Kraft recovery boiler operation with splash plate and/or beer can nozzles — a case study

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ABSTRACT: In this work, we study a boiler experiencing upper furnace plugging and availability issues. To improve the situation and increase boiler availability, the liquor spray system was tuned/modified by testing different combinations of splash plate and beer can nozzles. While beer cans are typically used in smaller furnaces, in this work, we considered a furnace with a large floor area for the study. The tested cases included: 1) all splash plate nozzles (original operation), 2) all beer can nozzles, and 3) splash plate nozzles on front and back wall and beer cans nozzles on side walls. We found that operating according to Case 3 resulted in improved overall boiler operation as compared to the original condition of using splash plates only.

Additionally, we carried out computational fluid dynamics (CFD) modeling of the three liquor spray cases to better understand the furnace behavior in detail for the tested cases. Model predictions show details of furnace combustion characteristics such as temperature, turbulence, gas flow pattern, carryover, and char bed behavior. Simulation using only the beer can nozzles resulted in a clear reduction of carryover. However, at the same time, the predicted lower furnace temperatures close to the char bed were in some locations very low, indicating unstable bed burning. Compared to the first two cases, the model predictions using a mixed setup of splash plate and beer can nozzles showed lower carryover, but without the excessive lowering of gas temperatures close to the char bed.

Application: CFD modeling can be used for better understanding of boiler process and furnace behavior with different liquor spray scenarios before actual modifications. Also, the most suitable liquor spray scenario can be identified with CFD modeling in terms of number/type/location of splash plate nozzles and beer can nozzles.

Efficient, stable, and safe operation of kraft recovery boilers may experience both mechanical and process challenges. The main process-related problems are fouling of heat transfer tubes and plugging of flue gas passages by fireside deposits [1]; tube corrosion and cracking due to corrosive deposits and the flue gas environment; floor tube damage due to uneven bed burning or very high heat flux near walls; poor smelt reduction and unsteady smelt run-off; and high air emissions due to poor combustion.

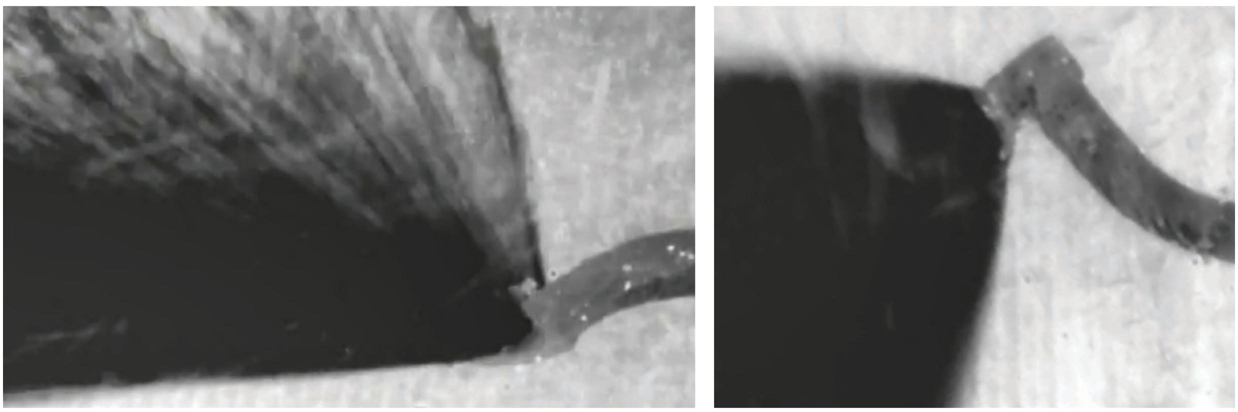
Proper design and tuning of the air system and appropriate liquor spray can help to improve boiler operation. Computational fluid dynamics (CFD) modeling is an established research tool for studying the kraft recovery process. The CFD modeling of recovery boilers has been utilized since the late 1980s, when several research groups independently developed the first comprehensive CFD models for recovery boiler combustion [2-7]. Many researchers further studied furnace processes and combustion [8-11]; the char bed process [12-15]; air system reviews [16-19]; and validation of CFD modeling in general [20-24]. The latest work in this area is integrated study of the flue gas flow and superheating process in a recovery boiler using CFD and 1D process modeling [25]. Ideally, the black liquor sprayed into the recovery boiler should form a droplet size small enough to dry and to partially pyrolyze before reaching the char bed, but large enough to avoid being entrained in the flue gas flow as carryover [26]. The spray droplet size and size distribution and spray parameters are the key variables in controlling the droplet combustion, char burning, entrainment, and carryover.

The present work is a case study of a relatively large operating boiler with a floor area of 100 m^2, firing dry solids > 80% and experiencing upper furnace plugging and availability issues. In-furnace camera inspection indicated that the liquor droplet carryover from the side wall liquor guns was significantly high. Comparison of the carryover behavior of the furnace with the existing opposing high secondary air system with a semi-interlaced air system using CFD modeling determined that the air system is functioning well in terms of carryover. The air system results are not further discussed in this work, but instead, this work focuses on CFD model predictions of different liquor spraying conditions for the boiler in question. The impact of liquor nozzle type on model predictions is studied by carrying out simulations of the three liquor spray system cases: 1) operation using splash plate nozzles only, 2) using beer cans only, and 3) using mixed splash plate and beer can nozzles on different walls. Model results are compared to the actual operational experiences from the boiler, providing additional insight into the details of the furnace processes and behavior.

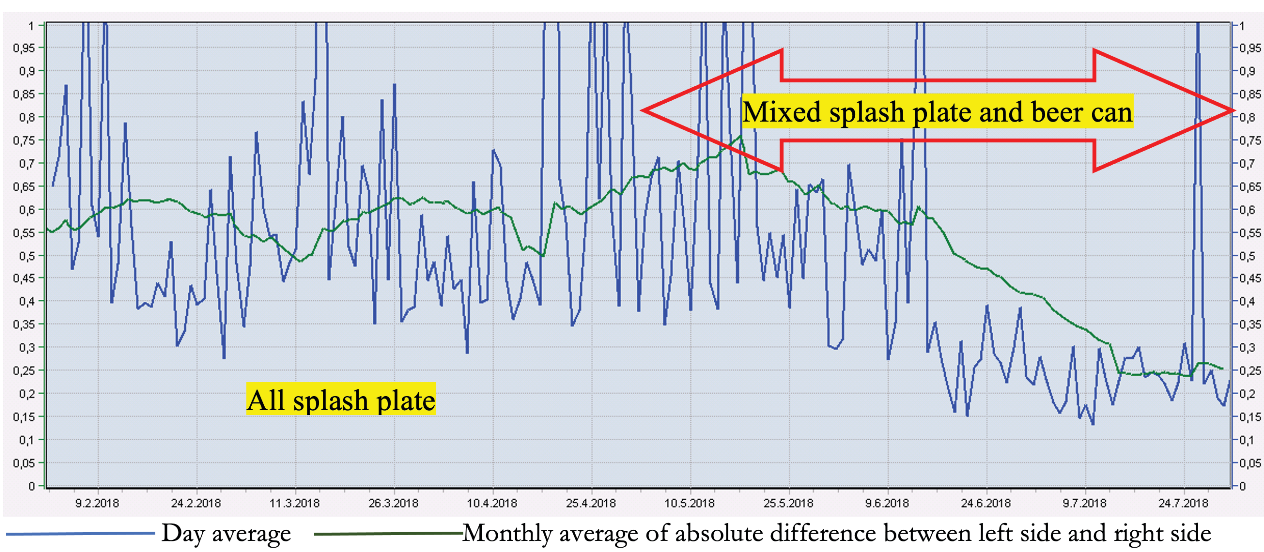
CASES STUDIED

The studied boiler is a relatively large operating boiler experiencing upper furnace plugging and availability issues. Characteristic features include relatively high carryover and asymmetric flue gas flow indicated by temperature and oxygen concentration differences between the left and right sides of the boiler, as well as plugging in the superheater area; these can lead to an unscheduled shutdown of the boiler, typically after three to nine months of operation.

