such solution shown in Figure 39, is the SpoutRunner™ system developed by B&W Diamond Power. The device employs a mechanically guided cleaning tool driven by a pneumatic actuator to remove solidified smelt from the spout in a controlled and repeatable manner. By automating the cleaning process, the system significantly decreases the time operators must spend in the hazardous smelt area, thereby improving occupational safety, reducing ergonomic strain, and enhancing the overall stability of smelt flow and dissolving tank operation. (Babcock & Wilcox Diamond Power, 2023.)

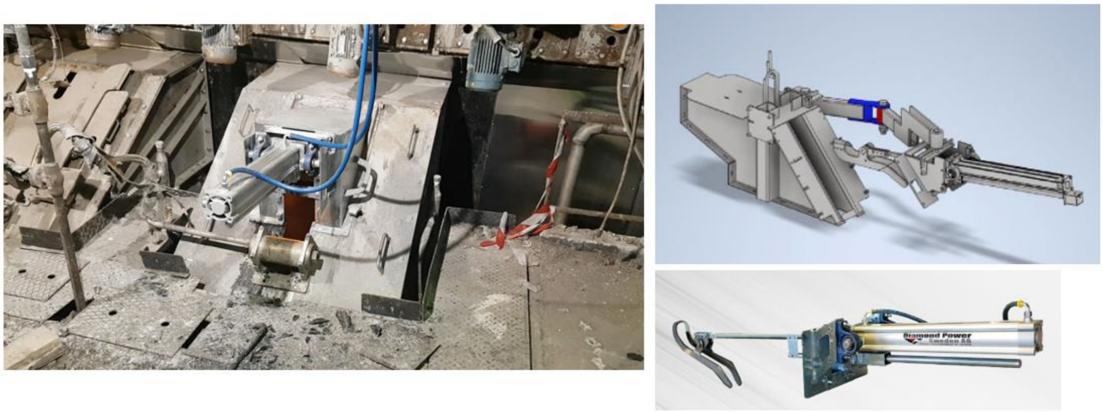


FIGURE 39. Spout runner by B&W Diamond Power (Babcock & Wilcox Diamond Power, 2023)

To provide maximum protection against smelt-related hazards, Valmet has developed a smelt spout robot that utilizes an industrial robotic unit for cleaning. The robot is suspended from a beam-mounted linear track, allowing it to travel along the spout line, illustrated in Figure 40. With its inverted installation, valuable floor space is preserved, improving accessibility to the spouts. Rather than relying on several separate tools, the system employs a single multi-purpose cleaning device, streamlining the process and enhancing efficiency. Depending on the mill layout, the robot can be installed either on the floor or hanging from the ceiling, and it may operate with or without a linear track, offering flexibility in integration.

In addition to replacing manual rodding, the smelt spout robot can perform water washing of the spouts. A key feature of the system is a monitor camera mounted on the robot adapter, which travels along the linear track together with the robot. This enables operators to observe the robot's operation directly from the control room and intervene only when required, thereby improving both safety and efficiency.

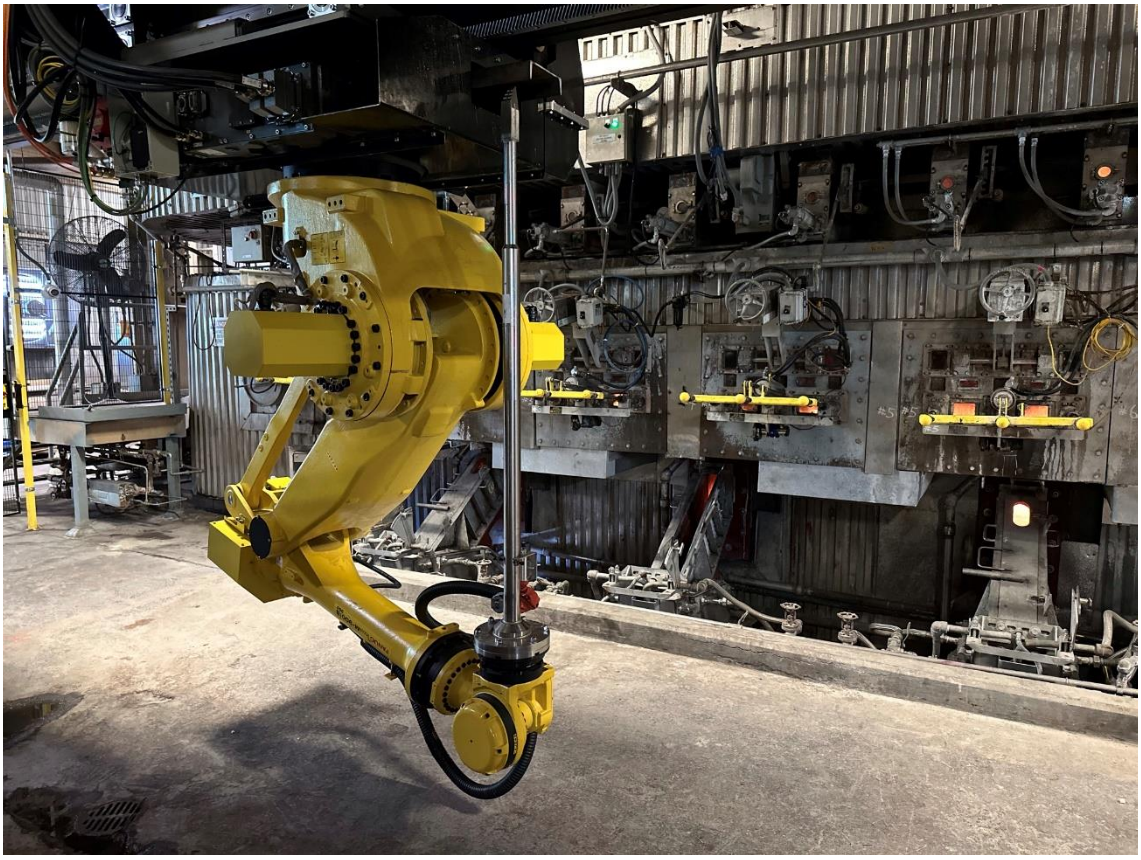


FIGURE 40. Valmet smelt spout robot

4.4 Safety aspects

Operating a recovery boiler involves several significant risks for personnel. One of the most critical hazards is a smelt–water explosion, which occurs when water encounters molten smelt. Even a small amount of water can trigger such an event, as it vaporizes within fractions of a second, causing a rapid increase in both volume and pressure. Depending on the conditions, this pressure rise may range from 10 to 100,000 kiloPascals, generating forces strong enough to deform furnace walls. Violent smelt dissolution poses a direct threat to operators and can also damage equipment. (Vakkilainen 2005.)

The dissolving tank area is particularly hazardous: it is noisy, and many operators feel uneasy working near the smelt spouts. Risks include burns from smelt splashes or green liquor ejections. During heavy smelt run-off, the tank's venting capacity may be exceeded, leading to the release of fumes, mist, and total reduced sulfur (TRS) around the tank. Such incidents are often accompanied by loud bangs and vibrations throughout the building, and in extreme cases, structural damage to the tank or its surroundings may occur. These events are classified as dissolving tank explosions, which represent one of the most serious safety risks in recovery boiler operations. The dissolving process itself is essentially a continuous series of small, controlled smelt–water interactions. To moderate the intensity of these reactions, molten smelt is dispersed into droplets by a steam jet. In the dissolving tank, the smelt is then mixed with weak white liquor, forming green liquor Despite this, the system remains vulnerable to larger, uncontrolled explosions. Such incidents may arise from several causes, including the sudden opening of a plugged smelt spout, variations in black liquor quality, accumulation of insoluble materials, or an excessively high liquid level in the dissolving tank. In severe cases, these explosions can damage both the recovery boiler and the dissolving tank and may even result in hardware failures. (Tran et al., 2006 & Tran et al. 2015b.)

Tran and Jones (2017) describe the formation mechanisms of smelt spout plugging, noting that numerous studies and reports have examined its causes. Maintaining a smooth smelt flow is essential for stable kraft pulping operations, yet the flow can occasionally become sluggish, leading to partial or complete blockage. This phenomenon, commonly referred to as *jellyroll smelt*, occurs when a mass of low viscosity smelt forms and obstructs the spout opening. The danger lies in the accumulation of molten smelt behind the blockage. For operators, attempting to open a plugged spout under these conditions is highly hazardous, as large volumes of smelt may suddenly rush out. Such uncontrolled discharges, known as smelt run-offs, can trigger smelt–water explosions and cause severe damage to the dissolving tank. These incidents represent a serious safety risk, and operator fatalities have been reported.

5 APPLICATION OF INDUSTRIAL ROBOTICS IN SMELT SPOUT CLEANING

According to ISO (2021) Robotics is a multidisciplinary field that combines mechanical engineering, electrical engineering, and computer science to design and build machines, called robots, that can perform tasks autonomously or semi-autonomously. An industrial robot is defined as an automatically controlled, reprogrammable, multipurpose manipulator with at least three degrees of freedom, which may be fixed in place or mobile.

5.1 Definition and significance of robotics in industry

According to ISO (2025) definition of an industrial robot is “An automatically controlled, reprogrammable, multipurpose manipulator, intended for use in industrial automation applications. It has at least three programmable axes and may be either fixed in place or mobile.”

A robotic system consists of four primary components: the power source, the control system, the mechanical unit, and the tool. Depending on the robot type and the cell configuration, the mechanical unit may include various mechanical joints, axes, control valves, limit switches, and sensors. The design, handling capacity, and type of mechanical unit are determined by the specific requirements set for the robot. (Gupta et al. 2017, pp. 463–464.)

A robot’s power source plays a decisive role in its performance and suitability for specific tasks. Motion can be driven by hydraulics, pneumatics, or electric systems, each offering distinct advantages. Hydraulic drives are typically chosen when exceptionally high load capacity is required, while pneumatic drives are favored in applications where rapid movement is essential, but only limited handling capacity is needed. Electric servo motors, on the other hand, provide a balanced compromise, delivering moderate load capacity and speed that can be tailored through motor design. The selection of the power source is therefore closely linked to the operational demands placed on the robot. (Gupta et al. 2017, pp. 464.)

The control system can be regarded as the brain of a robotic system. The robot controller functions as both a communication and data-processing unit, responsible for managing the robot's movements based on information received from sensors integrated into the system. Most industrial robots are equipped with microprocessors- or computer-based controllers, which perform computational tasks in coordination with tools, grippers, and other peripheral devices. (Gupta et al. 2017, pp. 464.)

The definition of a robot arm, or manipulator, varies depending on context. According to Fanuc (2016), a robot is described as a series of mechanically connected links driven by electric servomotors. The junction points between these links are referred to as joints or axes. While the number of axes can differ, most industrial robots are equipped with six axes (Figure 41) (Fanuc 2016).

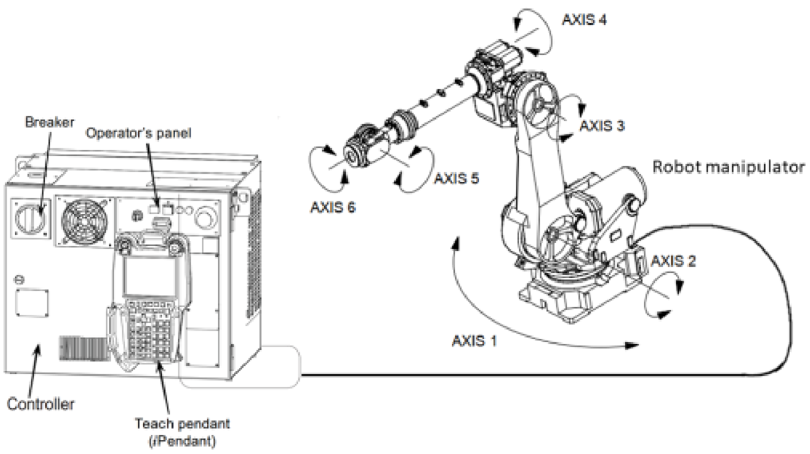


FIGURE 41. Fanuc robot system with robot controller and manipulator (Fanuc 2016)

The robot controller functions as the central unit of the system, incorporating a power supply, operator controls, control circuitry, and memory for managing both robot motion and interaction with external devices (Fanuc 2016). Operation can be performed either through an operator panel or a teach pendant, the latter being a handheld control device illustrated in Figure 41 & 54.

