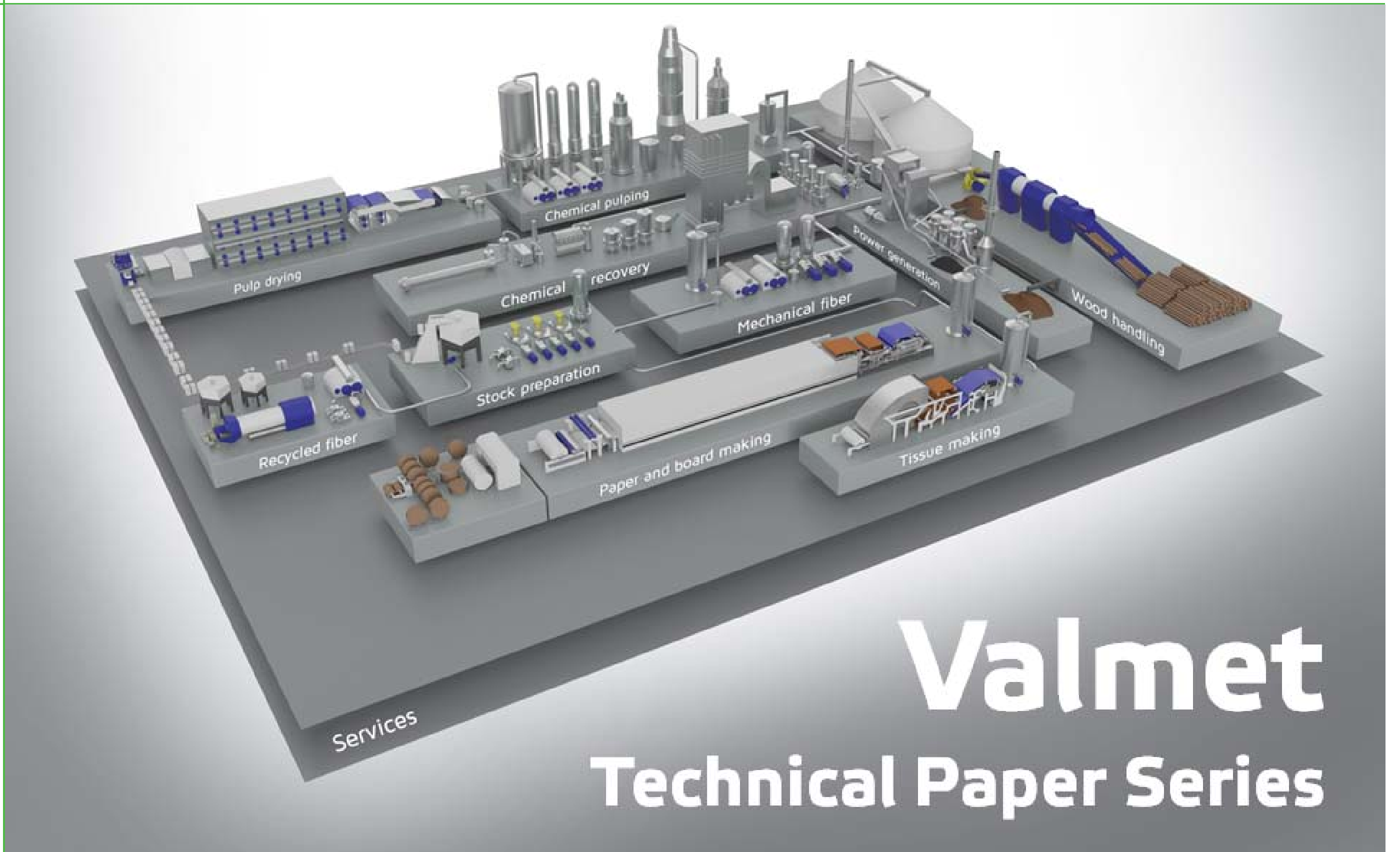

Improved recovery boiler cooling and washing practices

Executive Summary

A method employed by Valmet for bed cooling monitoring with thermocouples is presented. The rationale for selecting the number and the location of thermocouples as well as the conditions at which water washing can begin safely are reviewed. Cases are presented to demonstrate the general applicability.