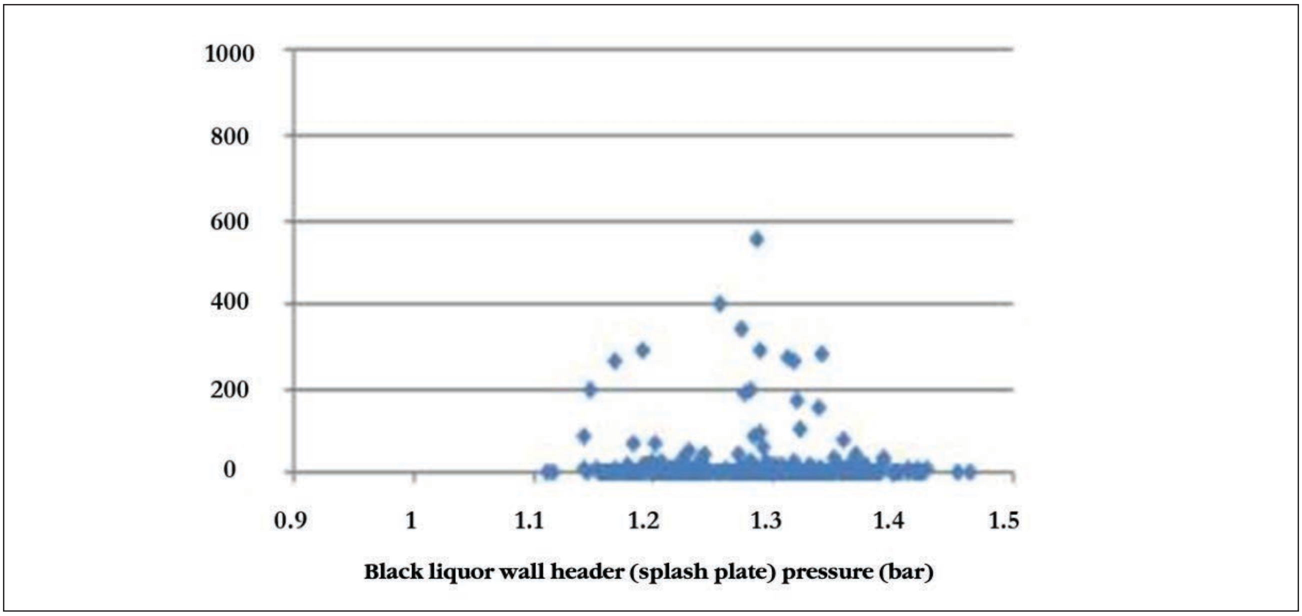
We studied the boiler with in-furnace cameras to better understand the lower furnace combustion situation. The in-furnace cameras showed liquor sprays, particularly from the side wall liquor nozzles, to be mostly entrained toward the upper furnace. **Figure 1** shows how part of the liquor spray is directed strongly toward the upper furnace from the splash plate liquor nozzle. Additionally, flue gas flows toward the front wall were observed to be characterized by stronger turbulent fluctuations and flows toward the upper furnace. In contrast, the flue gas flows toward the rear wall were characterized by less turbulent flow and less tendency of gases to flow upward. To improve performance and increase boiler availability, we tuned/modified the liquor spray system by testing different combinations of splash plates and beer cans. We completed this tuning before the CFD modeling. The tested cases included: 1) all splash plate (original operation) nozzles, 2) all beer can nozzles, and 3) mixed splash plate and beer can nozzles, with splash plates on the front and back walls and beer cans on the side walls. Figure 1 shows an image of the beer can liquor spray.



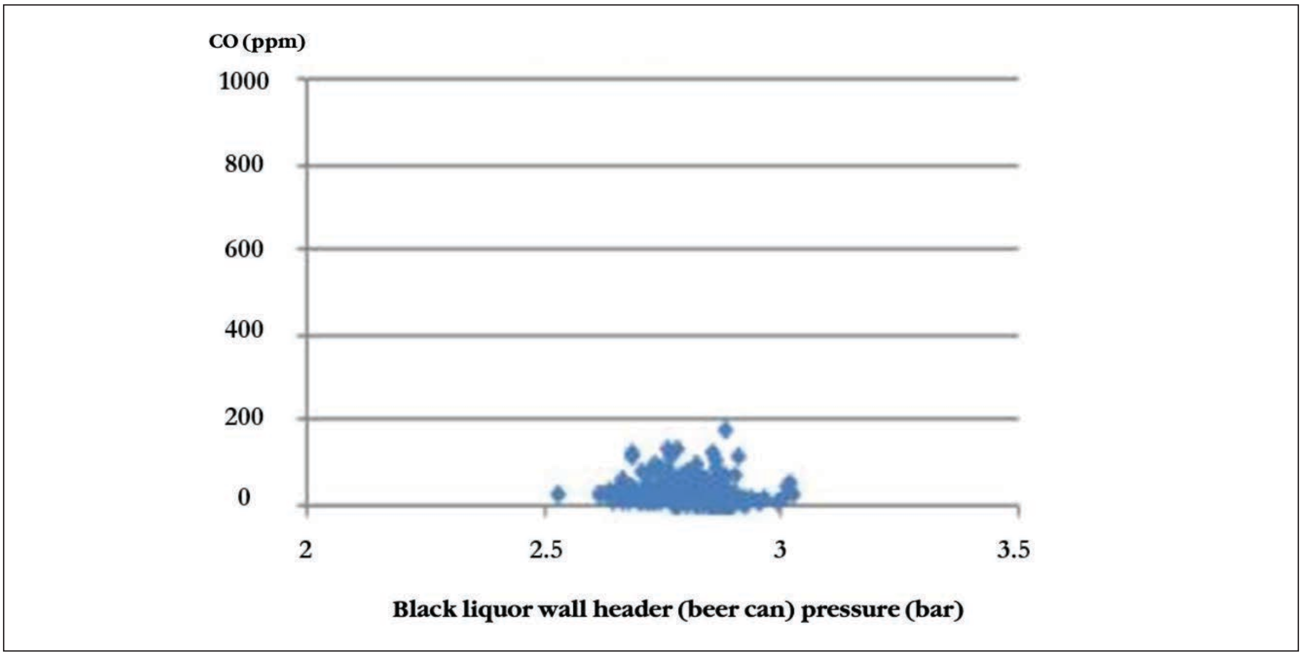
1. Splash plate (left) and beer can sprays captured by the in-furnace camera



2. Flue gas oxygen difference between the left and right sides of the boiler.



3. Carbon monoxide fluctuations in splash plate operation.



4. Carbon monoxide fluctuations in mixed splash plate and beer can operation.

In general, the operation with beer can liquor nozzles resulted in lower carryover. However, using only beer can nozzles sometimes caused unstable smelt flows, unstable char bed behavior, and in some cases, an increase in the asymmetric combustion and flue gas flow. Operating with the combination of splash plates on front and back walls and beer cans on side walls was ultimately considered to result in improved overall boiler operation as compared to the original condition of using splash plates only.

Figure 2 presents process data on the flue gas oxygen difference (left vs. right side of boiler) during the original operation with all splash plate liquor nozzles, as well as during operation with mixed splash plate/beer can nozzles. During the evaluation period, the boiler symmetry was improved; after a few months, the average excess oxygen difference between the left and right sides decreased from 0.6% to 0.3%, as shown in Fig. 2.