The smelt spout robot is based on a 6-axis FANUC M900iB/360 model mounted on a linear track (Figure 40). Track installation enables the robot to move linearly along the spout line, thereby reaching a wide range of positions. Depending on the track length and application, a single robot with track motion can replace multiple static robots when extended reach is required. Furthermore, when an external axis is added to a 6-axis robot, the system can be classified as a 7-axis robot. (Gan and Tang, 2011.)

5.2 Operating principle of smelt spout cleaning robot

The smelt spout cleaning robot is designed to operate in a demanding industrial environment characterized by high temperatures, corrosive substances, and limited accessibility. Its operating principle is based on automated mechanical cleaning, where a robotic arm or linear actuator maneuvers a cleaning tool along the smelt trough to remove hardened smelt deposits and maintain flow efficiency to dissolving tank.

To facilitate understanding of the robot's functionality, its operation is explained in a manner like the actual programming code. A simplified flowchart of the robot operation is presented in Figure 42. The robot program is composed of multiple TP programs, which are written in FANUC's teaching playback programming language. The main TP program governs the overall operation by assigning smelt spouts to be cleaned in a specific order. This is achieved by calling other TP programs that are dedicated to individual tasks.

For clarity, the programming structure is simplified into two categories: the main program and smelt spout specific programs, the number of which corresponds to the number of spouts. In practice, however, each smelt spout specific program calls several additional TP programs, reflecting the modular and hierarchical nature of the robot's control logic.

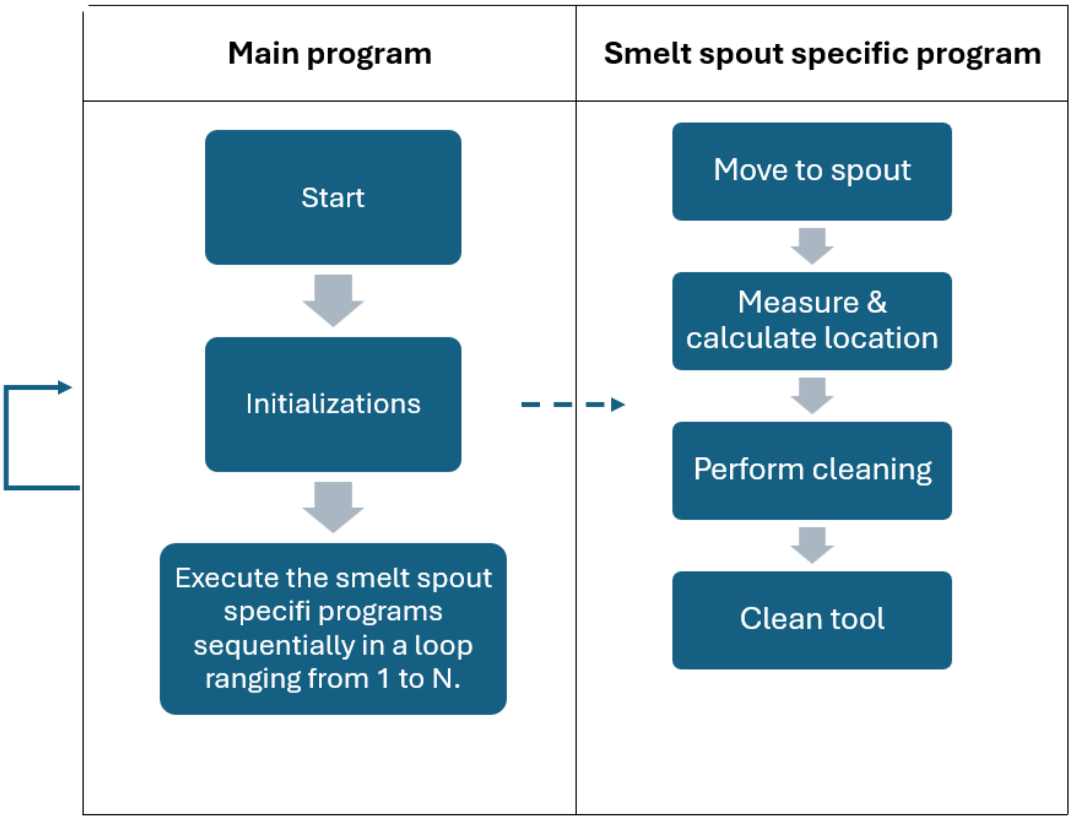


FIGURE 42. The main sequence program iterates through the smelt-spout-specific programs in a loop, executing the cleaning tasks in order. Each smelt-spout-specific program, in turn, performs its operations by calling additional TP-programs

Each smelt-spout program follows a defined operational sequence. The robot first determines the location of the current smelt spout and establishes its user frame. Once the position is verified, the hatch is opened, the cleaning procedure is executed, and the hatch is subsequently closed. The cycle concludes with tool cleaning to ensure readiness for the next operation. This sequence is repeated for all smelt spouts in a loop governed by the main program.

The cleaning process itself is performed mechanically with a rod tool. Robot motion is predominantly point-to-point, progressing linearly from an approach position to the target location. This trajectory planning reduces the likelihood of the tool becoming lodged in hardened smelt and enhances the predictability of tool deflection during operation.

At present, the robot performs an identical cleaning procedure for each smelt spout, regardless of its condition. Due to the absence of sensors, the system cannot evaluate spout cleanliness autonomously. However, operators retain manual control via the DCS, allowing them to activate or deactivate individual spouts for cleaning.

The implementation of automatic cleanliness assessment would enable the use of differentiated cleaning programs tailored to the condition of each smelt spout. For example, relatively clean spouts could be excluded from the cleaning cycle, while those with significant deposit accumulation could be assigned either a light or heavy cleaning procedure. A light cleaning program would involve fewer cleaning positions and shorter execution time, whereas a heavy program would apply a more extensive sequence to ensure thorough removal of hardened material.

Such condition-based cleaning logic could be supported by machine vision technology. A vision system or analysis of CCTV footage from the control room could be used to evaluate the cleanliness of each spout prior to cleaning. This would allow the robot to select the appropriate cleaning program dynamically, improving both operational efficiency and tool longevity.

5.2.1 Location and movement of smelt spouts in recovery boiler

The positioning of smelt spouts can theoretically vary in multiple directions and angles, depending on the load conditions of the recovery boiler. Although the boiler itself is suspended from a fixed steel structure, it is capable of moving relative to this support. Such movements (shown in Figure 43) may occur vertically downwards or as a twisting motion around its axis.

In addition, the boiler’s width increases as a function of temperature due to thermal expansion. These effects, which influence the relative location of the smelt spouts, have been illustrated in a simplified schematic of the recovery boiler.

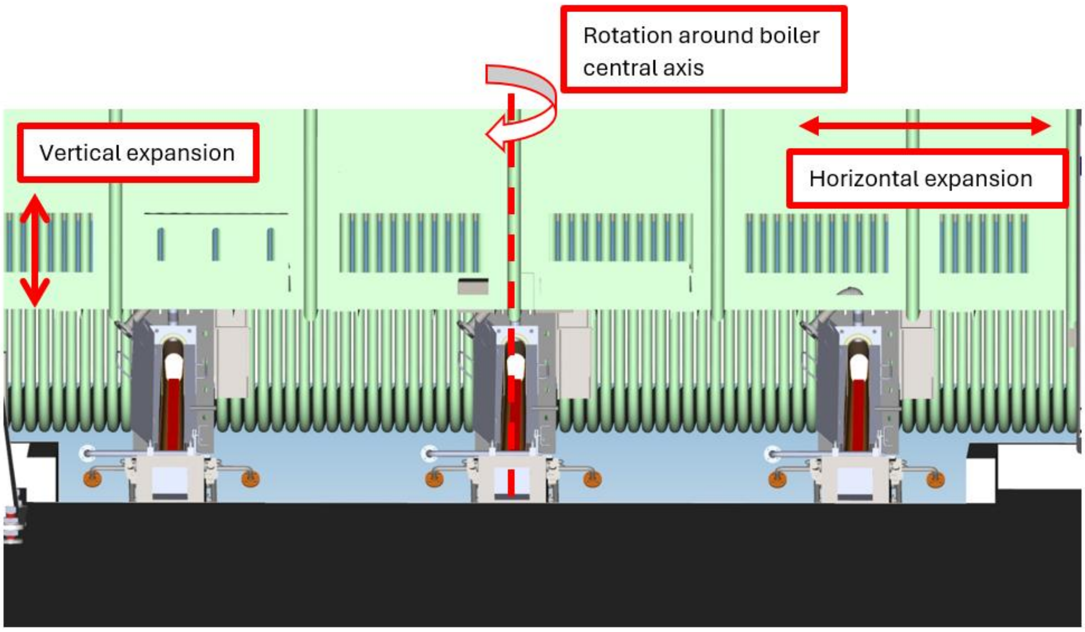


FIGURE 43. Movement of the recovery boiler due to thermal expansion effects

Boiler displacements in both vertical and horizontal directions can be estimated through calculation. In addition, the unit may also undergo twisting around its axis. Contributing factors include an uneven char bed, variations in air distribution, and irregularities in black liquor spraying. Among these movements, the most pronounced occurs in the vertical direction, where the difference between a cold and a full-load recovery boiler can reach up to 30 centimeters. To account for these positional changes, the robot must update its location data prior to each cleaning cycle.

Field observations further indicate that rotational movement becomes relevant primarily when there is a substantial change in boiler load. Such conditions are relatively rare and typically arise only under exceptional circumstances, such as disturbances in other pulp mill processes, mechanical failures within the recovery boiler, or deliberate load reductions intended to prevent clogging. The duration of these situations may range from several days to a few weeks.

In the robot program, each smelt spout area is assigned a dedicated user frame in which the robot's positional data is stored. These frames are subject to rotational deviations caused by boiler movement, particularly under varying load conditions. According to FANUC’s convention, rotations are defined as follows: X-axis rotation corresponds to yaw (W), representing lateral turning; Y-axis rotation corresponds to pitch (P), indicating forward or backward tilting; and Z-axis rotation corresponds to roll (R), denoting axial twisting.

When spout positions are taught during high boiler load and the robot is later operated under reduced load, noticeable changes in tool clearance relative to spout walls have been observed. These deviations appear primarily in the Y-direction, suggesting that roll (R) is the dominant rotational influence. While yaw (W) may also contribute, its effect is difficult to verify during live operation due to the continuous flow of smelt and limited visibility. Figure 44 illustrates the user frame geometry and the rotational axes affecting spout alignment.

