ADVANCED COMBUSTION AND FLOW MODELING: COMPREHENSIVE MODEL STUDY IMPROVES RECOVERY BOILER OPERATION

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ABSTRACT

A Kraft recovery boiler was experiencing steam temperature degradation due to excessive fouling of the convection surfaces, leading to plugging within the generating bank. Build-up of deposits on these surfaces required the unit be taken off line for water wash cleaning after eight to ten weeks of operation.

Numerical combustion modeling was used to evaluate current boiler operation and assess the benefits of changes in operation and hardware required for improved operation. The Babcock & Wilcox Company's Combustion Model for Process Recovery boiler (COMO-PR™) was used to evaluate the boiler operation and design. This model is based on a fundamental description of interacting processes of turbulent flow, heat transfer and black liquor combustion [1,2]. Modeling of the boiler, as it was operated, showed a strong side-to-side imbalance in the gas flow and temperatures within the furnace, and a large amount of mechanical carryover that was adversely affecting boiler operation. Boiler testing and operating experience qualitatively confirmed model predictions.

The model was used to evaluate different methods of introducing air and liquor to improve flow uniformity and reduce the amount of inorganic material entrained by the combustion gases as carryover and fume. A significant improvement was predicted and then achieved, with simple operational and hardware changes to the existing air and liquor systems. A combination of firing strategies and operation of the secondary air ports to better interlace secondary air improved flow uniformity and reduced the predicted amount of carryover by 60%. The amount of fume generated increased slightly, but chloride content in the ash was lower and was easier to remove by sootblowing.

The functional performance of the unit was modeled relative to the superheater surface requirements. Modeling based on the operational history indicated that additional surface would be required to attain design steam temperature throughout a six month operational span.

BACKGROUND

The subject recovery boiler is a Babcock & Wilcox (B&W), single drum unit, installed and started up in 1989. It was sized for 1500 tonnes (3,300,000 lb) of dry black liquor solids per day, generating 63.7 kg/sec (505,000 lb/hr) of steam at 6136 kPa (875 psig) and 441C (825F). The unit was installed with some excess capacity for future expansion, and generally operates at about 80 to 85 percent of its rated capacity. Loading does fluctuate pending production levels in the mill. A schematic of the boiler is shown in **Figure 1**.

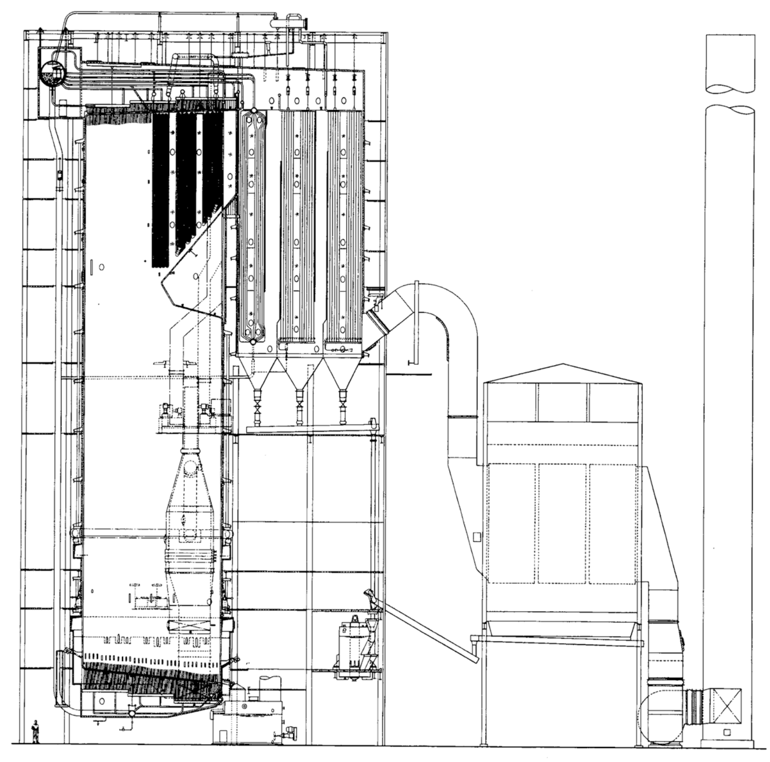

Figure 1. B&W Recovery Boiler.

Historically, the unit has experienced excessive superheater and generating bank fouling. From a start-up after a water wash and operating at about 85 percent of fuel firing capacity, the unit would make steam temperature and attemperate for about 2-3 weeks. Over a total span of 8-10 weeks, the steam temperature typically declined to about 400C (750F), at which time it was necessary to water wash the unit due to low steam temperature at the turbine. In addition, at about this same span, the boiler bank would be severely fouled which would have dictated washing had the superheater not done so.