The decreased left-right oxygen difference correlated with a decrease in flue gas carbon monoxide. **Figures 3 and 4** show carbon monoxide data from operation with splash plate nozzles and operation with mixed splash plate/beer can nozzles, respectively. In all the operational situations, there is always only one type of liquor gun on each wall. The oxygen and carbon monoxide also correlated with

Parameter	Units	All Cases
As-fired black liquor	tds/day	2895
Primary air	%	28
Secondary air	%	40
Tertiary air	%	32

I. Main boiler operational parameters (tds = tons of dry solids).

upper furnace temperatures. In general, low oxygen on one side of the boiler correlated with higher gas temperatures on the same boiler side; typically, the larger the boiler side-to-side oxygen and temperature differences, the more likely that carbon monoxide peaks were detected in the flue gas. The mixed splash plate and beer can operation was also observed to result in increased lower furnace temperatures as compared to the original operation with splash plates only. This observation is in line with the black liquor combustion becoming more concentrated toward the lower furnace and the char bed when using beer can nozzles.

MODELING

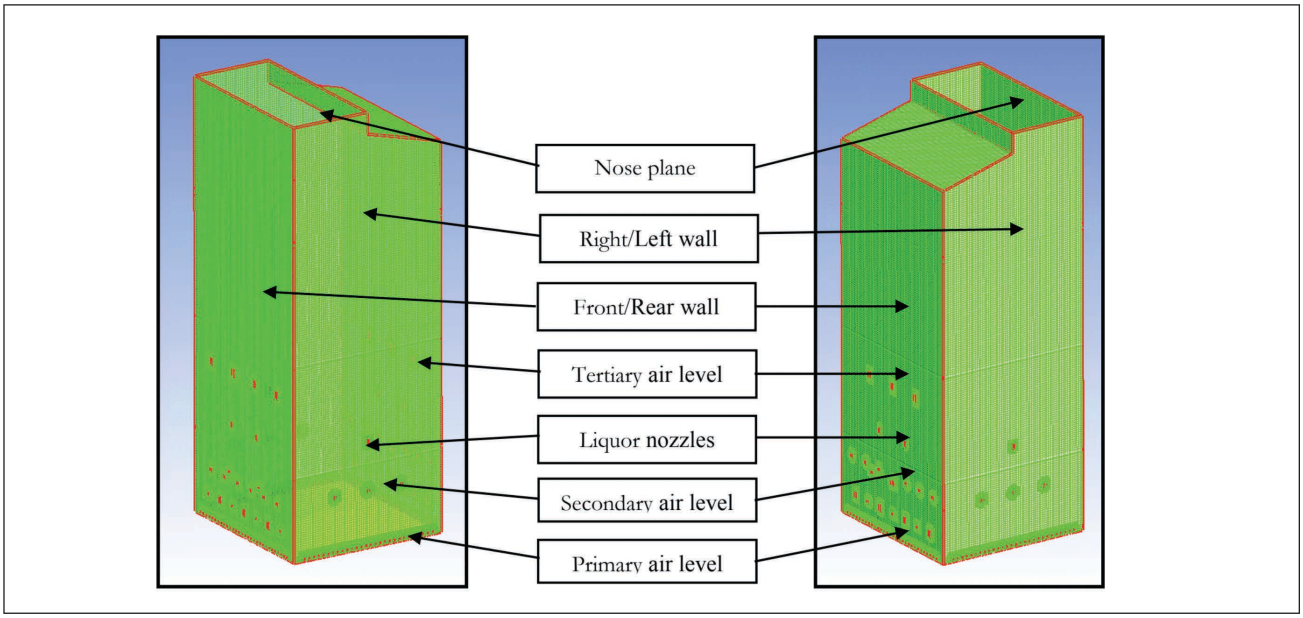
We performed steady-state 3D modeling of the lower furnace with the latest Ansys Fluent commercial codes [27] and in-house sub-models. The model is built with a reasonable number of elements. The viscous effects are modeled using a realizable k-epsilon turbulence model with standard wall functions.

We used an eddy-dissipation model for gas combustion and a discrete ordinates method for radiation heat transfer in the modeling. Liquor is injected as droplets. Water vapor and devolatilization gases are released from the droplet during flight, and the remaining combustible material (including water vapor, volatiles, and char carbon) are released when the droplet hits the char bed.

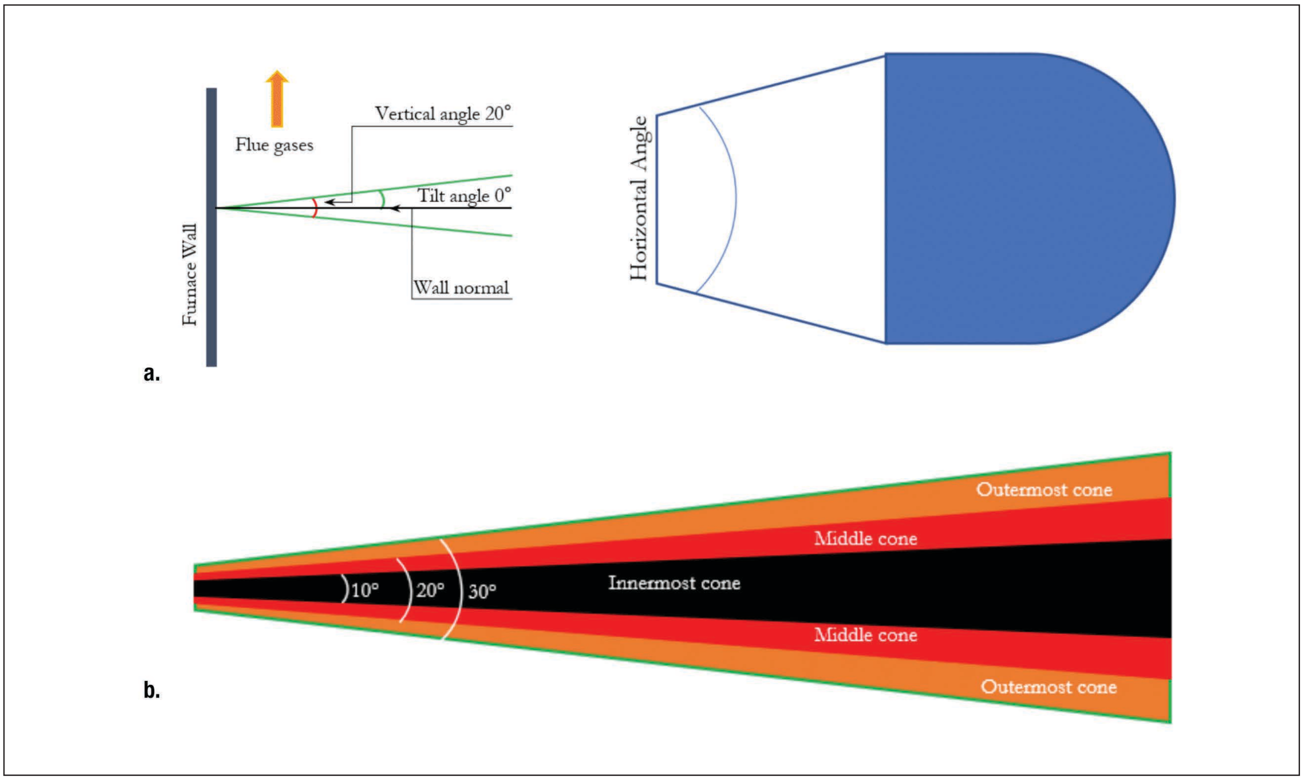
The main boiler operational parameters are shown in **Table I**. The relatively large furnace of width and depth approximately 12 m and height of approximately 32 m is modeled; the model starts 200 mm below the centerline of the primary air port and ends on the nose plane, as shown in **Fig. 5**. Combustion air is introduced from three main elevations; two of the levels, primary and secondary air, are located below the black liquor nozzles. The final level, tertiary air, is located above the black liquor nozzles. The secondary air is introduced as lower secondary and higher secondary. The amount of total combustion air and the air split between different air levels remain fixed for all simulation cases, as shown in Table I. This work focuses on the in-furnace processes, and the superheater area is not included in the modeling.