Bed cooling monitoring is used routinely after smelt extractions, as the remnants of the bed cool down at best so quickly that washing can begin simultaneously in economizers, boiler bank and the superheaters. And since smelt extraction removes a major portion of the bed, cleaning the floor becomes much easier and can in many cases be carried out using a method based on enhanced dissolution of smelt and the salt falling from the superheaters. This method, named Valmet Recovery Boiler Cleaning (previously known as Wash-X), employs mixing devices installed on the furnace floor during washing. The benefits of the method are illustrated with a few case studies.

Introduction

Traditionally, in small and midsize recovery boilers, the bed cooling has been addressed by using a certain minimum cooling time, typically 15 – 24 hours. This method is simple and very easy to use. And since small and midsize boilers have floor designs in which the smelt bed is typically at most 200 – 400 mm deep, the bed cools down relatively quickly and the used cooling times are therefore sufficiently conservative.

There are, however, exceptions. When the boiler is shut down abruptly so that the bed is not burned away, the remaining bed may be several meters high. In such cases, bed cooling assessment becomes much more difficult. For these instances, BLRBAC recommends that bed temperatures be monitored with thermocouples. However, the details, such as at what temperature cooling can be considered completed, are left to the discretion of the mill. The guidelines only state what "the majority of companies that provided input for these guidelines" have used.

In principle, the same approach could be applied also in extra-large (XL) boilers (all have decanting floors) with much thicker and consequently slower cooling beds. The downside is that bed cooling calculations indicate that bed cooling times in XL boilers should be increased to 30 – 50 hours. It is therefore not surprising that companies operating XL boilers are routinely using smelt extraction services, such as Valmet Smelt Extraction (previously known as Smelt-X), to remove the major portion of the bed while the boiler is still being fired so that the remnants of the bed cool down more rapidly.

However, none of the guidelines issued by any of the committees give detailed instructions on how bed cooling should be assessed after smelt extraction. Instead some general guidelines are given. For example, the BLRBAC Guidelines for Post-ESP Procedures for Black Liquor Recovery Boilers (2002) state the following:

"Each mill should have a written char bed cool-down procedure that includes the following:

- Procedures for use of bed cooling mediums such as sodium bicarbonate, liquid carbon dioxide or low-pressure steam (if they are to be used). If low-pressure steam is to be used, the procedures need to include provisions to prevent any condensate from entering the furnace.
- Type of thermocouple equipment and procedures to be used for probing the bed to check for hot spots.
- Maximum bed temperature allowable to start water washing in the furnace. For units with hearth designs that retain a residual pool of smelt, the procedures may also include a minimum time interval before water washing can commence.

The maximum bed temperature allowable to start water washing should provide enough safety-margin to take into account potential variations in smelt chemistry, the potential for localized hot spots and the inability to probe 100% of the bed. The maximum bed temperature used by the majority of companies that provided input for these guidelines is 800 °F."

Judging from the fact that the aforementioned recommendations are in a guideline for post-ESP procedures, the recommendations are written for a case in which the bed composition, height and temperature may vary greatly over the floor area. Some parts of the bed may be covered with char, which may burn several hours after the boiler shutdown, while in other locations molten material may be sheltered by a hard cover of sintered salt. It can therefore be difficult, and sometimes impossible, to say how the thermocouples should be installed and if their readings are indeed representative of the hottest spots in the bed. Therefore, it is only natural that a relatively low temperature limit for the maximum bed temperature (800 °F / 426 °C) has been chosen by many companies as a maximum bed temperature at which water washing can begin.