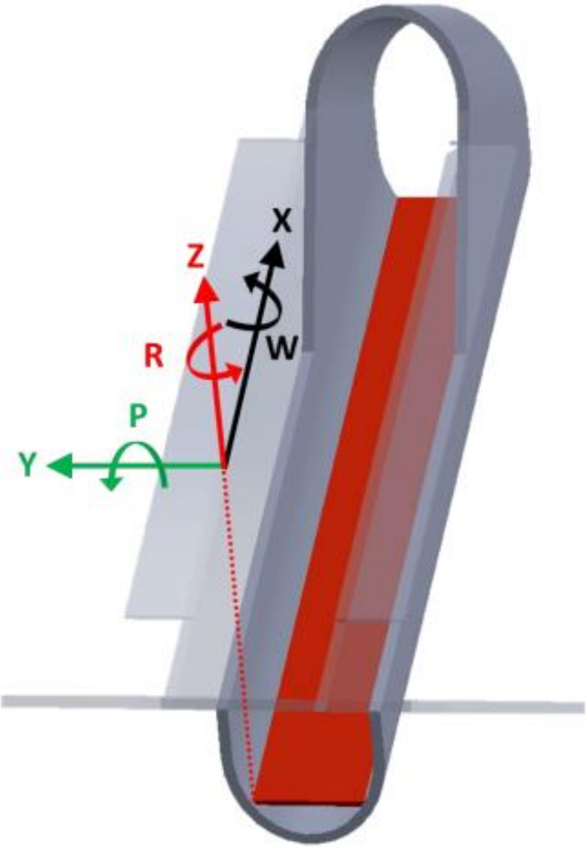


FIGURE 44. The illustration shows the smelt spout user frame with an extended Z-axis for clarity. R denotes roll, W denotes yaw and P denotes pitch (Lavonen, 2020)

5.2.2 Robot measurement procedure

At present, the position of smelt spouts is determined mechanically by guiding the robot tool tip to contact predefined surfaces. A collision detection routine is employed to identify solid boundaries within a specified spatial volume (Figure 45). This method relies on slow robot movements, during which the tool collides with a surface and the event is registered by monitoring changes in motor current values. Measurements are conducted independently along the X-, Y-, and Z-axes. The present configuration does not enable the measurement of angular displacement. Accurate determination of movement angles would require the use of additional reference points combined with a greater spatial separation between them, which exceeds the capabilities of the current setup.

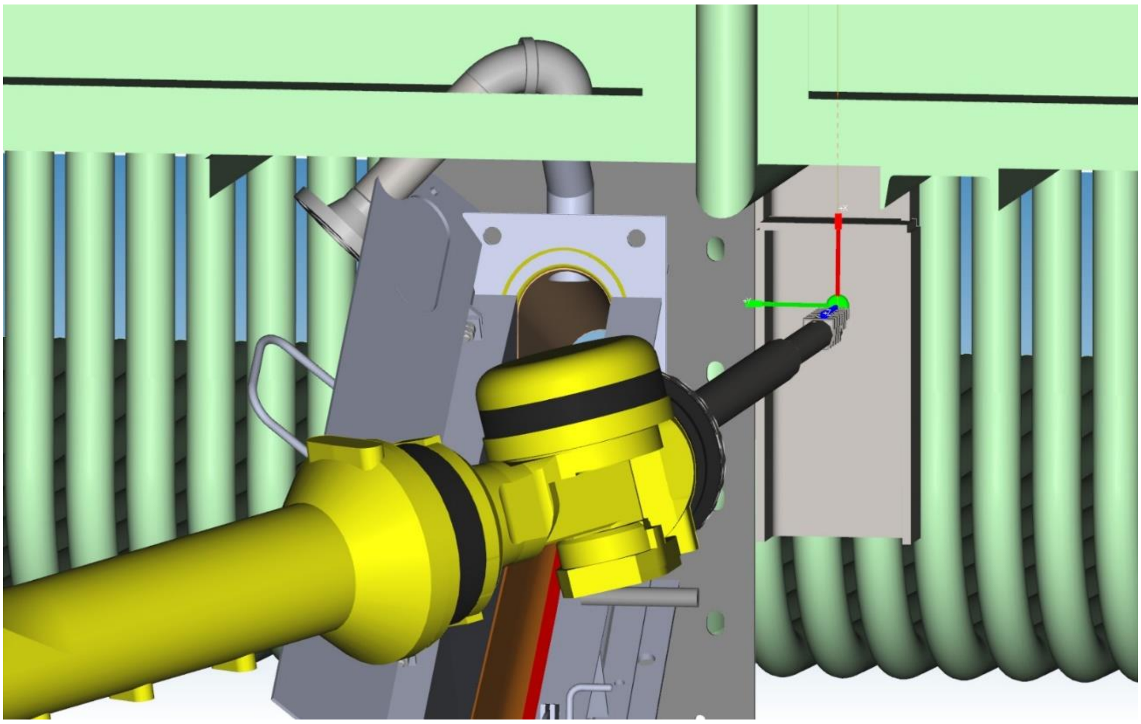


FIGURE 45. The surface used to measure the smelt spout position is located next to each smelt spout. The collision zone is shown in grey, and the movement of the tool tip is illustrated in red, green and blue.

Due to the hardening nature of smelt, the high forces involved, and the reliance on collision-based measurement of smelt spout locations, the robot tool itself must also be continuously monitored. Accumulated deposits on the tool tip, material loss, or bending of the tool can introduce significant errors if not accounted for.

Tool measurements are conducted using the same principle as for the smelt spouts, but the reference surfaces are positioned near the robot adapter. Based on these measurements, the tool center point (TCP) is recalculated to ensure positional accuracy. If the measured values fall outside predefined tolerances, the main sequence program prevents the robot from initiating the cleaning operation. In such cases, the tool must be manually inspected and replaced if necessary.

6 TOUCHSCREEN TECHNOLOGY

Touchscreen technology enables direct interaction with digital content by detecting the presence and location of a touch on the display surface. Unlike traditional input devices such as a mouse or keyboard, touchscreens allow users to engage with graphical interfaces intuitively and without intermediary tools. This capability has led to their widespread adoption across consumer electronics, kiosks, point of sale systems, automotive applications, and increasingly in industrial environments, where they serve as robust and efficient human–machine interfaces (HMI). (Bhalla and Bhalla 2010.)

6.1 Operating principles of touchscreens

Modern touch panels are primarily built upon four fundamental technologies: resistive, capacitive, surface acoustic wave (SAW), and optical (infrared (IR)). Each of these designs employs a distinct operating principle and therefore exhibits unique strengths and limitations. Resistive screens are valued for their durability and ability to function in harsh environments, while capacitive screens offer superior image quality and multi-touch capability. SAW technology provides precise input recognition but is sensitive to contaminants, and infrared systems enable versatile input methods with minimal physical wear. A systematic examination of these technologies is necessary to understand their suitability for industrial human–machine interface (HMI) applications. (Bhalla and Bhalla 2010.)

6.1.1 Resistive touchscreen

Resistive touchscreens consist of a glass or acrylic substrate coated with electrically conductive and resistive layers, typically using indium tin oxide (ITO) illustrated in (Figure 46). These layers are separated by microscopic spacers, and when pressure is applied to the flexible top sheet, electrical contact is established with the lower layer. The resulting change in voltage is processed by the touchscreen controller, which calculates the X and Y coordinates of the touch and relays them to the operating system. (Texas Instruments 2005.)

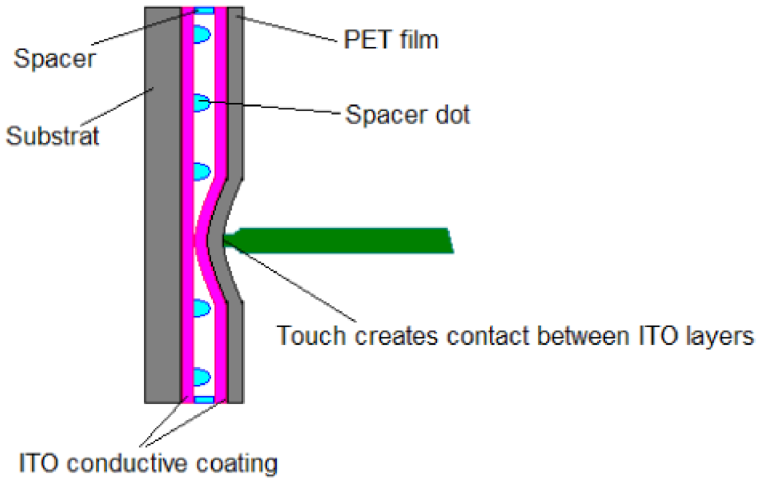


FIGURE 46.ITO conductive coating working principle (Linköping University n.d.)

Two common resistive architectures are the 4-wire and 5-wire configurations. The 4-wire design can additionally measure pressure as a third dimension, while the 5-wire design improves durability by using the second layer as a reference contact. Although resistive panels generally provide lower optical clarity (approximately 75%) compared to capacitive or infrared technologies, they are valued for their robustness, affordability, and ability to function reliably in environments with dust, moisture, or contaminants. (Bhalla and Bhalla 2010.)

Resistive touchscreens are widely applied in high-use and industrial contexts, including food service systems, retail point-of-sale terminals, medical monitoring devices, portable electronics, and process control instrumentation. Their resilience and cost-effectiveness explain their continued relevance despite the emergence of more advanced touchscreen technologies. (Bhalla and Bhalla 2010.)

6.1.2 4-wire resistive touchscreen technology

The four-wire resistive touchscreen represents the simplest and most widely manufactured resistive architecture. It consists of two conductive layers, typically coated with indium tin oxide (ITO), separated by spacers. When voltage is applied across one layer, a uniform potential gradient is established. Upon touch, the flexible coversheet contacts the lower layer, and the controller measures the resulting voltage to determine the X coordinate. The process is then reversed to calculate the Y coordinate. At any given time, three of the four wires are active in the measurement cycle. (Bhalla and Bhalla 2010 & Li *et al.* 2021.)

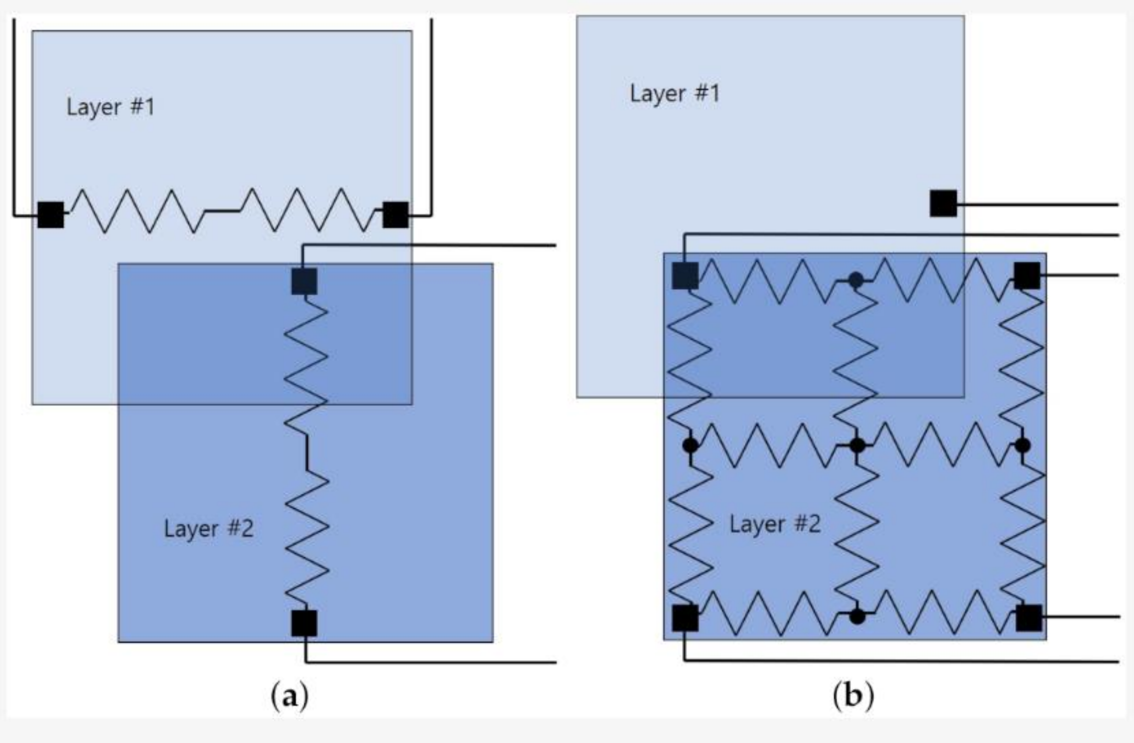


FIGURE 47. Most commonly used resistive touchscreen architectures. (a) Four-wire and (b) Five-wire (Li et al. 2021)

This design is cost-effective and straightforward to implement, which explains its prevalence in early portable devices and industrial applications. However, its primary limitation lies in the reliance on the flexible outer layer to maintain a uniform voltage gradient. Continuous mechanical stress on this layer can lead to microscopic cracks in the ITO coating, altering its resistance and thereby reducing linearity and accuracy over time. Consequently, while four-wire resistive technology offers affordability and simplicity, its long-term durability and precision are inferior compared to more advanced resistive configurations. (Bhalla and Bhalla 2010.)