Spray modeling

The black liquor with high dry solids content is sprayed into the furnace as coarse droplets for both splash plate and beer can type liquor nozzles. The droplet size and the size distribution have been studied [28] both in the laboratory and in the field, mostly for splash plate nozzles with specific liquor and operating conditions. In this study, the droplet size and size distributions are not measured in the field. Instead, we generated the droplets using Rosin-Rammler distribution with an 8-mm average droplet size and spread parameter of 3 for all liquor nozzles; this input is estimated based on published spray data [29]. In addition, a sensitivity study was done for range of mean droplet sizes to understand the impact of the spray assumptions on model results. Using the same av-



5. Lower furnace isometric view.



6. (a) Splash plate spray inner angles, and (b) beer can spray inner angles.

erage droplet size for both splash plate and beer can nozzles was not found to impact the main findings of this work. The results from the sensitivity study are discussed in more detail in the Results section of this paper.

Droplets are assumed spherical in the model. The splash plate nozzle simply consists of the flat plate of a rounded cross-section attached at an angle to the end of a pipe. All splash plates are 34 mm in size, the horizontal liquor spray angle is 150°, the vertical angle is 20°, and the spray tilt is 0°. The reference plane and angles are shown in **Fig. 6a**. When the liquor exits from the end of the pipe, it strikes the flat plate and is flattened into a sheet of liquid. The sheet then leaves the plate and breaks into droplets.

Each beer can nozzle is modeled as a hollow cone with three layers and three cone angles: innermost 10°, middle 20°, and outer layer 30°, as shown in Fig. 6b. The tilt angle of the beer can is -70° downward. The process of spray formation, events of sheet formation, breakdown into ligaments, and subsequent breakdown into droplets are similar to those for a splash plate, though the shape of a beer can nozzle is quite different from that of a splash plate [30]. Since no published data are available about beer can spray droplet size distribution, we considered the droplet size distribution of beer can spray to be the same as that for splash plate droplet size distribution for the modeling purpose.

The droplets are injected 200 mm inside the furnace.

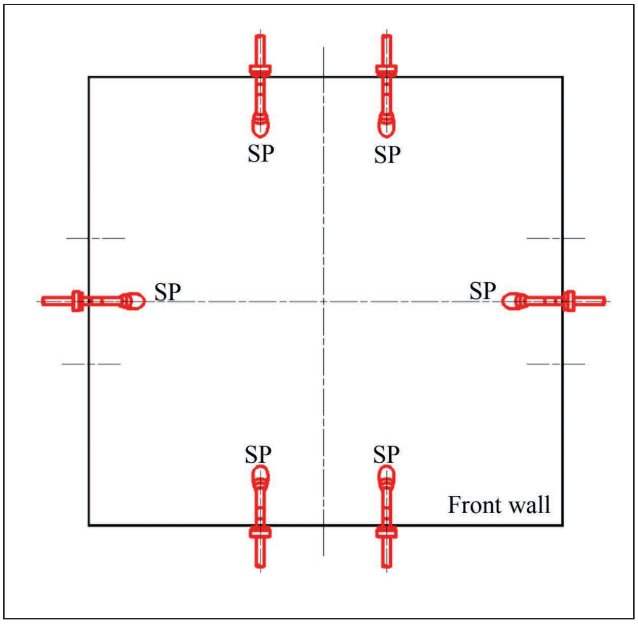
Parameter	Units	All cases
Black liquor dry solids	%	81.2
Density	kg/m^3	1443
Boiling point increase	°C	20.9
Spray temperature	°C	135.7

II. Liquor spray parameters.

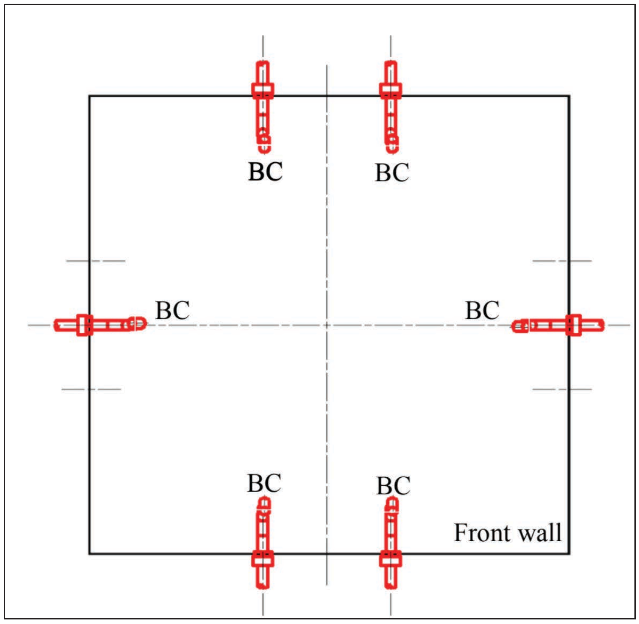
Black liquor composition and spray droplet size distribution parameters are maintained constant for all liquor nozzles, regardless of the type of nozzle used in the modeling, with the parameters shown in **Table II**. Droplet trajectories end when a droplet hits the bed or is entrained on the top of the furnace (nose plane), and the discrete phase conditions [31] for furnace walls are set to reflect the droplets during the calculation.

Simulation case: All splash plate type liquor spray (Case A)

The splash plate nozzles are placed as illustrated in **Fig. 7**. There are two nozzles on the front and rear walls. On each wall, the nozzles are placed on either side of the centerline, approximately 3 m apart. A single nozzle is placed on each side wall, each positioned at the centerline.



7. Case A: All splash plate (SP) spray.



8. Case B (simplified): All beer can (BC) type spray.

Simulation case: All beer can type liquor spray (Case B)

The all-beer-can case (Case B) is modeled similarly to Case A, with the difference being that all nozzles are beer can type. The placement of the nozzles is summarized in **Fig. 8**.

Simulation cases: Mixed splash plate and beer can type liquor nozzles (Cases C1-C3)

We modeled different scenarios of mixed splash plate and beer can operation, as shown in **Fig. 9**. All scenarios included two beer can nozzles in combination with four splash plate nozzles. The scenarios differ in the placement of the beer can nozzles. In the first scenario (C1), one beer can nozzle is placed on each boiler side wall. This scenario corresponds to the actual mixed nozzle operational situation at the boiler. Additional scenarios were simulated as a sensitivity study; we had not tested these scenarios in actual boiler operation. In the second scenario (C2), the beer can nozzles are placed on the front wall. In the third scenario (C3), the beer can nozzles are placed on the boiler rear wall.

RESULTS AND DISCUSSION

First, model sensitivity to droplet size is discussed followed by the main findings of model results in terms of differences in the predicted in-furnace processes between the simulation Cases A-C. We also discuss the results relative to the observations from actual boiler operation. The focus is on the impact of spray nozzle type on carryover, furnace temperatures, and bed burning stability.