Since no other temperature limit is mentioned in any of the guidelines issued by any of the committees, many mills also apply the same temperature limit for routine shutdowns, in which the size of the bed is controlled much better than in an emergency shutdown. This approach, however, leads to cooling times that are overly conservative.

Bed cooling monitoring

A regular procedure during a normal shutdown is to control liquor firing so that the char bed is burned away completely before firing ceases. This way the remaining material on the floor starts to cool right away as soon as auxiliary fuel firing is discontinued.

In addition, the amount of material remaining on the floor is usually minimized by operating the boiler so that the bed becomes fully molten during load reduction. Once black liquor firing ceases, the level of the molten smelt pool decreases gradually until it becomes equal to the level of the spout openings, and the smelt flow in the spouts ceases.

Once these steps are completed, it is relatively easy to say what part of the smelt bed will remain hot the longest. In recovery boilers with a decanting or sloped floor, the part of the bed that remains hot the longest is usually the volume just above the floor ditch, as this is where the bed is the thickest and heat transfer from the core of the bed to the surface is the slowest. In boilers with flat floors, the part of the bed that remains hot the longest is the part near the front wall, as it generally becomes covered by salt falling from the superheaters. The salt pile forming near the front wall acts as insulation and slows down cooling of the bed beneath the salt pile.

The task of monitoring the bed cooling becomes even easier once a major part of the bed is already removed when the load is reduced. This can be achieved with the Valmet Smelt Extraction service, in which smelt is extracted using air-powered ejectors. The ejectors can remove smelt so that only a few centimeters of thick molten pool remain, and the material remaining on the floor is mostly solidified smelt (**Figure 1**).

Figure 1. Recovery boiler floor at the end of smelt extraction

In a case such as this, it suffices that a few thermocouples are installed so they reach the remaining smelt puddle. The thermocouples can be installed through the primary air ports located above the ditch or, if the ditch is sufficiently close to the back wall, through the smelt spout openings. The number of thermocouples needed can be as low as two to four.

In boilers with a flat floor, the hottest part of the remaining bed can be slightly more difficult to determine, in particular if the whole floor cannot be inspected visually at the end of the smelt extraction. However, bed cameras are usually available and also some parts of the floor can be seen through the primary air ports, the smelt spout and the liquor gun openings. This allows for a thermocouple installation that provides reasonably high accuracy in measuring the maximum bed temperatures.

Maximum bed temperature allowable to start water washing

In principle, water washing can safely begin as soon as the smelt has solidified, as the heat transfer between smelt and water can occur at a rate high enough required for explosive vaporization just when the smelt can break up into tiny droplets. Only then can the heat transfer area become large enough.

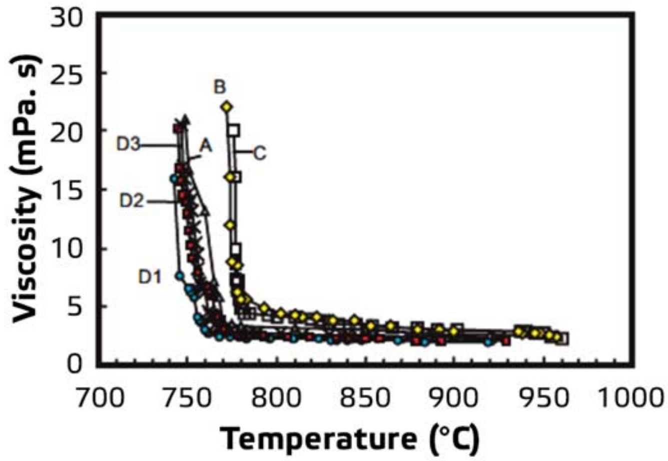

Figure 2. Smelt viscosity as a function of temperature, Kraft mill samples [1]

Numerous experiments with both simulated and mill smelts show that even though the smelt does not have a single melting point, but instead solidification occurs over a wide temperature range, it is the first freezing point (when solid material first forms) which is relevant here. For typical mill smelts, this temperature is 740 – 780 °C. Below this point smelt becomes very viscous, as shown for example in **Figure 2**.