6.1.3 5-wire resistive touchscreen technology

The five-wire resistive touchscreen improves upon the limitations of the four-wire design by using the stable bottom glass layer to establish voltage gradients for both the X and Y axes. Four wires are connected to the corners of the bottom layer, while a single wire connects to the flexible cover sheet, which functions solely as a voltage probe, illustrated in (Figure 47). During operation, the controller alternately applies voltage across pairs of corners to generate uniform potential fields. The coversheet then measures the resulting voltage, allowing the controller to determine the touch coordinates. (Bhalla and Bhalla 2010.)

This architecture offers significant advantages in terms of durability and accuracy. Because the coversheet is no longer responsible for maintaining uniform voltage gradients, wear or microscopic cracks in its conductive coating do not compromise linearity or measurement precision. As a result, five-wire resistive panels are more reliable and long-lasting than four-wire designs, making them particularly suitable for demanding industrial applications where robustness and consistent performance are critical. (Bhalla and Bhalla 2010 & Li *et al.* 2021.)

While the four-wire resistive touchscreen offers simplicity and low manufacturing cost, its reliance on the flexible coversheet for voltage gradients makes it prone to wear and reduced accuracy over time. In contrast, the five-wire design shifts the critical measurement function to the stable bottom layer, with the coversheet serving only as a probe. This structural difference results in greater durability, improved linearity, and higher reliability, particularly in demanding industrial environments. Consequently, the five-wire architecture is generally preferred where long-term precision and robustness are essential, despite its higher cost. (Linköping University n.d.& Bhalla and Bhalla 2010 & Texas Instruments 2005.)

6.2 Capacitive touchscreen

Capacitive touchscreens operate by storing electrical charges within a conductive coating applied to the panel surface. When a user touches the screen, a small portion of this charge is drawn to the point of contact, and the resulting change is measured by circuits positioned at the corners of the display. The controller then processes these signals to determine the precise location of the touch. Unlike resistive or surface acoustic wave technologies, capacitive panels require direct contact with a finger, as styluses or gloved hands generally do not produce the necessary electrical response. (Bhalla and Bhalla 2010.)

This technology is distinguished by its excellent optical clarity and mechanical reliability, since it contains no moving parts that could degrade with use. Moreover, capacitive screens are resistant to interference from external contaminants such as liquids, dirt, or grease, making them particularly suitable for consumer electronics and other environments where cleanliness cannot be guaranteed. The main limitation lies in their inability to register input through insulating materials, which restricts their usability in certain industrial or medical contexts. Capacitive technology is further divided into two principal categories, each optimized for specific applications. (Bhalla and Bhalla 2010 & Li *et al.* 2021.)

6.2.1 Surface capacitive technology

Bhalla and Bhalla (2010) describe surface capacitive touchscreens employing a design in which only one side of the insulating substrate is coated with a conductive layer, see (Figure 48). A small voltage applied to this layer generates a uniform electrostatic field across the panel. When a conductive object, typically a human finger, contacts the uncoated surface, a capacitor is dynamically formed at the point of touch. The controller determines the location indirectly by measuring changes in capacitance at the four corners of the panel. Because the system contains no moving parts, it offers moderate durability; however, its resolution is limited, and it is susceptible to false signals caused by parasitic capacitive coupling. As a result, surface capacitive technology is most often employed in relatively simple applications such as industrial control panels and public kiosks.

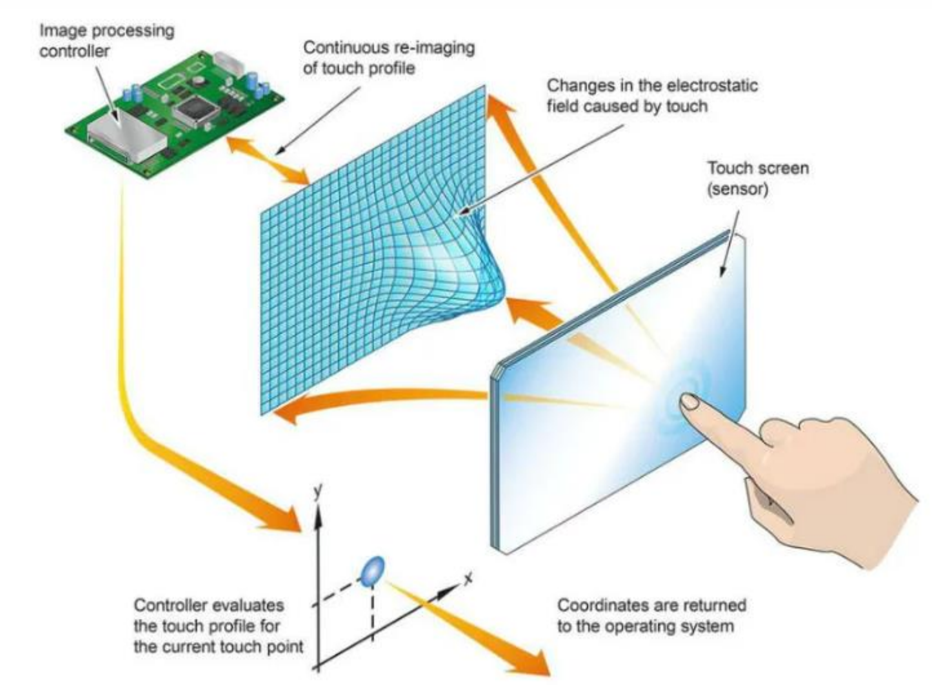


FIGURE 48. Working principle of capacitive touchscreen (Cardinal Peak 2023)

6.2.2 Projected capacitive technology

Projected capacitive touch (PCT) technology enhances accuracy and flexibility by etching the conductive layer into a grid of electrodes. This grid may be formed either by etching a single layer into intersecting patterns or by constructing two perpendicular layers of conductive material arranged as parallel lines. When a finger approaches the grid, it alters the capacitance of the nearest traces, and the controller computes the precise position from these changes. The use of an X–Y grid enables higher resolution than resistive technologies, while also providing excellent optical clarity. Projected capacitive panels are solid-state, scratch-resistant, and durable, and they can register input from gloved hands. These attributes make PCT particularly well suited for demanding environments, including industrial, outdoor, and other harsh applications where reliability and robustness are essential. (Bhalla and Bhalla 2010.)

6.3 Surface acoustic

Surface Acoustic Wave (SAW) technology represents one of the most advanced forms of touchscreen design. It operates through pairs of transducers, one transmitting and one receiving, positioned along both the X and Y axes of the panel. A series of reflectors are embedded along the glass surface to direct ultrasonic waves between the transducers, illustrated in (Figure 49). When the controller sends an electrical signal to the transmitting transducer, the signal is converted into ultrasonic waves, which are then refracted by the reflectors toward the receiving transducer. The receiving transducer reconverts the waves into electrical signals for processing. A touch event is detected when a finger or other soft conductive object absorbs part of the wave energy, thereby interrupting the transmission path. (Bhalla and Bhalla 2010).

Compared with resistive and capacitive technologies, SAW panels provide superior optical clarity, resolution, and light transmission, since the design relies entirely on glass without additional overlay layers that could degrade over time. This structure also contributes to high durability. However, SAW systems have notable limitations: they cannot be fully sealed against environmental contaminants, and performance may be compromised by dust, dirt, grease, or water. Furthermore, they require input from a finger, gloved hand, or soft stylus, as hard objects such as pens do not effectively absorb the acoustic waves. (Bhalla and Bhalla 2010 & Li *et al.* 2021.)

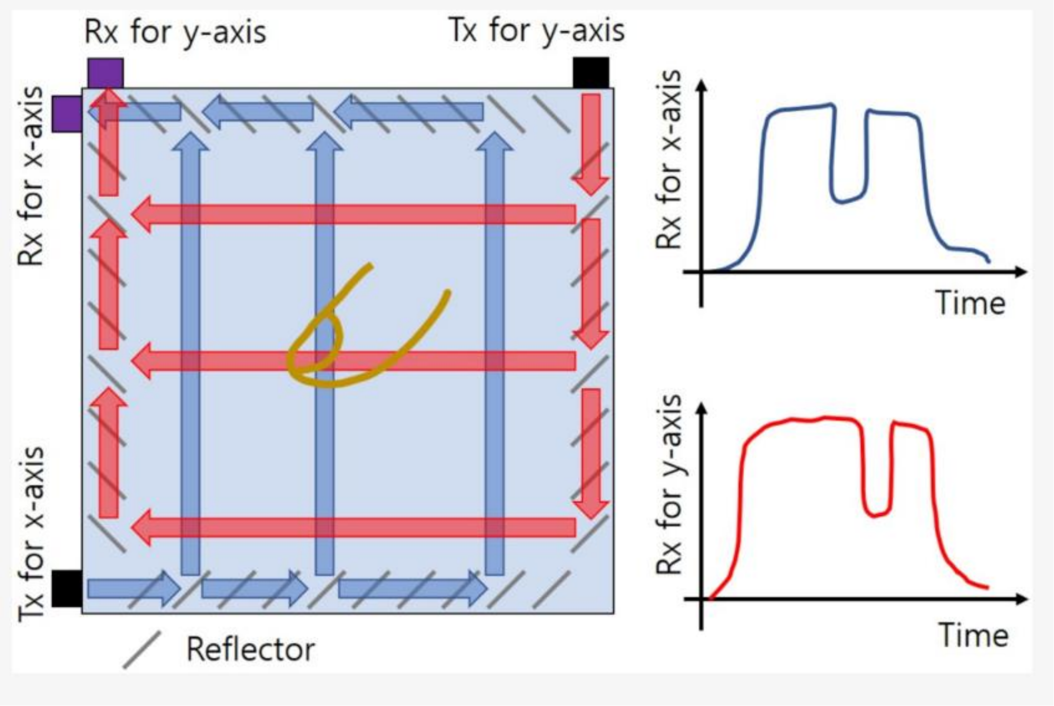


FIGURE 49. Ultrasonic waves travel across the panel; a finger touch absorbs part of the signal, and the resulting attenuation and delay are converted into precise touch coordinates (Li et al. 2021)

Despite these drawbacks, SAW technology is widely recommended for high-traffic indoor applications where clarity and robustness are prioritized, including ATMs, financial services, public information kiosks, and training systems. While more costly and environmentally sensitive than other touchscreen types, SAW panels combine excellent durability with unmatched image quality, making them a compelling option in controlled settings. (Bhalla and Bhalla 2010.)

6.4 Infrared (optical) touchscreen

Infrared (IR) touchscreens operate by projecting invisible light beams across the display surface. Traditional IR designs place transmitters along two edges of the panel and receivers on the opposite sides, forming a grid of intersecting beams. When a touch occurs, the light path is interrupted, and the controller determines the coordinates by identifying which receivers fail to detect the signal. This approach supports large-format displays and excellent optical clarity, as no additional layers are required on the glass. However, the need for a raised bezel to house the transmitters and receivers, along with the possibility of “ghost touches” during multi-point input, presents notable limitations. (Bhalla and Bhalla 2010 & Li *et al.* 2021.)