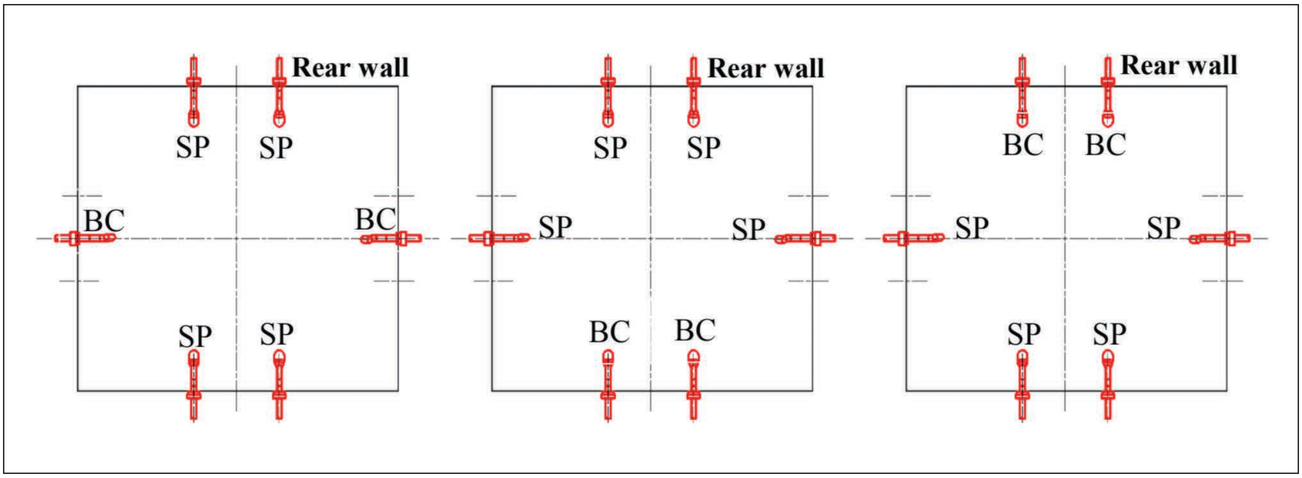
Model sensitivity to droplet size

The sensitivity of the model predictions to the average droplet size is briefly discussed here for the cases of all splash plate and all beer can modeling. To study the impact of average droplet size on model predictions, simulations are carried out where the mean droplet size is varied in the range of +/- 2 mm relative to the assumed mean droplet size of 8 mm. **Figures 10 and 11** show the temperature close to the char bed for simulation cases of all splash plate nozzles and all beer can nozzles, respectively. The temperature pattern near the char bed remains relatively similar for a range of mean droplet sizes. However, there is clear difference in the char bed temperature distribution between the splash plate and beer can cases. The temperature above the char bed is interpreted as an indicator of char bed stability in this work. In the all the splash plate cases, the temperature above the char bed remains relatively uniform and high, independent of the mean droplet size, which in this work is interpreted as stable char bed operation. In contrast, in the all beer can cases, the temperature above the char bed remains relatively nonuniform with locally low temperatures, independent of the mean droplet size, which in this work is interpreted as a sign of unstable char bed operation.

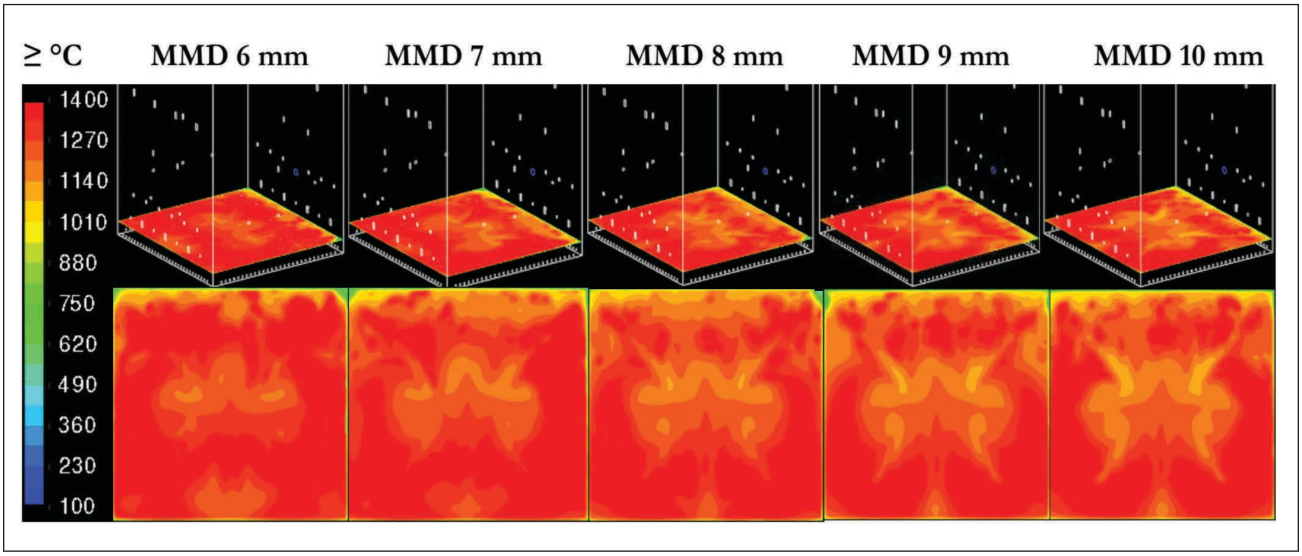
The droplet carryover is clearly sensitive to the mean droplet size, as shown in **Fig. 12** for both splash plate and beer can. Interestingly, the carryover for splash plate with mean droplet size of 10 mm is almost the same compared to the beer can spray with mean droplet size of 6 mm. The type of spray is influencing the predicted carryover more than the mean droplet size variation within a range of +/-2 mm.

Gas flow patterns, fate of droplets and carryover

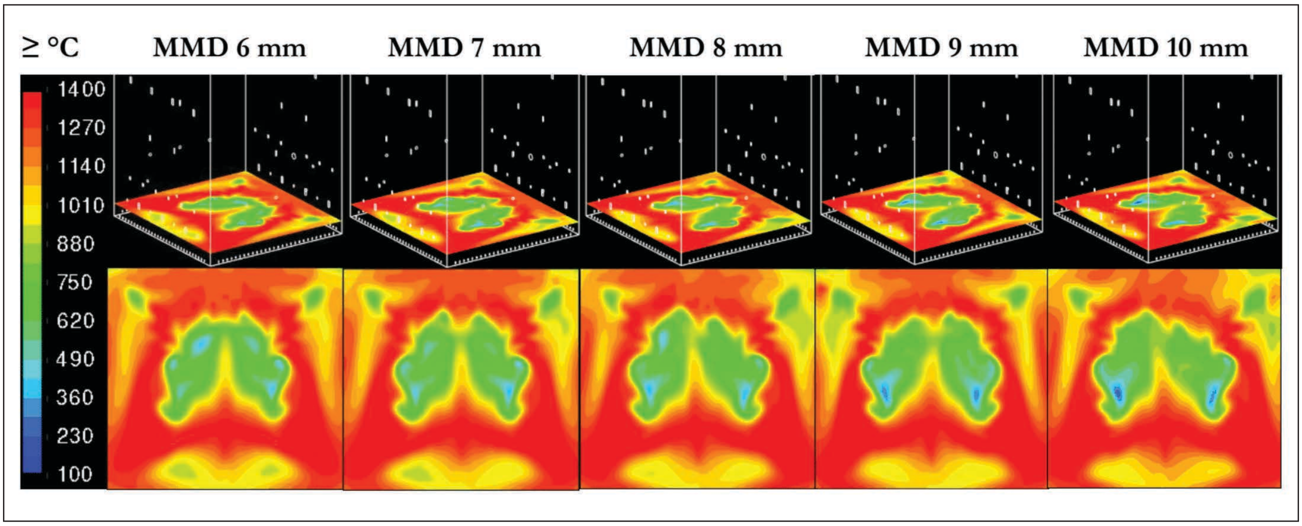
In all simulation cases, flue gas flow is slightly pushed toward the front wall and a small degree of recirculation ap-