In the fall of 1996, the mill approached B&W about working together to review the unit performance and define the actions that would be necessary to achieve six-month runs between water washes, while maintaining the steam temperature at the design conditions of 440C (825F),

Table I is a summary of some of the unit's key design parameters. Liquor firing was accomplished in the suspension mode using one plate type nozzle in the center of each wall. Firing solids were in the 70-72% range. The air system was three level, sized for a 40%, 50%, 20% of total air distribution of primary, secondary and tertiary, respectively. Overall, furnace sizing was conservative, as the 865C (1589F) furnace exit gas temperature and the 2444.5 kW/m^2 (775,000 Btu/hr-ft^2) plan area heat release rate indicates.

An operating history review indicated that the unit had experienced excessive carryover in the suspension firing mode. Operational changes to increase wall drying and tertiary air to the maximum did reduce carryover, and added stability to the lower furnace. Carryover remained excessive, however, relative to fouling rates. Liquor composition remained relatively constant over the operating history span except for the chloride content, which increased from 0.02% to 0.95%, on a dry basis. The complete analyses are shown in **Table II**.

Upon completion of the review it was concluded that, based on the fouling characteristics of the liquor, the superheater surface was insufficient and carryover would have to be reduced. Since liquor admission alternatives had not, in and of itself, reduced carryover to tolerable levels; further reductions, if achievable, would lie in air system modifications. Prior to actual hardware changes, the unit would be modeled with the existing air system and superheater surface. Various modifications would be modeled including new superheater arrangements, the results would be reviewed and the final modifications would be mutually decided based on the model predictions.

Table 1. Summary of key design parameters.

	Unit Design Parameters	As Modified
Width, m (ft)	9.4 (30.92)	
Depth, m (ft)	10.8 (35.42)	
Plan Area, kW/m^2 ($Btu/hr\text{-}ft^2$)Heat Release	2444.6 (775,000)	
Furnace Exit Gas Temp, C (F)	865 (1590)	
Boiler Bank Inlet Gas Temp, C (F)	643 (1157)	578 (1074)
Superheater Surface, m^2 (ft^2)	4189 (45,091)	6782 (73,000)
Primary Air Flow, percent	40	35
Secondary Air Flow, percent	50	39
Tertiary Air Flow, percent	20	26
Liquor Guns	4 (one center of each wall)	4 (one center of each wall)
Firing Solids, percent	70	70
Firing Method	Suspension	Suspension/Wall

Table 2. Analysis of liquor properties.

Compound, percent weight	Design	Operating	Current
Na	20.42	19.70	20.06
C	35.79	37.10	34.68
H2	3.67	5.10	3.83
S	4.73	4.57	4.66
02	33.56	30.60	34.43
K	1.81	1.97	1.80
CI	0.02	0.95	0.46
Inert	0.00	0.00	0.00
HHV, kJ/kg (Btu/lb)	14,411 (6200)	14,579 (6280)	13,553 (5831)

SUPERHEATER ADDITION

The superheater modification consisted of adding a large radiant platen in front of the existing superheater and arch as shown in **Figure 2**.

In consideration of the high chlorides, it was desirable to reduce the gas temperature entering the generating bank to as low as practical. Referring to Table 1, the original superheater surface was 4189 m^2 (45,091 ft^2) and the design gas temperature entering the superheater was 865C (1590F). The minimum surface addition required to bring the steam temperature back to design level with the current fouling characteristics was calculated to be 920 m^2 (9909 ft^2) or plus 22%. A larger superheater was selected containing an additional 2592 m^2 (27,909 ft^2) or 62% more surface area, This larger superheater absorption lowered the predicted boiler bank inlet gas temperature from 643C (1157F) to 579C (1074F).

The new superheater bank was made the first bank in the steam flow path using saturated steam to reduce the corrosion potential on the lower loops. In addition, the lower loops exposed to direct furnace radiation were supplied with alloy materials to further resist corrosion. The original primary and secondary banks became the new secondary and tertiary. A new attemporator was located between the new primary and the original primary superheater banks to control the steam temperature entering the original superheater to within the design limits.