Several advanced IR-based schemes have been developed to overcome these challenges. Planar scatter detection (PSD) employs a waveguide under total internal reflection (TIR) conditions, shown in (Figure 50). A touch disrupts the TIR, scattering light toward multiple receivers, which then use complex analysis to compute the touch location. PSD offers high clarity and multi-touch capability, but larger panels demand significant computational power. Frustrated total internal reflection (FTIR) similarly relies on TIR, but the touch location is determined from light escaping toward the opposite plane of the waveguide. External cameras or vision sensors capture these signals, and the resulting images are processed to identify the touch coordinates. Embedded LCD solutions further integrate IR transmitters into the backlight and vision sensors within pixel areas, enabling compact implementations. (Bhalla and Bhalla 2010 & Li *et al.* 2021.)

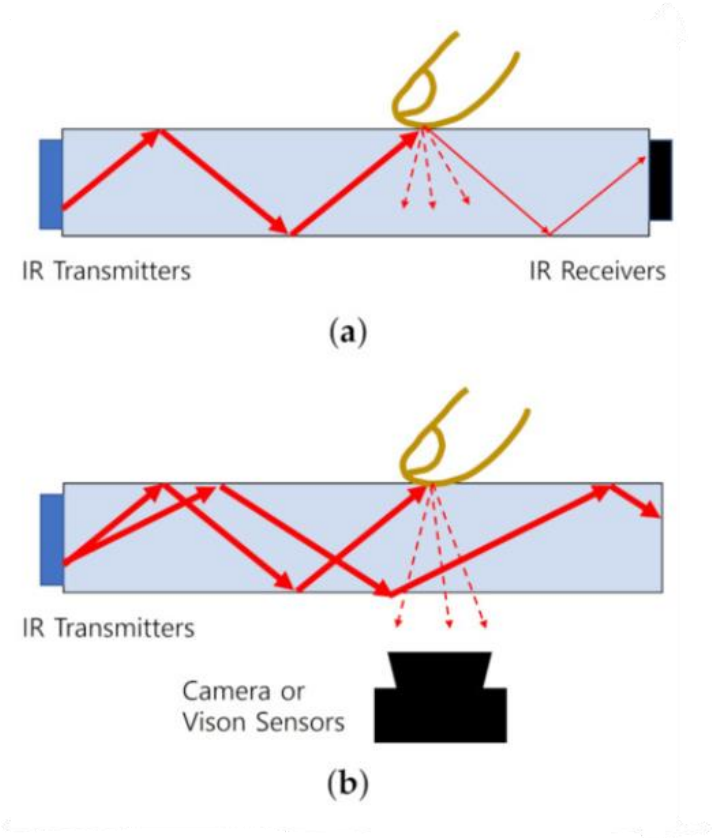


FIGURE 50. (a) Planar Scatter Detection (PSD) (b) Frustrated Total Internal Reflection (FTIR) Lit et al. 2021

Infrared touchscreens are distinguished by their ability to detect virtually any input, including bare fingers, gloved hands, styluses, or pens. This versatility makes them particularly suitable for outdoor environments and point-of-sale systems, where conductive input cannot be guaranteed. Unlike capacitive technologies, IR systems do not require patterned coatings on the glass, which enhances both durability and optical clarity. (Bhalla and Bhalla 2010 & Li *et al.* 2021.)

6.5 Justification for selecting resistive touchscreen technology

In industrial environments, the choice of touchscreen technology must be guided by durability, accuracy, multi-touch capability, and environmental resistance. Resistive touchscreens meet these requirements in a pragmatic and cost-effective manner. Their pressure-sensitive design allows reliable operation with a wide range of input devices, including gloved hands and styluses, which is essential in harsh conditions where bare-finger input cannot be guaranteed. Although resistive panels are more susceptible to mechanical wear than glass-based alternatives, they remain sufficiently robust for controlled industrial settings and can withstand exposure to dust and moisture when properly sealed.

Accuracy is another decisive factor: resistive technology provides precise single-point input, ensuring dependable control and data entry in process environments where errors cannot be tolerated. While resistive panels do not inherently support advanced multi-touch gestures, industrial applications typically prioritize functional reliability over complex gesture recognition, making this limitation acceptable. Finally, resistive screens demonstrate strong environmental resistance, as they are less affected by electrical noise and lighting variations compared to optical or capacitive systems.

Taken together, these attributes explain the selection of resistive touchscreen technology: it balances durability and accuracy with versatility of input, offering a dependable solution tailored to the operational demands of industrial contexts.

6.6 Selected touchscreen solution of robot HMI control

We selected Beijer X2 pro 15 operator panel because it combines industrial durability, versatile connectivity, and a resistive touchscreen suited for harsh environments. Several factors explain its suitability:

Durability and Environmental Resistance

- The panel is built with a powder coated aluminum housing and a polyester glass resistive touchscreen, ensuring robustness against mechanical stress and long service life.
- It carries IP65 front sealing, protecting against dust and water ingress, and operates reliably in a wide temperature range from –10 °C to +60 °C.

- Certified for marine and industrial use (DNV GL, ABS, BV, KR, LR, CCS, NK), it meets stringent standards for environments where vibration, humidity, and contaminants are common.

Accuracy and Input Flexibility

- The resistive touchscreen supports up to 1 million touch operations, and unlike capacitive panels, it can be operated with gloved hands, styluses, or other tools, a critical requirement in pulp mill and industrial settings where operators often wear protective gear.
- This ensures precise single point input for process control and data entry, aligning with industrial needs for reliability over multitouch gestures.

Connectivity and Integration

- Equipped with multiple serial ports (RS232, RS422/485, CAN) and dual Ethernet interfaces, the panel integrates seamlessly with existing automation systems.
- It runs iX Runtime software, supporting advanced HMI functions such as alarms, recipes, and dynamic visualization, which are essential for process optimization and operator efficiency.

Safety and Compliance

- Certified under UL 610101/2201 and equivalent CSA standards, the panel meets international safety requirements for electrical equipment.
- This compliance ensures safe deployment in regulated industrial contexts.

7 SOFTWARE DEVELOPMENT AND USER INTERFACE DESIGN

This chapter presents the software development process and user interface design for a new touchscreen-based control system created for the smelt spout robot operating at the recovery boiler. The goal of the work is to replace the robot’s previous control method with a more intuitive, reliable, and operator-friendly interface that improves both usability and operational safety in a demanding industrial environment. The chapter outlines the design principles, technical choices, and implementation steps that guided the development of the system, beginning with an overview of Human–Machine Interface (HMI) technologies relevant to this application.

7.1 Human machine interface

Digital transformation has fundamentally reshaped industrial operations, increasing the need for technologies that support effective interaction between human operators and increasingly complex machinery. Human–Machine Interfaces (HMIs) address this need by providing a structured and intuitive way for users to monitor, control, and interpret industrial processes. As the visual and interactive layer of Supervisory Control and Data Acquisition (SCADA) systems, HMIs translate large volumes of process data into human-readable information, enabling operators to make informed decisions in real time (Sverko & Galinac Grbac, 2023.)

Although the global HMI market is expanding rapidly, projected to grow from approximately $5.8 billion to over $11 billion by 2030, the concept itself has evolved over several decades. Early industrial systems relied on manual switches and indicator lights, but modern HMIs now range from simple graphical displays to advanced touchscreen panels capable of presenting dynamic process data, alarms, diagnostics, and control functions. This evolution reflects broader trends in Industry 4.0, where digitalization, connectivity, and data-driven decision-making are central themes. (Cyngn 2024).

A key distinction must be made between HMIs and SCADA systems. HMIs provide direct interaction with specific machines or processes, offering real-time visualization and control at the operator level. SCADA systems, on the other hand, aggregate data from multiple HMIs and field devices across an entire facility, providing higher-level supervision, data logging, and analytics. In practice, HMIs act as the operator's window into the process, while SCADA serves as the overarching management layer that is illustrated in (Figure 51). (Sverko & Galinac Grbac, 2023 & Cyngn 2024.)

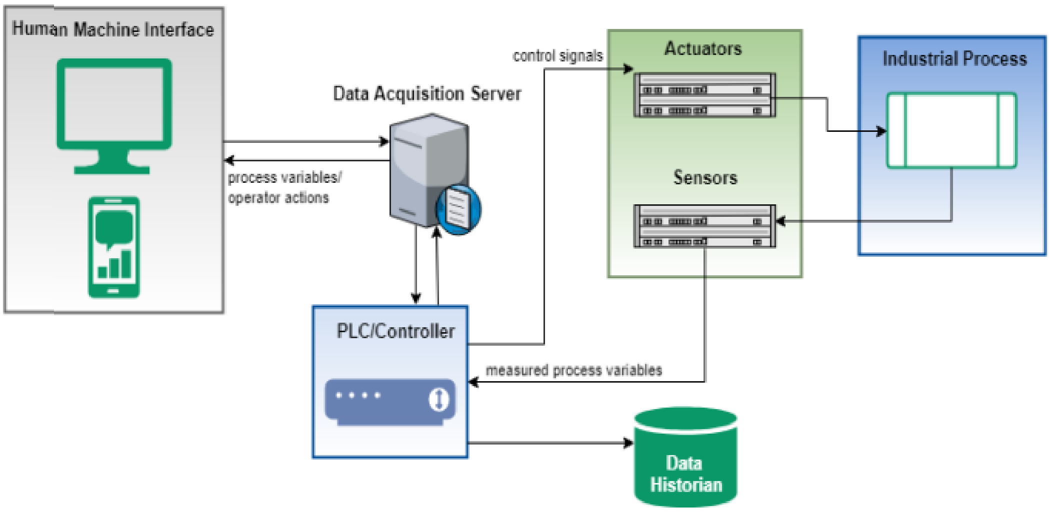


FIGURE 51. Example of HMI based industrial control system (Qasim et al., 2020)

Modern HMIs rely on several core components. Programmable Logic Controllers (PLCs) form the backbone of industrial automation by collecting sensor data such as temperature, pressure, flow, or speed and executing control logic. Control systems integrate this data with actuators and feedback loops to maintain stable operation. Software applications then present this information through user-friendly interfaces, offering visualization tools, alarm handling, and system diagnostics. Inputs and outputs, including touchscreens, keyboards, displays, and indicator lights, facilitate interaction between the operator and the machine. (Sverko & Galinac Grbac, 2023 & Cyngn 2024.)

Contemporary HMIs employ a variety of interface types. Graphical User Interfaces (GUIs) use icons, buttons, and visual elements to simplify interaction, while touchscreen-based HMIs allow operators to manipulate controls directly through tapping, swiping, or gesture-based input. Touchscreens are particularly valuable in environments requiring rapid adjustments, continuous monitoring, and clear visualization making them a natural fit for modern production lines and industrial robots. (Sverko & Galinac Grbac, 2023 & Cyngn 2024.)

As expectations for usability rise, driven largely by the widespread familiarity with smartphone interfaces industrial HMIs are increasingly expected to offer the same level of responsiveness, clarity, and intuitiveness. This shift underscores the importance of designing HMIs that not only meet technical requirements but also support human-centric interaction, situational awareness, and operational safety. (Sverko & Galinac Grbac, 2023 & Cyngn 2024.)

7.2 HMI design for safe and efficient robot operation

The primary objective of the HMI design was to create robust, an operator-friendly interface that provides all essential functions required for the robot's daily operation. The interface needed to support the most critical actions, including start and stop commands, alarm acknowledgment, and returning the robot to its home position in the event of a malfunction. To ensure both usability and operational safety, certain advanced functions were placed behind a password-protected administrative menu. These functions were intended solely for commissioning and testing purposes, as modifying the associated parameters could compromise the robot's ability to perform its tasks reliably. By separating everyday controls from configuration-level settings, the design supports intuitive operation while preventing unintentional changes that could affect system performance.