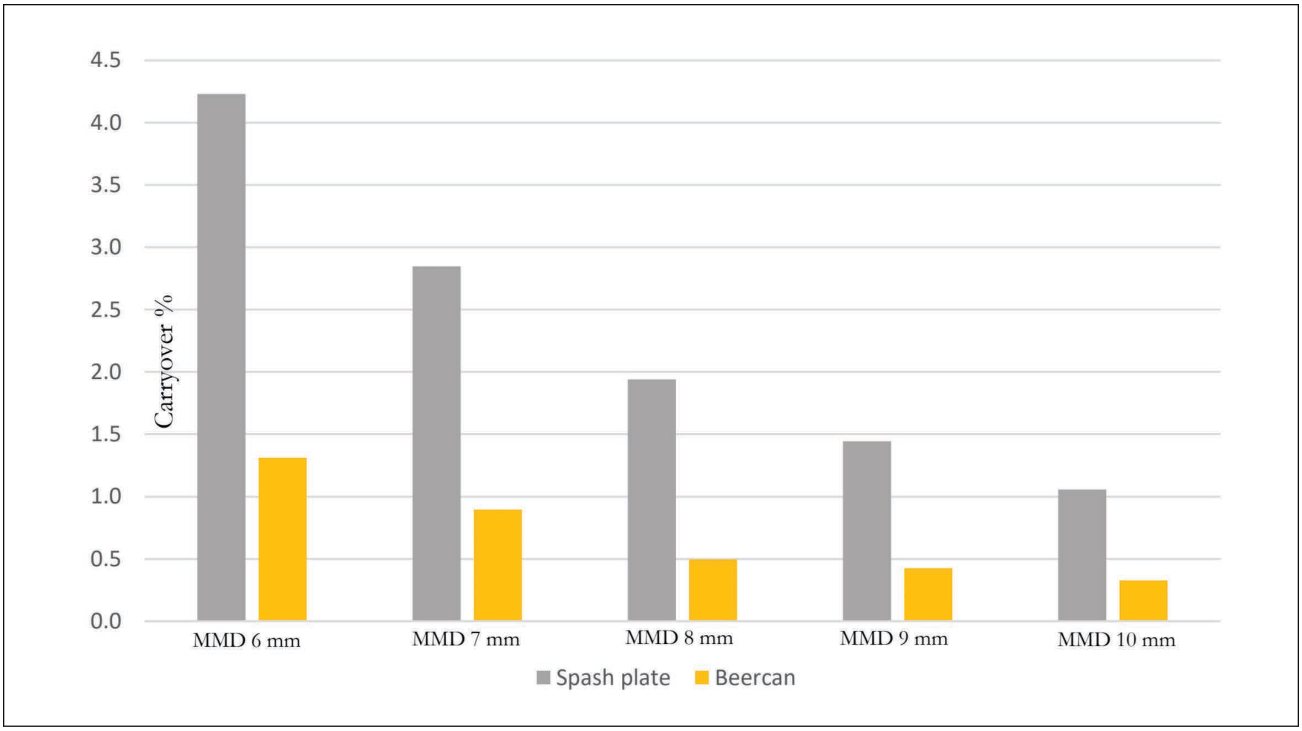
9. Splash plate (SP) and beer can (BC) combined operations: Case C1, Case C2, and Case C3.



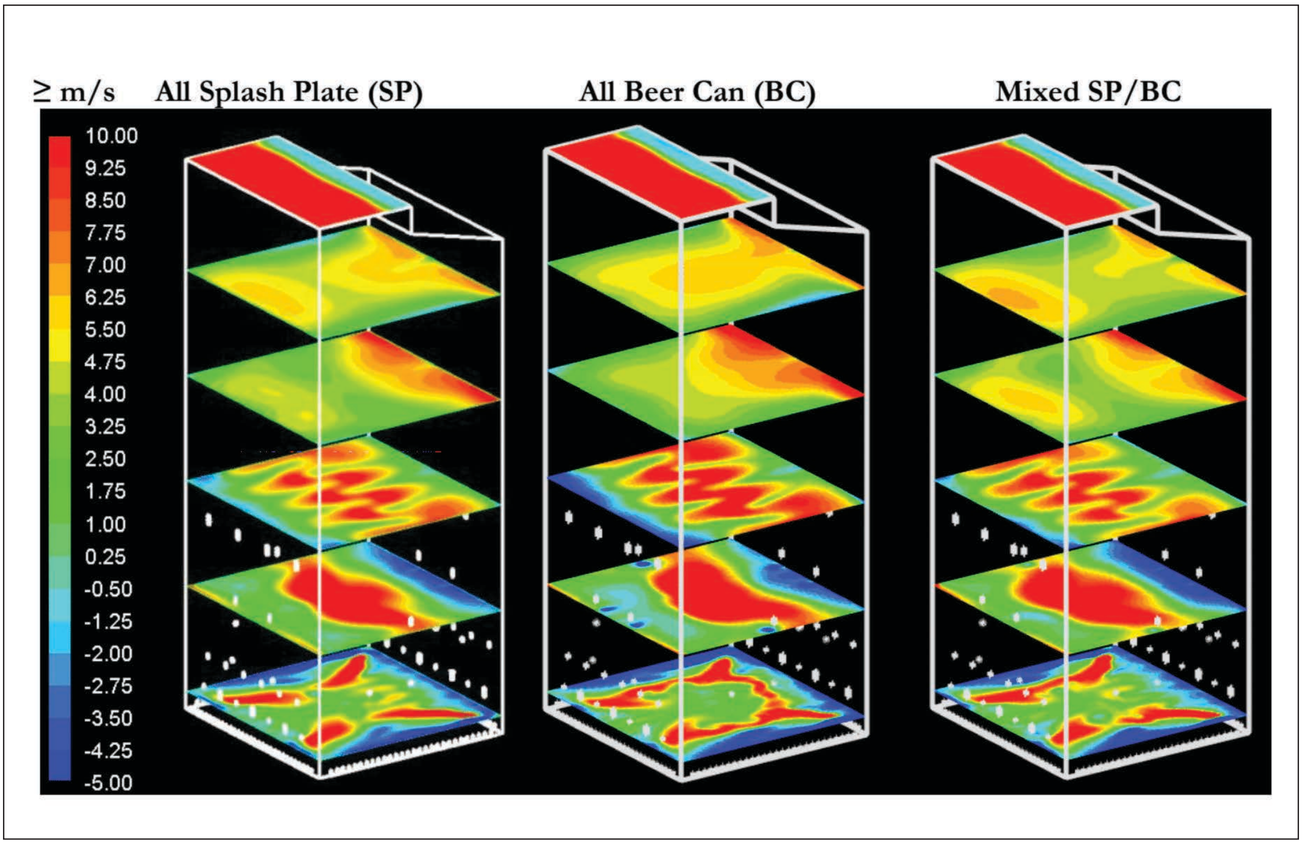
10. Temperature inside furnace with all splash plate nozzles for the range mean droplet size (MMD = mass median diameter).