The largest experimental study of smelt-water explosions was carried out by Battelle Institute between 1969 and 1972. In this study, hundreds of experiments were carried out with different smelts [2]. The conclusion of the study was that the minimum temperature for explosion was the first freezing point of the salt mixture.

The BLRBAC Guidelines for Post-ESP Procedures for Black Liquor Recovery Boilers mentions that also potential variations in smelt temperature should be taken into account when maximum bed temperature allowable for water washing is set. High concentrations of chlorine, potassium and thiosulfates can lower the first freezing temperature.

It is possible that the bed may contain some local pockets or layers with extra high levels of these compounds, and these volumes hence may stay molten longer than the rest of the bed. Although the existence of such pockets has not been verified, the results from floor tube measurements show that at least in some boilers, floor tubes experience temporarily high temperatures, and one explanation is that the temperature fluctuations are caused by local melting of smelt with a very low initial freezing point.

While it may be possible that there are parts of the bed which have relatively low first freezing points during normal operation, it is hard to imagine how these parts should survive unmixed with the rest of the bed when the main bulk of the bed has melted. At this point, the char bed covering the bed during normal operation is completely gone, and the remaining bed becomes exposed to radiation and convection heat from liquor and auxiliary fuel firing.

The bed temperatures that tend to remain close to 820 °C as long as the char bed exists usually increase substantially soon after the char bed disappears. As a result, the molten layer becomes deeper, while the frozen layer above the floor tubes becomes thinner. Consequently, any bed material with a lower than average first freezing temperature is likely to become mixed with the rest of the molten bed.

The smelt pool can also be made homogeneous by actively circulating the bed. This can be done by closing the primary air dampers on one side and opening them on another side in each wall. The swirling primary air tends to push the smelt pool surface so that it also starts to swirl. After a while, any deposits with high chlorine, potassium or thiosulfate concentrations are mixed within the pool such that the mixture becomes diluted. As a result, the bed has a first freezing point that varies only by a few degrees and is close to a bulk smelt first freezing point, which is typically 740 - 780 °C. Moreover, this can be verified by installing thermocouples into the smelt pool so that the thermocouples measure smelt temperature from the bottom, i.e. from the interface between molten and frozen smelt.

Thanks to reduced variations in smelt chemistry, the elimination of local hot spots, and the ability to probe the locations that are most likely the hottest, 500 °C (932 °F) was selected as the maximum bed temperature allowable to start water washing. It is believed that this temperature will provide a considerable safety-margin, which makes the risk of smelt-water explosions lower than in a situation with no smelt extraction and monitoring of the smelt bed temperature with thermocouples using 426 °C (800 °F) as the maximum bed temperature. This means that the risk of smelt-water explosions can be reduced by carrying out smelt extractions in every outage. This is particularly the case in washing outages, when there is extra pressure to minimize the cooling time prior to washing the superheaters.

Examples of bed cooling monitoring

In the first example, a recovery boiler with a capacity of 2500 tDS/day was shut down for a maintenance outage and smelt extraction was carried out in order to enhance bed cooling. The boiler had a decanting floor with the ditch about 3 m from the back wall. The minimum smelt bed volume without extraction is about 45 m^3.

During load reduction, black liquor flow and temperature, the flow of oil and air were controlled so the char bed became gradually lower and disappeared totally before all start-up burners were in operation. As soon as the last liquor gun was removed and all start-up burners were in operation, four ejectors were installed. The ejectors were operated for 1 hour and 40 minutes, during which about 75% of the smelt volume was removed. The material remaining on the floor was mostly solid and hence could not be removed by extraction. As soon as the extraction was completed, four thermocouples were installed through the primary air ports closest to the ditch in the side walls. The results are shown in **Figure 3**.