In addition to usability considerations, the touchscreen interface was introduced to replace the robot's traditional handheld controller. The original control device was both complex to operate and posed significant safety risks. Using the handheld controller required the operator to stand in close proximity to the robot while issuing manual commands, exposing them to molten smelt splash hazards and potential mechanical accidents with robot. This was a direct consequence of the robot needing to be operated in manual mode, where each movement had to be entered through the controller. The new touchscreen-based system enables the robot to be operated through predefined programs in automatic mode, eliminating the need for the operator to remain within the hazardous area. This approach not only improves safety by reducing human exposure but also minimizes the likelihood of operator error and significantly accelerates troubleshooting during abnormal situations.

7.3 Software development process

This chapter outlines the development process of the Human–Machine Interface (HMI) software designed for the smelt spout cleaning robot operating at recovery boiler. The development followed a structured approach, beginning with the definition of functional and safety requirements, followed by system architecture planning, interface design, implementation, and testing. Each phase was guided by the need to improve usability, minimize operator error, and ensure reliable integration with the existing control infrastructure. The following sections describe each stage of the development process in detail.

7.3.1 Requirements definition

The development process began with a systematic review of all operational scenarios and functional requirements necessary for the safe and efficient use of the robot. As outlined earlier, the most critical functions included the ability to start and stop the robot, acknowledge alarms, and return the robot to its home position in abnormal situations. Another essential requirement was the inclusion of a language-selection feature, allowing the interface to switch between English and Portuguese. This was necessary because the operators were not proficient in English, while the robot maintenance team did not speak Portuguese, making bilingual support crucial for effective communication. Additional functional requirements included the ability to view tool calibration values and to drive the robot into a designated service position when maintenance operations were needed.

A major consideration in industrial environments is ensuring the safety of operators. Because the touchscreen interface functions similarly to a distributed control system, the robot must be operated in automatic mode when using the HMI. This requirement significantly reduces the risk of operators being struck by the robot, as automatic operation mandates that all cell doors are closed, reset, and confirmed to be clear of personnel before the robot can start. Any attempt to open a door during operation triggers a limit switch, which immediately stops the robot in place. This interlocking mechanism ensures that the robot cannot move while an operator is within the hazardous area, thereby providing a fundamental layer of protection and supporting safe day-to-day operation.

Another key requirement was that the system had to be highly user-friendly and intuitive to support safe and uninterrupted daily operation. In practical terms, this means using large fonts, clearly visible buttons, and a logical naming convention for all actions and interface elements. The design goal was to create an interface that operators could navigate confidently even without prior training, minimizing the likelihood of user errors during routine tasks. Nevertheless, comprehensive operating manuals were provided to the customer to ensure proper understanding of the system and to support formal training when required.

7.3.2 System architecture planning

The touchscreen interface functions in principle in the same way as a distributed control system (DCS). The panel sends predefined digital signals, each of which triggers a specific action in the robot. All available functions are therefore mapped to corresponding control signals, ensuring deterministic and predictable behavior. The robot’s PLC is integrated into the mill’s existing Valmet DNA system, while the touchscreen operates as an additional DCS station that communicates directly with the robot. Through this architecture, the HMI acts as a dedicated control node that issues command the robot via standardized signal pathways, enabling reliable and safe operation within the broader automation environment.

The software planning phase was divided into four main categories: the user interface, system logic, alarm handling, and macro programs. At the beginning of the project, the user interface was intentionally given lower priority, as the primary focus was on implementing all required functions and programs before refining the visual layout. To support quick and intuitive status recognition, a “traffic-light” color-coding scheme was adopted. Key indicators, such as cell status, robot home position, and whether the robot was in automatic mode, were displayed in either green or red depending on their current state. Corresponding symbols were also incorporated to further enhance clarity and reduce the cognitive load on the operator. Most of the detailed UI adjustments, however, were carried out during the final stages of hot commissioning, as practical improvements emerged during real-world testing and operator feedback played a significant role in shaping the final design.

Since the touchscreen interface effectively functions as a distributed control system (DCS), there was no need to develop separate logic specifically for the screen. Instead, all operational logic was implemented or planned to be implemented within the robot’s control system during the commissioning phase. The HMI serves purely as a field-level tool for issuing commands and monitoring status, with its role limited to transmitting predefined control signals to the robot. The core logic governing robot behavior resides in the PLC and is described in detail in Chapter 5.2.

Although the complete alarm list is available in the control room DCS, a selected set of alarms was also implemented in the HMI to enable faster troubleshooting during abnormal situations. By displaying alarms directly on the touchscreen, the operator can immediately identify the cause of a malfunction without needing to consult the control room. Not all alarms from the robot’s logic were transferred to the HMI, as the robot can generate hundreds of different alarm types. Instead, only the most relevant and frequently occurring alarms, such as collision alarms, over-current alarms, and cell-door-open signals, were included. This approach significantly improves troubleshooting efficiency, especially considering that the robot’s original controller can store only the 100 most recent events, whereas the HMI can retain thousands. As a result, the HMI provides a more comprehensive historical record of system behavior, supporting quicker diagnosis and more effective maintenance.

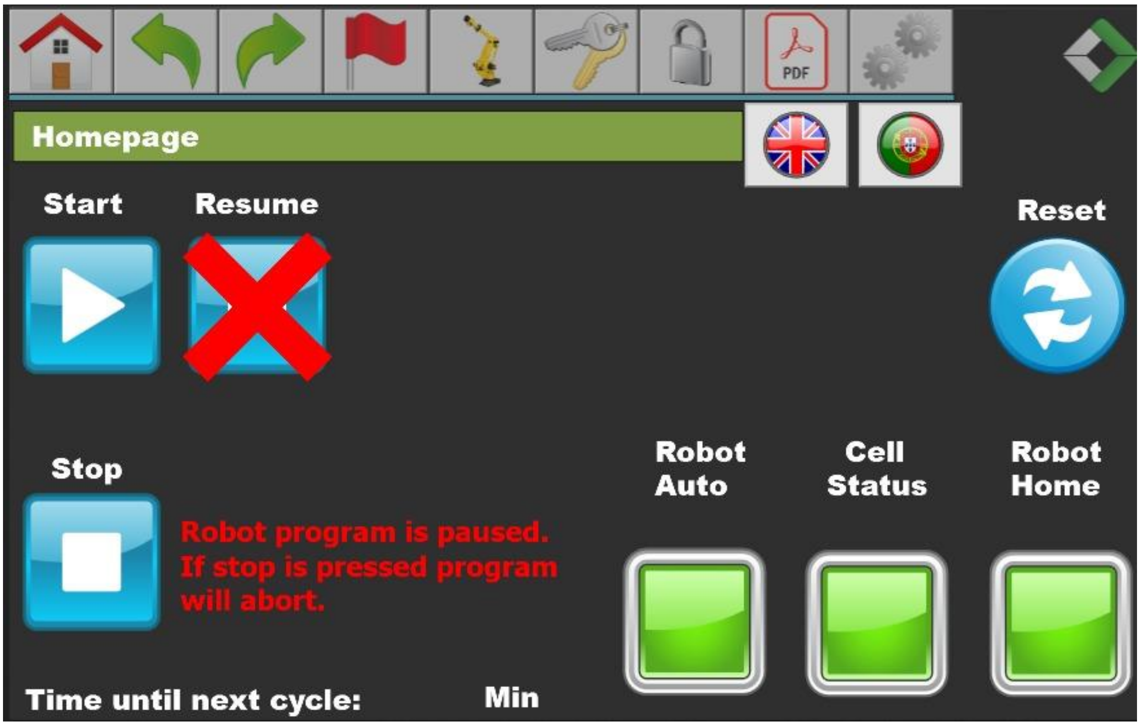
Macro programs provide the mechanism for “driving” the robot directly from the HMI. A macro program is a predefined sequence that can be triggered by a digital signal once specific conditions, such as the robot being in its home position, are met. The macro programs implemented for operator use include Retract Tool, Robot to Home Position, and Robot to Service Position. These same functions exist in the robot’s original pendant but executing them through the pendant is significantly more complex and requires the robot to be in manual mode. The HMI-based approach allows these operations to be performed safely in automatic mode.

The Robot to Home Position macro moves the robot from its current location back to the defined home position. The Robot to Service Position macro drives the robot to a dedicated maintenance position, used for tasks such as tool replacement or mechanical inspection. The Retract Tool macro is intended for abnormal situations, such as when the robot collides with material while cleaning the spouts. When activated, the macro retracts the tool in 10-centimetre increments away from the spout. This sequence is repeated until the tool is fully clear, after which the Robot to Home Position macro is used. This stepwise retraction ensures that the tool does not strike any obstacles inside the spout during the return movement, thereby reducing the risk of further damage and supporting safe recovery from collision events.

7.3.3 UI design phase

As mentioned earlier in Chapter 6.6, a resistive touchscreen was selected for the HMI, as it best met the operational and environmental requirements of the application. The layout of the interface was designed to be navigated through a set of clearly defined menus. A row of tabs at the top of the screen allows the operator to select a specific category, under which the corresponding functions are organized. The functionalities were divided into the following tabs: the Home menu, Next and Previous page buttons, Alarms, Robot Control, an Admin login menu, a

PDF page for displaying digital documentation such as robot manuals, and a Settings menu. This structure provides a logical and intuitive navigation model that supports efficient daily operation and reduces the cognitive load on the user.



Robot program is paused. If stop is pressed program will abort.

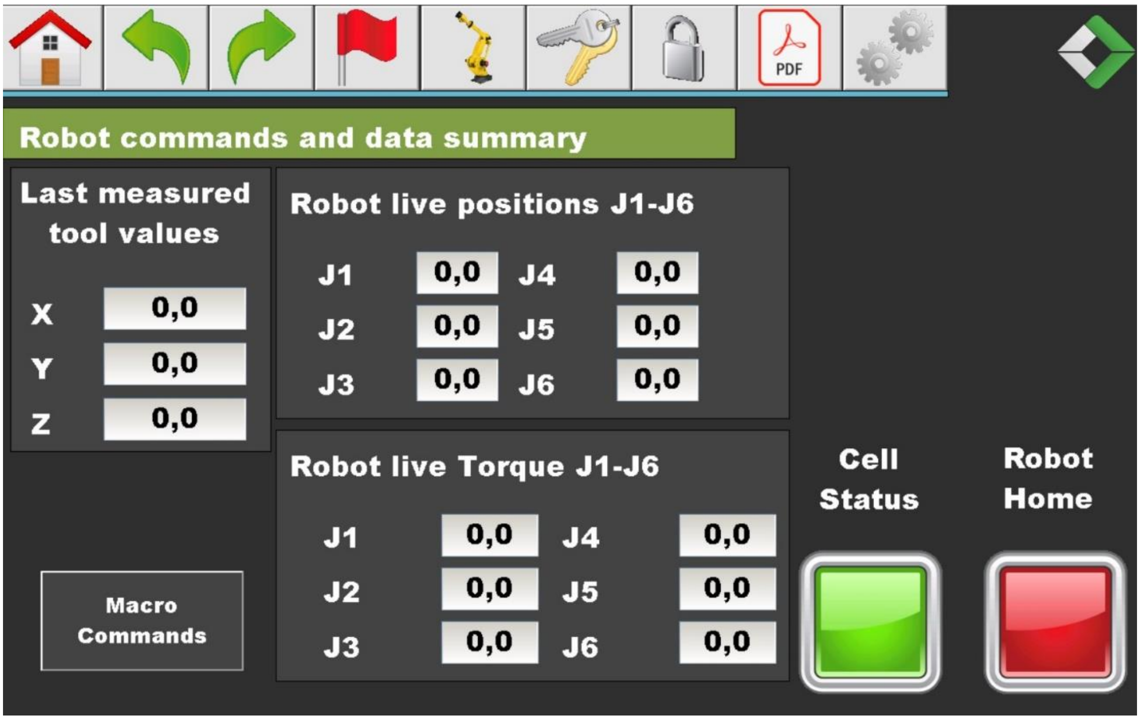
FIGURE 52. Screen main page layout from Beijer ix developer

The homepage contains all the primary functions most frequently used by operators, including Start, Resume, Stop, Reset, language selection, and an overview of the system status. As illustrated in Figure 52, certain functions can be automatically blocked under specific conditions to prevent operator errors and unintended actions. Sending an incorrect signal at the wrong moment may cause issues in subsequent operations and could require the operator to return the robot to its home position using macro programs or the original pendant. These blockades are implemented either by displaying a red cross and disabling the button or by hiding the button entirely while the robot is in motion.