11. Temperature inside furnace with all beer can nozzles for the range mean droplet size (MMD = mass median diameter).



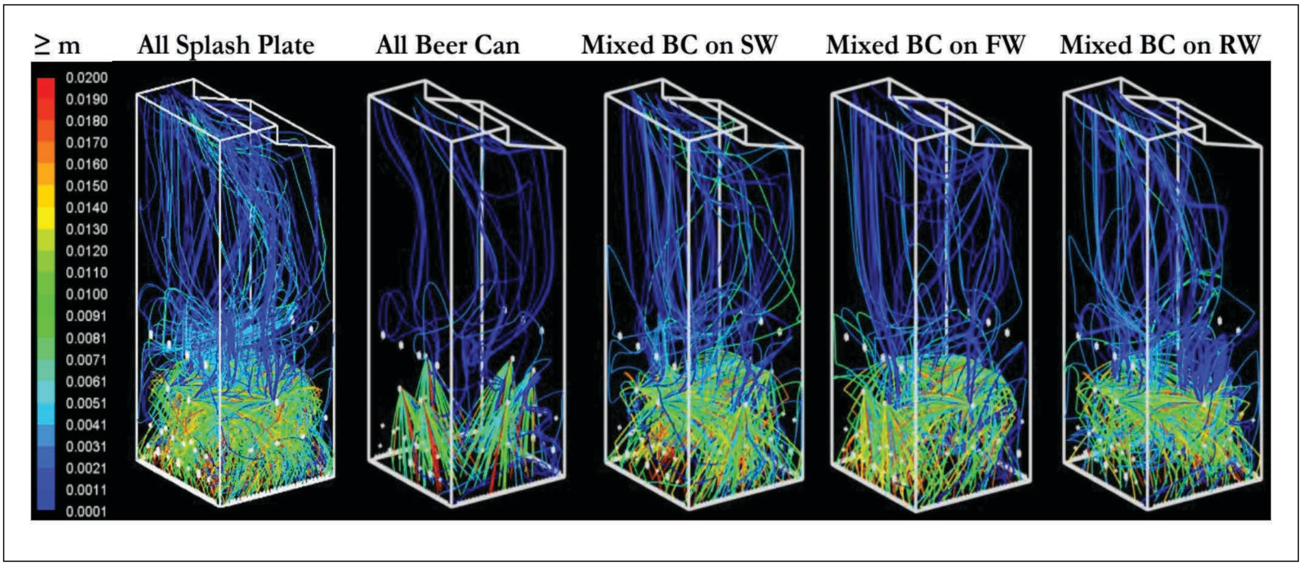
12. Results show that droplet carryover is sensitive to mean droplet size for both splash plate and beer can spray (MMD = mass median diameter).



13. Vertical velocity counter for the three simulation cases: all splash plates, all beer cans, and mixed splash plate/beer cans.

Parameter	Splash Plate		Beer Can		Mixed Beer Can on Side Walls		Mixed Beer Can on Front Wall		Mixed Beer Can on Rear Wall	
Unit	**kg/s**	**%**	**kg/s**	**%**	**kg/s**	**%**	**kg/s**	**%**	**kg/s**	**%**
In flight conversion to gas phase	11.8	28.5	5.7	13.8	9.8	23.8	9.9	24.0	9.8	23.6
Droplet to bed	28.7	69.6	35.3	85.7	30.8	74.7	30.9	74.9	30.9	74.9
Carryover	0.8	1.9	0.2	0.6	0.6	1.4	0.5	1.1	0.6	1.5

III. Comparison of carryover and droplets with the different spraying conditions.



14. Droplet trajectories: all splash plate (SP), all beer can (BC), and mixed operation nozzles (FW = front wall; RW = rear wall; SW = side walls).

pears on the rear wall close to the liquor guns, as shown in **Fig. 13**. These modeling results are in line with observations from the boiler.

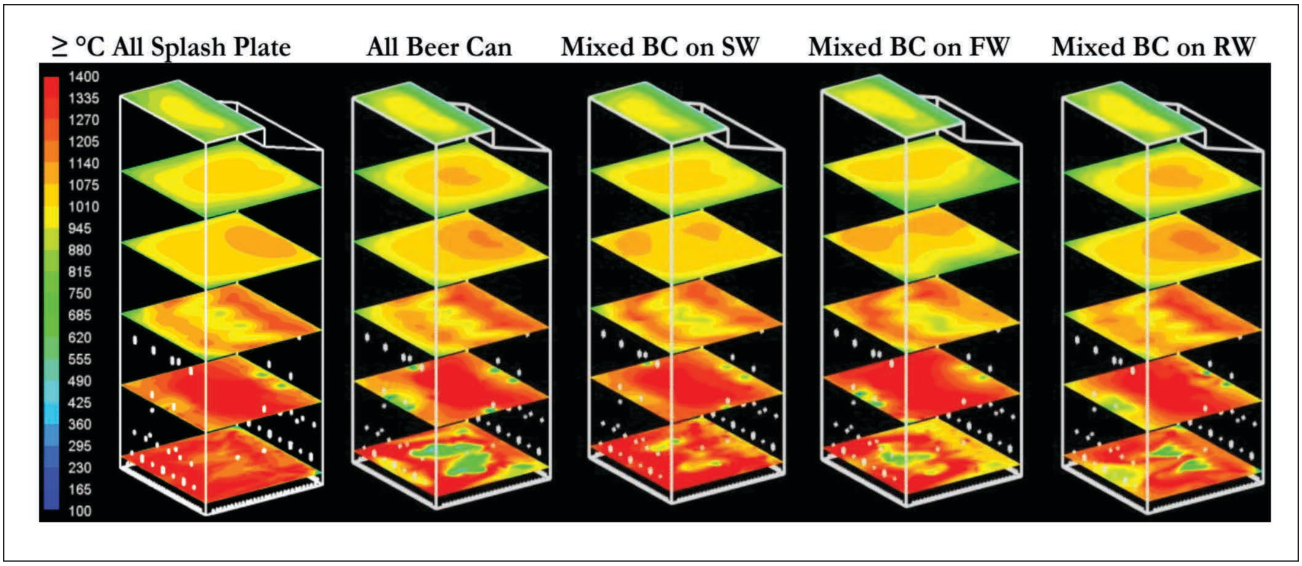
In all cases, the local high velocity flue gas seen at the center of the furnace contributes to the entrainment of the droplets, resulting in carryover. In **Table III**, carryovers for the different spraying conditions are compared with with each other. While carryover and droplet hits on the walls were high when only splash plate nozzles were used, they were significantly reduced when beer cans were used. The all-beer-can-type modeling yielded the lowest carryover and the highest share of droplet mass fraction reaching the char bed. The mixed beer can and splash plate models showed moderate carryover.

The location of the beer can nozzles during the mixed splash plate and beer can modeling had an impact on carryover. Beer cans on the front wall had lower carryover than the other two scenarios of beer cans on the side walls and rear wall. The connection between the flue gas flows and carryover are seen when comparing the mixed-operation scenarios of placing the two beer can nozzles on either the front or the rear wall. As seen in Fig. 13, the flue gas flow is directed more toward the bullnose close to the front wall. Placing the beer can nozzles on the front wall reduces carryover to a greater degree than placing beer cans on the rear wall where the gas flow is not as strongly directed upwards. The smaller droplets of <3 mm were predominantly entrained by the flue gas flow irrespective of the type of spray used in the modeling, as shown in **Fig. 14**.