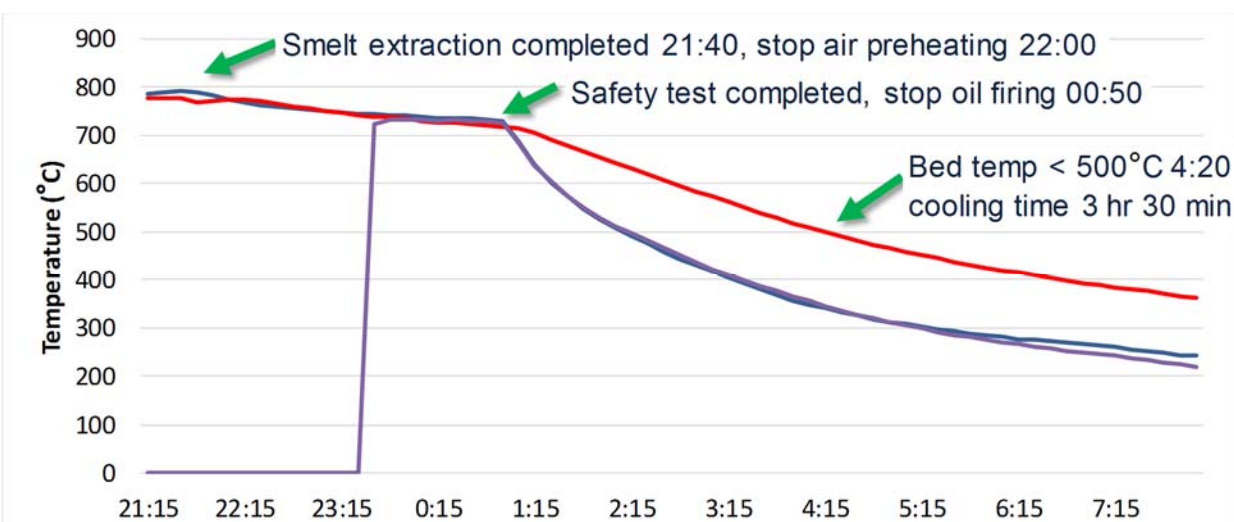

Figure 3. Bed temperatures during cooling period when cooling has been enhanced through smelt extraction

In this case, the remaining smelt pool was only a few centimeters thick on top of a solid layer and it cooled to below 500 °C in 3 hours and 30 minutes. According to a study made for the Finnish Recovery Boiler Committee, the cooling time without smelt extraction would in this case have been 22.5 hours. This implies that that the bed cooling was in this case accelerated by about 19 hours. The water washing actually began after the boiler had been depressurized so that the floor tube material temperature was below 150 °C, and by this time the bed material temperatures were well below 500 °C. The washing of the furnace and the superheaters could therefore be carried out with a greatly reduced risk of smelt-water explosions, compared to a situation in which water washing would have started after 22.5 hours without smelt extraction.

Figure 4. Bed after shutdown with thermocouples installed

In the second example, a recovery boiler with a capacity of 800 tDS/day was shut down for a maintenance outage. The boiler had been operated for a long time without proper bed cameras, and consequently with a bed so high that hard piles of sintered salt had formed inside the bed. These piles could not be melted quickly after the char bed was burned away. As a result, relatively high piles of salt remained on the floor after the firing ceased. Since these piles were clearly higher than the rest of the remaining bed, two thermocouples were installed so that the tip of both thermocouples were pushed into the piles (**Figure 4**).

An effort was made to install the thermocouples so that they would measure the temperatures in the core of the two piles. The results are shown in **Figure 5**.