The functions were also programmed so that repeated button presses have no effect. This prevents accidental double activation of commands and ensures that each action is executed only once, even if the operator presses the button multiple times in quick succession. This design choice reduces the risk of unintended robot movements and contributes to safer and more predictable operation.

From the homepage, the operator can also view the status of the robot, the cell, and whether the robot is currently in its home position. In addition, a cycle-timer display has been implemented to show the remaining time until the next cleaning cycle. This timer can be adjusted from the DCS within a range of 1–60 minutes, allowing operators to fine-tune the cleaning interval according to process needs.

The second most important menu is the Robot Control menu, visible in Figure 53, which is accessed by selecting the yellow robot icon. This menu provides operators with direct access to the robot's macro commands, allowing them to drive the robot to its home position or to the designated service position. The page also displays the most recently measured tool values, enabling operators to identify when the tool is worn or bent beyond acceptable tolerances and therefore requires replacement. In addition, live position and torque values are shown, offering valuable real-time information that supports troubleshooting and helps diagnose abnormal behavior during operation.



Last measured tool values

X 0,0
Y 0,0
Z 0,0

Robot live positions J1-J6

J1	0,0	J4	0,0
J2	0,0	J5	0,0
J3	0,0	J6	0,0

Robot live Torque J1-J6

J1	0,0	J4	0,0
J2	0,0	J5	0,0
J3	0,0	J6	0,0

FIGURE 53. Robot control page from Beijer ix developer

As mentioned earlier, some of the HMI functions were placed behind an admin-level password. These functions are intended exclusively for robot servicing, troubleshooting, or commissioning activities. Allowing unrestricted access to these settings would pose a significant operational risk, as modifying parameters or digital outputs from this menu could cause the robot to behave abnormally. Restricting these functions to authorized personnel ensures that only trained technicians can adjust critical settings, thereby maintaining safe and reliable operation of the system.

7.3.4 Testing & validation

Because no test robot or simulation environment was available, the HMI could not be fully tested before installation. As a result, only limited offline verification, such as interface navigation, color-coding, and button logic, could be performed during development. All functional testing that required real robot responses had to be carried out onsite during commissioning, once the HMI was connected to the actual robot and PLC. This constraint influenced the software development process and shifted a significant portion of validation activities to the commissioning phase.

7.4 Comparison between robot teach pendant and the new HMI system

The previous method for operating the robot is shown in (Figure 54). This method relied entirely on the teach pendant, which is the standard control device supplied with Fanuc robot systems. The pendant also functions as the “brain” of the system, as it contains the robot’s program memory and provides the interface for modifying programs and driving the robot in manual mode. Since the robot cannot operate without the pendant connected, it was stored in its dedicated storage box next to the new HMI screen, ensuring it remained available for maintenance, programming, and manual operations when required.

FIGURE 54. Fanuc teach pendant

The primary reason for customers to adopt the HMI solution is improved occupational safety. With the previous teach-pendant-based method, the robot had to be placed in manual mode to execute macro movements. This required operators to stand close to the robot while driving it, ensuring that it did not collide with surrounding structures. Such proximity exposed operators to significant risks, including smelt splashes and alkaline fumes. The entire purpose of the robot is to eliminate the need for operators to manually clean the spouts, yet the old control method still required personnel to enter the spout deck area, often during abnormal boiler conditions, which are precisely the situations that increase the likelihood of hazardous splashes.

With the new HMI, the robot can remain in automatic mode, and operators no longer need to enter the cell during recovery or repositioning tasks. This allows them to maintain a safe distance from the process and reduces exposure to hazardous conditions. In addition, the HMI eliminates many potential human errors, as all available functions are predefined and validated during commissioning.

Incorrect or unsafe commands can be hidden or deactivated based on the robot’s current state, as described earlier in the UI design chapter. This ensures that operators cannot accidentally select an inappropriate program, further enhancing both safety and reliability.

The touchscreen also reduces the time required to operate the robot, as all necessary commands can be executed directly from the HMI. With the previous operating method, the operator first had to switch the robot to manual mode from the controller, retrieve the teach pendant with its cables, and enter the robot cell. After completing the operation, the pendant had to be packed back into its storage box, reset the cell, and inform the control room that robot could be started.

Another significant factor is that, when the robot functions as intended, operators rarely need to drive it manually. As a result, the use of the teach pendant can easily be forgotten. The pendant contains a large number of buttons, the text is small, and the interface is entirely in English. Operating it always requires pressing at least two buttons simultaneously, as the dead-man switch on the back must be held down at all times. In free-drive mode, the operator must press the dead-man switch, the shift button, and the corresponding joint jog button simultaneously. This is often difficult, especially when wearing protective gloves. Due to the long intervals between manual operations, operators may also need to consult instructions to perform these tasks correctly.

With the touchscreen, the same functions are easy and intuitive to execute. For example, macro program execution is guided step-by-step with clearly numbered instructions (1, 2, and 3), making the operation fast and straightforward even for a first-time user. This results in shorter operating times with the robot, thereby freeing operators to perform other essential tasks.

Since the HMI functions similarly to a DCS terminal, the possibilities for modification are nearly limitless. Elements such as the layout, navigation structure, and available functions can be tailored precisely to the customer’s requirements. This flexibility also creates opportunities for further development and future expansion of the system.

8 INSTALLATION AND COMMISSIONING

Commissioning refers to the phase in which the developed HMI and robot control system are transferred from the design environment to the actual process. In this stage the hardware is installed, the communication interfaces are connected, and the system is verified under real operating conditions. Commissioning ensures that the HMI, robot, and process equipment function together as intended and that all safety-related and operational requirements are met. The following sections describe the installation work and the subsequent steps required to bring the system into full operation.

8.1 Hardware installation

The main consideration during the installation of the touchscreen was to ensure that it was positioned so the operator could always maintain visual contact with the robot. It was also essential to protect the screen from the highly hazardous environment surrounding the spout deck. The installation was carried out by mounting three separate cabinets side by side, from left to right: an electrical cabinet for the required components, a dedicated storage box for the teach pendant, and the cabinet housing the touchscreen itself (Figure 55).

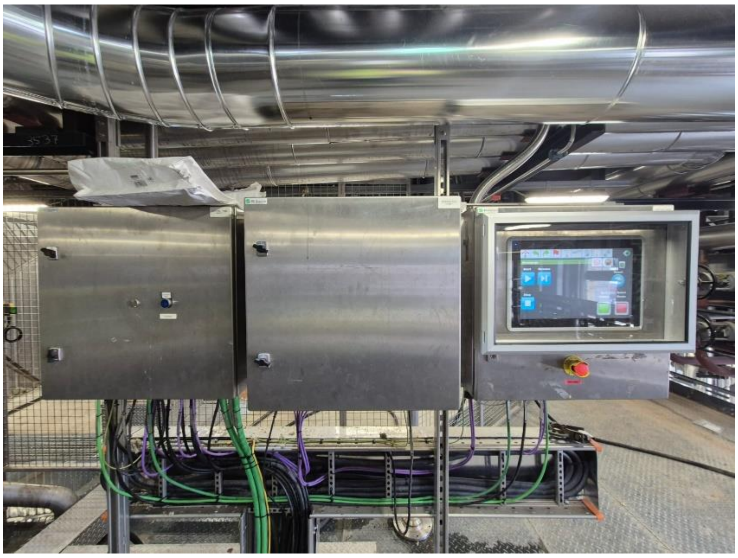


FIGURE 55. Electrical-, pendant- and touchscreen cabinets

The screen was protected with an IP69-rated polycarbonate cover. The cover is both water- and dust-proof, and it can be locked when necessary. This protection ensures a longer lifespan for the screen in the hazardous operating environment and shields it from accidental impacts.

8.2 Panel mounting

The touchscreen itself was installed on the door of the cabinet. This placement ensures that all electrical connections remain inside the enclosure and fully protected. The installation was carried out by cutting an appropriately sized opening in the door and mounting the screen in place. The screen is equipped with a removable back frame, which like the front frame, is larger than the cutout. This design, which illustrated in (Figure 56) allows the installation to be completely sealed, preventing water or dust from entering the cabinet and reaching the electrical wiring.

FIGURE 56. Backside of the touchscreen

The cabling from all three cabinets to the robot was routed through a cable tray installed at floor level. Originally, the cables were intended to be brought from above, but modifications to the upper-level structures required a different approach. For this reason, the floor-level cable tray was covered with stainless steel plating see (Figure 57), to ensure that it could withstand the harsh operating environment.


20/06/2025 18:17

FIGURE 57. Cable tray covered with stainless steel

8.3 Safety checks

The installation incorporates two separate safety logics: the robot system's internal safety logic and the boiler safety logic implemented through the HIMA system. These logics operate together, as certain boiler safety conditions require the robot to perform predefined actions when a safety signal is triggered.

From the boiler safety logic, two functions had to be tested during commissioning: the boiler rapid drain test and the smelt-spout cooling water conductivity alarm. In both scenarios, the robot must immediately stop the cleaning cycle and return to its home position. This behavior ensures that the robot does not cause additional damage to the boiler or surrounding equipment during abnormal conditions. For example, a leak in the smelt spout can cause a rapid increase in cooling water conductivity, and in such a situation mechanical cleaning by the robot could worsen the leak. The safety interlocks therefore prevent the robot from operating when the process conditions are unsafe.

The recovery boiler's firing liquor load (MCR %) is also used as an interlocking condition for the robot system. This ensures that the robot cannot be started without sufficient liquor firing, as low firing levels cause thermal expansion movements in the boiler and result in minimal liquor flow on the smelt spouts. The limit is always finetuned during commissioning; in this case, it was set to 30 %. Due to the small size of the boiler, this firing capacity is already reached with only a few liquor sprayers in operation.

From the robot system's internal safety logic, several functions had to be tested during commissioning. First, the limit switches on the cell doors were verified to ensure that the robot stops immediately when a door is opened. All emergency-stop buttons were also tested individually to confirm that they reliably interrupt robot motion. Both the door switches and the E-stops were required to generate alarms in the control room, allowing operators to detect any unauthorized entry to the spout deck or any emergency situation.

The conditions for automatic operation were also checked to ensure that the robot cannot be started remotely while personnel are working inside the cell. The interlocks for this include the robot being in its home position, the cell doors being locked and reset, and the robot controller being in automatic mode. These interlocks collectively prevent unintended motion and ensure safe operation during all process states.

8.4 First test runs

The installation of the HMI system was carried out in April 2025 during the so-called cold commissioning phase. At this stage, the boiler is not yet firing liquor, and the objective is to prepare all equipment and control functions for the upcoming hot commissioning phase. Once liquor firing has started, the hot commissioning phase focuses on testing the automatic operation and fine tuning the program based on real process conditions. Hot commissioning was carried out in June 2025.

8.4.1 Cold commissioning test runs

A brief automatic operation test was successfully carried out during the cold commissioning phase. Under normal circumstances this is not possible due to the safety interlocks and the boiler’s thermal expansion. The interlocks that prevent the robot from running in automatic mode would need to be bypassed, and modifications to the HIMA safety system are not performed while the boiler is in operation, as there is a risk of unintentionally tripping the boiler. This could interrupt testing of other equipment or, in the worst case, cause a trip after liquor firing has already started, making the removal of interlocks unsafe.