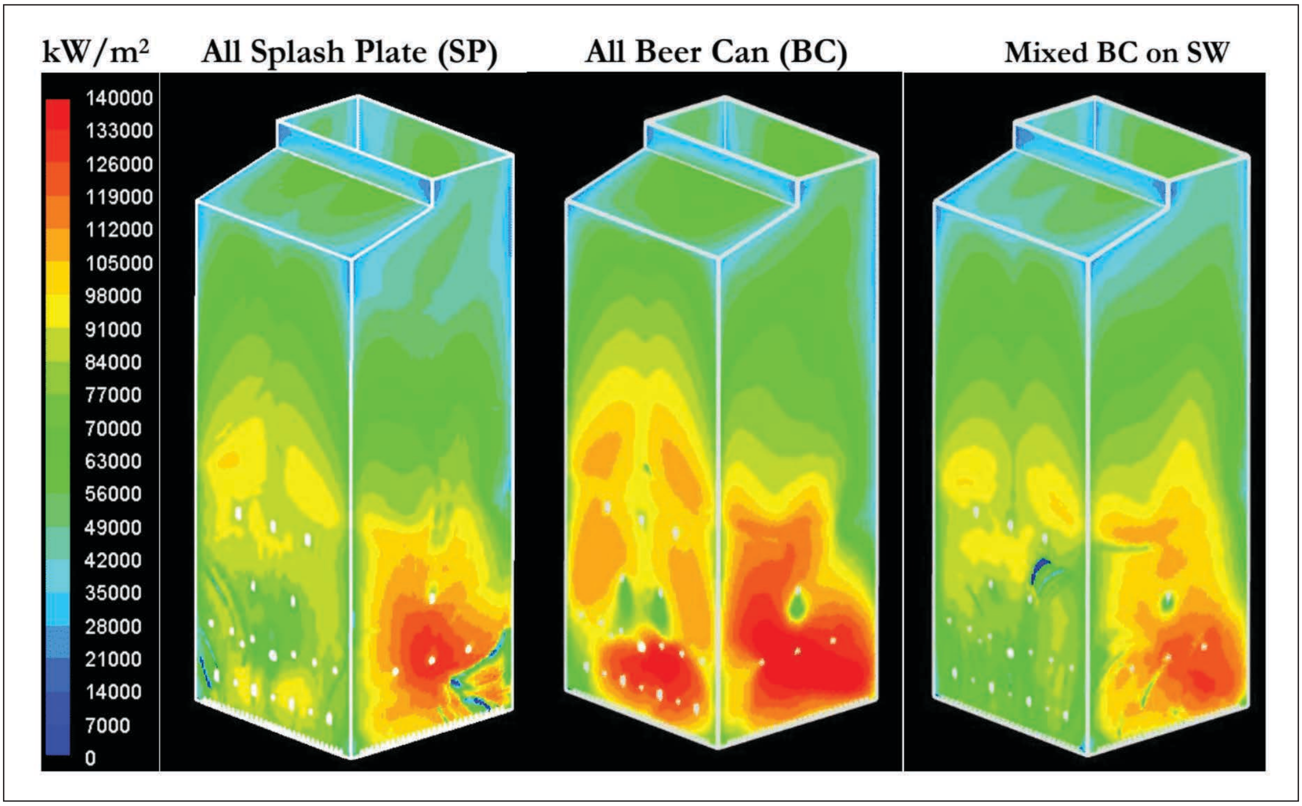
Figure 14 illustrates the clear differences in droplet trajectories. With splash plates only (Case A), the droplets travel a longer path compared to those from the beer can spray. Additionally, the distribution of liquor droplets is more uniform in splash plate operation, indicating good mixing and combustion at the secondary air level. For beer cans only (Case B), the droplets are landing more directly on the char bed, and the length of the liquor path appears shorter.

Furnace temperatures and char bed stability

As seen in **Fig. 15**, the temperature distribution immediately above the char bed was uniform in the case of splash plates only (Case A). The temperature distribution



15. Temperature inside furnace for all splash plate (SP), all beer can (BC), and mixed operation nozzles (FW = front wall; RW = rear wall; SW = side walls).



16. Heat flux on walls for all splash plates, all beer can, and mixed splash plate/beer can nozzles.

was significantly affected by the beer can liquor spray (Case B) due to the pattern of liquor distribution and droplet burning. In the case of the all-beer-can spray model, the droplets were landing in a concentrated pattern toward the center of the char bed. Poor distribution of liquor spray causes low-temperature spots on/near the char bed. The three modeled scenarios of mixed operation had reasonably good liquor distribution and uniform temperature near the char bed, with the beer cans on side walls exhibiting the most uniform temperature distribution. The trends observed in the model correspond to the observations during the actual boiler operation. We observed that using all beer cans resulted in unstable char bed operation, while we also observed that the original operation using all splash plates, as well as operating with mixed splash plates and beer cans, resulted in stable bed operation.

Heat flux in the lower furnace, particularly near the primary air level and the smelt spot area, was high in the case of all-beer-can-type spray modeling (**Fig. 16**). The cases using only splash plates and mixed nozzle types showed lower and more uniform heat fluxes.

CONCLUSIONS

This work discussed a boiler experiencing upper furnace plugging and availability issues. Characteristic features include relatively high carryover and left-right asymmetric flue gas flows, as well as plugging in the superheater area, resulting in unscheduled shutdowns of the boiler.

To improve the situation and increase boiler availability, we tuned/modified the liquor spray system by testing different combinations of splash plates and beer cans. This work considered a furnace with a floor area of 100 m^2 firing dry solids > 80%. Tested cases included: 1) all splash plate (original operation) nozzles, 2) all beer can nozzles, and 3) mixed splash plate and beer can nozzles, with splash plates on the front and back wall and beer cans on side walls.

In general, the beer can liquor guns resulted in lower carryover. However, using only beer can nozzles resulted at times in unstable smelt flows, unstable char bed behavior, and in some cases, an increase in the asymmetric combustion and flue gas flow. Operating with splash plates on the front and back walls in combination with beer cans on the side walls in the end resulted in improved overall boiler operation, compared to the original condition of using splash plates only. However, using beer cans may affect the lifespan of the lower furnace due to higher heat flux around the primary air port openings and smelt spout openings; this phenomenon needs to be further assessed.

We conducted CFD modeling of the boiler for a better understanding of the impact of black liquor nozzle type on predicted in-furnace processes. We studied three cases, corresponding to the cases tested at the mill and listed previously.

We found some of the model predictions to be in line with the actual results from the boiler. Simulation using only beer can nozzles resulted in a clear reduction of carryover. At the same time, this case yielded uneven predicted char bed temperature and heat flux on the walls. These predictions can be interpreted to be in line with the actual results from the boiler, which showed bed instability when using beer can nozzles only.

Compared to the original operation of using splash plate nozzles only, the model predictions using mixed splash plate/beer can nozzles showed lower carryover but without excessive lowering of gas temperatures close to the char bed. **TJ**

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About this journal

ABOUT THE AUTHORS

We wanted to study and understand efficient, stable, and safe operation of kraft recovery boilers with CFD modeling and operational feedback. The present work is a case study of a relatively large operating boiler experiencing upper furnace plugging and availability issues. In-furnace camera inspection and actual operational experiences from the boiler were discussed in comparison with CFD model predictions to gain additional insight into the details of the furnace processes and behavior.

Understanding the real-time combustion behavior with different spray options was challenging. The CFD modeling helped to get the additional insight into the furnace processes.

We learned that a mixed set-up of splash plate and beer can nozzles showed lower carryover, but without the excessive lowering of gas temperatures close to the char bed. Interestingly, using beer can nozzles (with splash plate) may affect the lifespan of the lower furnace due to higher heat flux around the primary air port openings and smelt spout openings. This phenomenon needs to be further assessed.

For mills, CFD modeling can be used for a better understating of boiler processes and furnace behavior with different liquor spray scenarios before actual modifications.

Also, the most suitable liquor spray scenario can be identified with CFD modeling in terms of number/type/location of splash plate nozzles and beer can nozzles. The case studies can be extended for optimized liquor firing options. The next step is to improve the prediction of liquor droplet size distribution and validation of the carryover.

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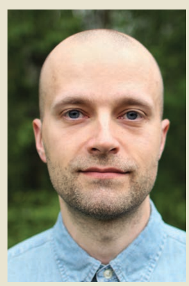

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