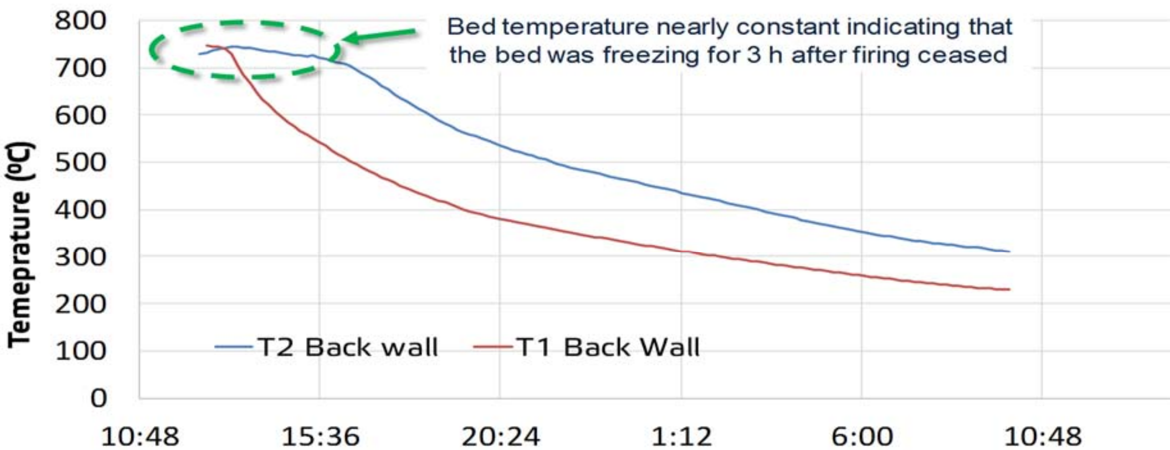

Figure 5. Smelt bed temperatures during cooling period (without smelt extraction)

The results imply that there was indeed a hot spot inside one of the piles so that even though both piles appeared completely solid when inspected visually (there were no indications of cracking and hence no glowing "magma" was visible), one of the piles contained a molten core that solidified only gradually during the first three hours after firing ceased. During this time the bed temperature remained relatively stable and above 700 °C, indicating that that heat was being continuously released as a result of solidification. Only after solidification was completed did the core of the bed start to cool down, much at the same tempo as the other pile had already been cooling previously. In this case the maximum allowable bed temperature of 500 °C was reached after 9 hours. However, since there were no guarantees that there were no other and even hotter spots that were not detected by the thermocouple measurements, a decision was made to use the normal cooling time, which in this case was 24 hours.

It is noteworthy that all cooling trends in both **Figures 3 and 4** show steadily decreasing values over the entire temperature range below 700 °C. This implies that there was no smelt with a low freezing temperature, as any such smelt would have resulted in a pause during which bed temperatures would have remained the same. This is in fact true also for all measurements carried out. These observations support the hypothesis that even if there is some smelt with a lower than normal first freezing temperature during normal operation, it is very unlikely that that any such smelt would survive the reduction in load and freezing without mixing with the bulk bed.

In conclusion, using 500 °C as the maximum allowable bed temperature for water washing appears to work well when the following conditions are met:

- The char bed is completely removed during load reduction (only some loose pieces of char may float on top of the molten salt pool)
- The bed is molten and covers the whole floor prior to smelt extraction
- The smelt bed is reduced in size and volume by smelt extraction
- Thermocouples are installed so that they reach the location where the smelt remains hot the longest
- The bed temperatures decrease steadily, indicating that no phase change is taking place, i.e. all of the smelt has already solidified.

In these conditions water washing is safe, and most likely much safer than without smelt extraction, but with a more conservative maximum allowable bed temperature.

Water washing after smelt extraction

Since bed cooling after smelt extraction can proceed as quickly, if not quicker than boiler depressurization, there is no longer any reason to delay water washing in superheaters, boiler bank and/or floor. As a result, washing can now start simultaneously in all these areas as soon as the material temperatures are low enough.