Another major obstacle is the boiler’s thermal expansion. During cold commissioning the boiler is in its “up” position, which means the robot program must be modified to allow the cleaning cycle to run in automatic mode. In larger boilers this becomes problematic due to the robot’s limited reach, especially around the large primary air ducts. Adjusting the program for this position is also time-consuming, which is why automatic operation is typically tested only during the hot commissioning phase.

In addition, many other installations and mechanical work around the spout deck are often still ongoing during cold commissioning. Because no personnel are allowed on the spout deck when the robot is operating automatically, these unfinished tasks normally prevent any automatic testing from being carried out. However, due to the small size of the boiler in this installation, we were able to perform a short automatic test already during cold commissioning.

8.4.2 Hot commissioning test runs

As mentioned earlier, the goal of the hot commissioning phase is to finetune the entire robot system so that it operates exactly as intended. With liquor firing now available, the robot’s performance can be evaluated under real process conditions. The first step was to run the cleaning program at low speeds in manual mode. This is essential, as it allows potential collision points or functional issues to be identified before moving to higher-speed automatic operation. The operational speed for the robot program was also set during this stage; in this installation the speed was limited to 80 %. With only two smelt spouts, the robot has more than enough time to complete the cleaning cycle, and higher speeds would only increase mechanical wear.

Once the cleaning performance was satisfactory, we proceeded to test the touchscreen interface. This involved going through every function one by one and verifying the system response. During these tests we intentionally opened doors, pressed emergency-stop buttons, and activated various screen functions to check for any programming inconsistencies. Any issues discovered during this process were corrected by modifying the program to eliminate the identified faults.

After confirming that the touchscreen and all safety functions operated as intended, we began continuous 24/7 automatic operation. The purpose of this phase was to “drive faults out” of the system by exposing it to real operating conditions and identifying any remaining weak points. It also allowed us to observe how operators interacted with the system, which provided valuable feedback for further improvements. Since the operators are the ones who will work with the robot daily, their input is especially important. This phase also offered an opportunity to provide additional training and support in areas where operators felt they needed more guidance.

8.5 Operator training

The majority of the training sessions were conducted during the cold commissioning phase. These sessions covered the entire robot system, and all operator shifts, shift supervisors, maintenance engineers, production managers, and members of the Valmet commissioning team participated. The main focus was on operator training, which was scheduled during their regular working shifts. A translator was present due to the language barrier between the commissioning team and the operators.

The training sessions were held on the spout deck so that participants could see the equipment and its functions in real operating conditions. The training also included hands-on exercises, allowing operators to use both the teach pendant and the touchscreen to control the robot.

Additional hands-on training sessions were arranged during the hot commissioning phase for anyone who requested them. This was necessary because there was a time gap between the initial training and the start of automatic testing, and some operators were on summer vacation during the first training period.

8.6 Final handover and acceptance

After completing the commissioning, the robot was left to operate in automatic mode, eliminating the need for operators to manually rod the smelt spouts. It was agreed with the customer that the touchscreen would undergo a six-month test period, during which any modifications requested by the customer would be implemented. The test period began in June 2025 and was completed in November 2025 in full agreement with the customer.

The customer was satisfied with both the robot’s performance and the touchscreen’s functionality and availability. During the test period, only one site visit was required for robot-related matters, and it was not related to the touchscreen. During that visit, additional feedback regarding the touchscreen was collected, and all feedback was positive. The screen itself remained in very good condition thanks to its protective cover, although the cover had accumulated some dirt over time.

Operators are highly motivated to keep the robot in continuous operation, as it significantly reduces their workload and improves working conditions.

9 RESULTS AND ANALYSIS

Since the touchscreen availability is directly tied to the robot's availability, the robot's performance was also evaluated in this chapter. The robot operated as intended throughout the test period, and no issues were observed that were caused by the touchscreen or the program logic. The only operational stoppages occurred when personnel entered the robot cell and triggered the door limit switches, which correctly stopped the robot. During the test period the boiler experienced a trip, and the robot was unable to start until sufficient liquor load was restored. This confirmed that the safety interlocks functioned exactly as designed.

Feedback from mill personnel indicated that both the robot and the touchscreen operated without problems. The user-friendly design and the clarity of the operating instructions received positive comments from operators. The touchscreen program covered all situations encountered during the test period, and no missing functions were identified. The touchscreen achieved 100% availability during the entire test period. The robot experienced one week of downtime due to the lack of spare rodding tools; however, since the rodding tool is a wear part and its replacement is the customer's responsibility, this was not counted as system downtime. Operators performed regular inspections inside the robot cell once every shift, which helped identify potential issues before they developed into failures.

The HMI system itself proved to be highly robust. Functionally it operates as a secondary DCS layer that integrates seamlessly with the robot system. Major failures would only be expected in the case of hardware damage, such as short circuits or water and dust ingress risks that can be effectively mitigated during installation. Additionally, the program logic is password-protected both in the teach pendant and on the touchscreen, preventing any unauthorized or accidental modifications.

Hiding certain buttons during specific phases of the robot program also proved to be a beneficial design choice. Some operators initially misunderstood the purpose of these buttons and attempted to use them at inappropriate times. After explaining the reasoning behind hiding them, operators appreciated the approach, as it reduces the likelihood of human-related errors and makes the system more intuitive to use.

Quantitative comparison with the previous manual rodding method was not possible, as no reliable data exists on the exact time operators spent on the spout deck before the robot installation. In addition, the touchscreen was installed simultaneously with the robot, which means that separate availability or performance comparisons between the HMI and teach pendant cannot be made.

10 CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the main conclusions drawn from the project and presents recommendations for future development and use of the system.

10.1 Conclusions

The main objective of this thesis was to design and implement an intuitive touchscreen interface that integrates seamlessly into the existing robot control system. This goal was fully achieved. The robot operated as intended throughout the commissioning and test period, with no interruptions caused by programming errors or the HMI system. The safety logic functioned precisely and prevented all potential hazardous situations, ensuring that automatic operation remained stable and reliable.

The touchscreen interface met its design requirements by providing a clear, user-friendly, and error-free control platform. All functions required for daily operation were available, and no missing features were identified during the test period. The system achieved 100 % availability, demonstrating strong technical reliability. The touchscreen also successfully extended the robot's operational capabilities by enabling smoother execution of tasks and offering operators more control options than before.

From an occupational safety perspective, the system significantly reduced the need for personnel to spend time on the smelt spout deck, directly supporting the goal of minimizing exposure to hazardous environments. Operators reported that the robot made their work easier and safer. Their involvement during commissioning helped reduce errors and allowed them to contribute valuable development ideas. Training sessions and hands-on practice increased operator confidence and ensured that the system could be used effectively from the start.

Overall, the system met all goals set for this project. The technical implementation was successful, and commissioning progressed smoothly despite the inability to pretest the touchscreen functions before installation. The robot and HMI system proved to be well suited for this type of industrial environment, even under challenging and hazardous conditions. The results indicate that the developed solution provides a robust foundation for future improvements and broader application in industrial robotics. These findings form a solid basis for defining practical recommendations for both the customer and future Valmet projects.

10.2 Recommendations

Based on the results and observations from the commissioning and test period, the following recommendations are proposed for future use and development of the system.

For future projects, it is recommended that Valmet advises customers to maintain an adequate stock of spare rodding tools. Since the rodding tool is a wear component, the lack of replacements can lead to unnecessary downtime, as observed during the test period. Continuous operator training is also beneficial, especially when customers request modifications to the robot system. Such training can be efficiently provided during scheduled service visits. The customer's current practice of performing daily inspections and routine maintenance has proven highly effective, and it is strongly encouraged to continue this approach.

For Valmet's internal development, the HMI layout and logic used in this project should be adopted as a standard for upcoming installations. The interface proved to be clear, user-friendly, and robust in daily operation. The feature of hiding certain buttons during specific phases of the robot program was particularly successful, as it reduced the likelihood of human-related errors and improved overall usability. It is also worth noting that in smaller boilers, partial automatic testing can be performed already during the cold commissioning phase, provided that other spout deck work allows it. This can significantly shorten the overall project schedule.

Documentation and operating instructions received positive feedback from the customer. It is therefore recommended to continue producing instructions in the same clear and structured manner on future projects.

In future thesis projects, several research directions could be explored to further develop and evaluate the system. One potential area is the collection and analysis of quantitative data, such as robot utilization rate, cleaning time, downtime events, and the remaining amount of manual work required. This type of data would enable more precise performance comparisons between automated and manual methods. Another relevant topic is the evaluation of potential benefits of remote diagnostics in troubleshooting robot or HMI-related issues, especially in mills where on-site support is limited. Additionally, the touchscreen interface could be further developed based on long-term user feedback, allowing future studies to examine how new features or layout improvements influence usability, safety, and operational efficiency.

11 DISCUSSION

From a technical perspective, this project provided valuable experience in touchscreen technology, PLC programming, commissioning practices, and safety-logic automation. The work also highlighted the importance of understanding how different system components interact in real industrial environments. From a project-management standpoint, the project was demanding, as our team consisted of only three people while multiple installations were ongoing around the world. This occasionally created resourcing challenges and emphasized the need for efficient planning and prioritization. One of the key lessons learned was the importance of clear and direct communication with the customer. When expectations, progress, and potential issues are discussed openly, many problems can be resolved before they materialize, and the final system is more likely to meet the customer's needs.

A notable technical challenge during the project was related to the door limit switches. Because the signal path was routed through several switches over a long distance, the signal occasionally broke for a few milliseconds, causing the robot to shut down. This issue was resolved by adding short timers (5 ms) in the PLC logic. Although adding a delay to a safety-related signal may sound risky, the duration was so short that it had no impact on the robot's stopping time, while significantly improving signal stability. This experience reinforced the importance of understanding both the technical and practical aspects of safety-related signals in complex installations.

If I started the project again, I would place more emphasis on testing the touchscreen functions before the commissioning phase. The lack of pre-testing created unnecessary pressure on the schedule, as there was no certainty that the interface would work as intended once installed. During on-site commissioning, ensuring that the robot cell is fully ready on time would also be a priority. Delays, such as the limit switch issue, can quickly compress the schedule, especially when operator training is planned during cold commissioning. If the cell cannot be reset, it becomes impossible to demonstrate essential functions such as resetting the cell and operating in automatic mode, which also prevents touchscreen testing.

One of the most significant limitations of the project was the language barrier. Most operators spoke limited English, and the robot team's understanding of Portuguese was minimal. Fortunately, the commissioning team included personnel fluent in both languages, which helped bridge the gap. Another limitation was the lack of quantitative data. There was no reliable way to measure performance differences between the touchscreen, manual rodding, or teach pendant operation. As a result, the evaluation of performance relied heavily on operator feedback rather than numerical comparison.

The project was strongly dependent on theoretical understanding and literature review, as no quantitative performance metrics were available. There is also very limited published material on implementing touchscreen-based control systems for smelt spout robots, which made it necessary to examine boiler-specific factors that influence smelt behavior and, consequently, robot performance. This was Valmet's first touchscreen installation of this type, meaning there were few predefined expectations or reference cases to guide the work.

Finally, the project reflects a broader trend toward increased automation in hazardous industrial environments. Stricter occupational safety requirements and the recognition that worker health cannot be compromised are driving the adoption of robotic solutions. This project reinforced the assumption that tasks traditionally performed manually, especially those involving exposure to heat, chemicals, or physical risk, will increasingly be handled by automated systems due to both safety and performance benefits.

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FIGURES

TABLES

Table 1. Compositions of softwood black liquor (Alakangas et al. 2016, 113)