Since stress corrosion cracking may occur in floor and wall tubes clad with 304L, if the tube temperature is 160 – 220 °C and tubes are in contact with hydrated salt, it is necessary to proceed with pressure reduction so that material temperatures in the floor tubes are below 150 °C before water is introduced into the furnace. In practice this means that water washing of the furnace has to be delayed until the drum pressure is below 3 – 5 bars.

Using several sootblowers instead of just one of two can result in a substantially lower washing time, as merely doubling the number of sootblowers available for water washing can reduce the water washing time for economizers, boiler bank and superheaters by 50%. Depending on the boiler and the soot blower system design, this may be possible with modest upgrades, such as investing in a second wash water pump or new piping to the sootblowers. Even using the same number of sootblowers, but changing the order in which they are used, can achieve significant savings in outage time.

For example, since the time for bed cooling can be shortened with smelt extraction, water can be safely introduced into the furnace at the same time as the economizer washing normally begins; washing can now begin as safely from the superheaters and then proceed to the boiler bank and lastly to the economizer, i.e. in reversed order. This arrangement has the added benefit that when washing is started from the superheaters, there is more time to dissolve the salt that falls down from the superheaters during washing, as dissolving can now take place also during washing of the boiler bank and economizer.

Boilers in which the salt that falls down from the superheaters tends to remain on the floor even after washing of the superheater, so that it interferes with scaffolding, can especially benefit from this simple alteration. The benefits can be even better in cases when the floor needs to be cleaned for inspections and/or repairs, as the reversed washing sequence reduces the amount of material on the floor and hence reduces the amount of salt that has to be removed by hydroblasting and/or manually.

Superheater washing can begin soon after depressurization, since the condensation of the superheater steam controls the superheater material temperatures the same way as saturated water controls material temperatures in other parts of the boiler. Superheater temperatures must therefore follow water saturation temperatures, which tend to decrease as pressure goes down. This is particularly true for superheater sections in the furnace, as they are constantly cooled by air flowing through the furnace and carrying out the heat released by the condensing steam.

The same cannot be said for those parts of the superheaters that are outside the furnace, such as the headers. Steam can stay superheated here because there is no heat sink. For this reason, the superheater temperature measurements, which actually measure material temperatures in the headers, do not give realistic information on the superheater temperatures in the furnace. Thus, the decision on superheater washing should not be made on the basis of measured superheater temperatures, but on the basis of drum pressure and bed and floor temperatures.

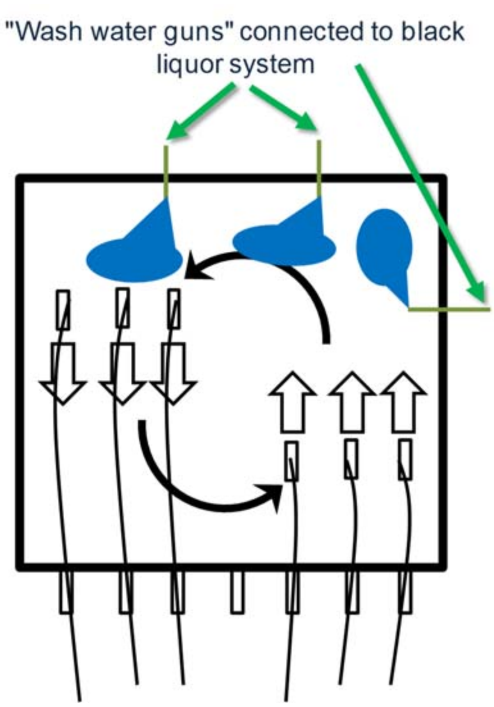

Figure 6. Arrangement for floor washing

Salt that falls down from the superheaters and remaining smelt after extraction can be difficult to dissolve using only the water that rains down from the soot blowers, since only a part of the water sprayed into the superheaters will find its way to the pile of salt near the front wall. In addition, the water pool forming on the floor easily becomes stratified, with salty water laying still on the bottom and relatively clean water flowing on the top and out from the furnace. In these conditions, no dissolving takes place.

These shortcomings can be rectified with a service that was developed named Valmet Recovery Boiler Cleaning. The pile of salt near the front wall is dissolved by spraying warm or hot water onto it using the liquor guns and/or nozzles installed in the primary air ports or burner openings. The smelt and salt is efficiently dissolved by mixing and circulating the water in the pool at the furnace floor using mixing devices placed in the pool. One such arrangement is shown in **Figure 6**.

Washing the floor can begin as soon as the remaining bed has cooled down and the boiler is depressurized, i.e. at the same time that soot blower washing starts, and it can also end at the same time. During washing, clean water is sprayed onto the floor, but the water flow rate is controlled so that the density of the effluent leaving the furnace stays well below the saturation point. This enables efficient dissolving of the salt, without using too much water. The locations and directions of the water nozzles and liquor guns are altered during washing so that all areas where salt rises above the water surface are wetted. The mixing devices are operated with pressurized air or water and they are in continuous operation during washing.

Once the soot blower washing is complete and the density and flow of the effluent decreases, salt and smelt are being removed at a low rate. At this point, water spraying and mixing in the pool can be stopped. The remaining water is then removed using the same ejectors that were used for smelt extraction.

Figure 7. Floor after washing in a recovery boiler with 1600 tDS/day capacity

This type of floor washing has been provided since 2015, and a dozen projects have been carried out. The experiences gained indicate that the salt from the superheaters can be removed by dissolving it with water, but the removal of the smelt on the floor depends on the amount of non-process elements in the smelt.

Figure 8. Floor after washing in a recovery boiler with 3600 tDS/day capacity

If the concentrations of non-process elements, such as Ca, Mg, Si, and Al are high, it is likely that the majority of the smelt that remains on the floor after smelt extraction will remain there also after the washing sequence. But if the amount of non-process elements in the smelt is low, the smelt can be efficiently dissolved such that most of the smelt remaining on the floor after smelt extraction can be removed. The end results of washings are shown in **Figures 7 and 8**.

The results shown in **Figure 7** are all the more impressive since they were obtained with the very tight schedule shown in **Table 1**.

In this case the total time reserved for cooling and washing was only 24 hours. This time was sufficient to clean the floor without hydroblasting. Also, the results shown in **Figure 8** were obtained with only dissolving, no hydroblasting.

Action	Time
Liquor firing stopped	Sunday 0700
Smelt extraction during oil firing	Sunday 0700 – 1100
Oil firing stopped	Sunday 1100
Cooling and depressurization	Sunday 1100 – 1500
Washing with soot blowers	Sunday 1500 – Monday 0600
Floor washing with mixing devices	Sunday 1900 – Monday 0600
Removal of wash water	Monday 0600 – 0700
Safety roof installation	Monday 0600 – 0900
Removal of smelt remnants with hosing	Monday 0900 – 1100

Table 1. The outage schedule for a recovery boiler with 1600 tDS/capacity using smelt extraction and floor washing services

Conclusions

In many cases the length of a mill outage is set by the time needed for recovery boiler cooling, washing, inspections and repairs. The ways cooling and washing are carried out can be optimized so that the total outage time can be reduced. The reductions in the total outage time can be obtained by:

- removing most of the smelt while the boiler is still firing black liquor and auxiliary fuel(s)
- monitoring the bed cooling so that washing can start immediately after the bed is cooled to 500 °C
- washing the superheaters first or simultaneously with the other parts of the boiler
- washing the floor with clean water sprayed onto the floor, keeping the water in the pool mixed and circulating using mixing devices installed on the floor.

The experience gained so far indicates that when these actions are carefully planned and systematically executed, significant time savings can be achieved. Usually this does not happen overnight, but instead over a period of a couple of years, as the outage practices and procedures are modified step by step to gradually optimize the outcome.

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This white paper combines technical information obtained from Valmet personnel and published Valmet articles and papers.

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