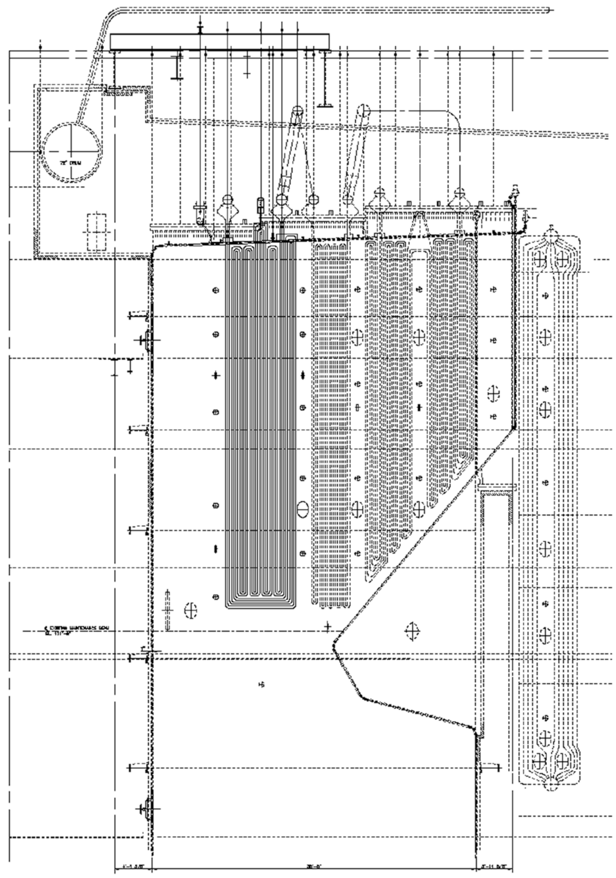

Figure 2. Superheater addition.

MODEL DESCRIPTION

Combustion modeling of a recovery boiler is used to simulate black liquor combustion. The model used in this study is based on a fundamental description of various interacting processes of turbulent flow, chemical reactions, and heat transfer [1] The essential components of the model are shown in **Figure 3**. A fully coupled solution is achieved with all of these elements. The ability to predict furnace flow and temperature distribution is needed to evaluate air system design and operation. The ability to simulate combustion processes on the walls and char bed is also needed to understand and evaluate alternate firing strategies. Predictions of the fume formation and carryover are needed to evaluate fouling and plugging of convection surfaces. The model used in this study is the most comprehensive available for such analysis. Details of this model including recent technical enhancements have been described in recently published technical papers [1-4].

Development of combustion modeling as a tool to evaluate changes in operation and design of recovery boilers was not complete at the time this unit was originally designed. Recent improvements in computer processing speed, coupled with fundamental research by universities, have improved the capabilities and cost effectiveness of modeling as both a design and operating tool for recovery boiler applications.

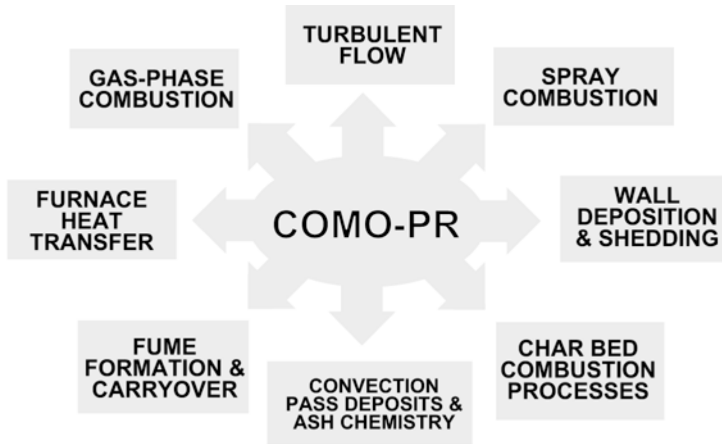

Figure 3. Combustion model for process recovery boilers.

APPROACH TO MODELING

The base case model of the boiler was set up using operating data measured during stable operation over about an 8-hour period. Individual air port, burner port and furnace parameters were measured and recorded to provide inputs into the model for mass flow, velocity, and temperatures. Observations of upper furnace conditions such as carryover bias, temperature profiles, long-term trends of steam temperature decay and operator comments were recorded. A high degree of mechanical carryover was noted on the left-hand side of the furnace at the nose arch observation doors.

Black liquor samples were collected to determine elemental analysis and heating value. Liquor parameters (temperature, pressure and flow rates) and firing arrangements (gun position, orientation and nozzle design) were provided as inputs to the model. The initial droplet size distribution was calculated from mass and momentum balances for the black liquor sheet leaving each splash plate. Twelve discrete size groups approximated the distribution of flow and drop size for each liquor gun (**Figure 4**).

The geometry of the unit was modeled using 85,854 active control volumes to represent the furnace and convection surface. Variable grid resolution was used to resolve areas around air jets in the secondary and tertiary air systems.

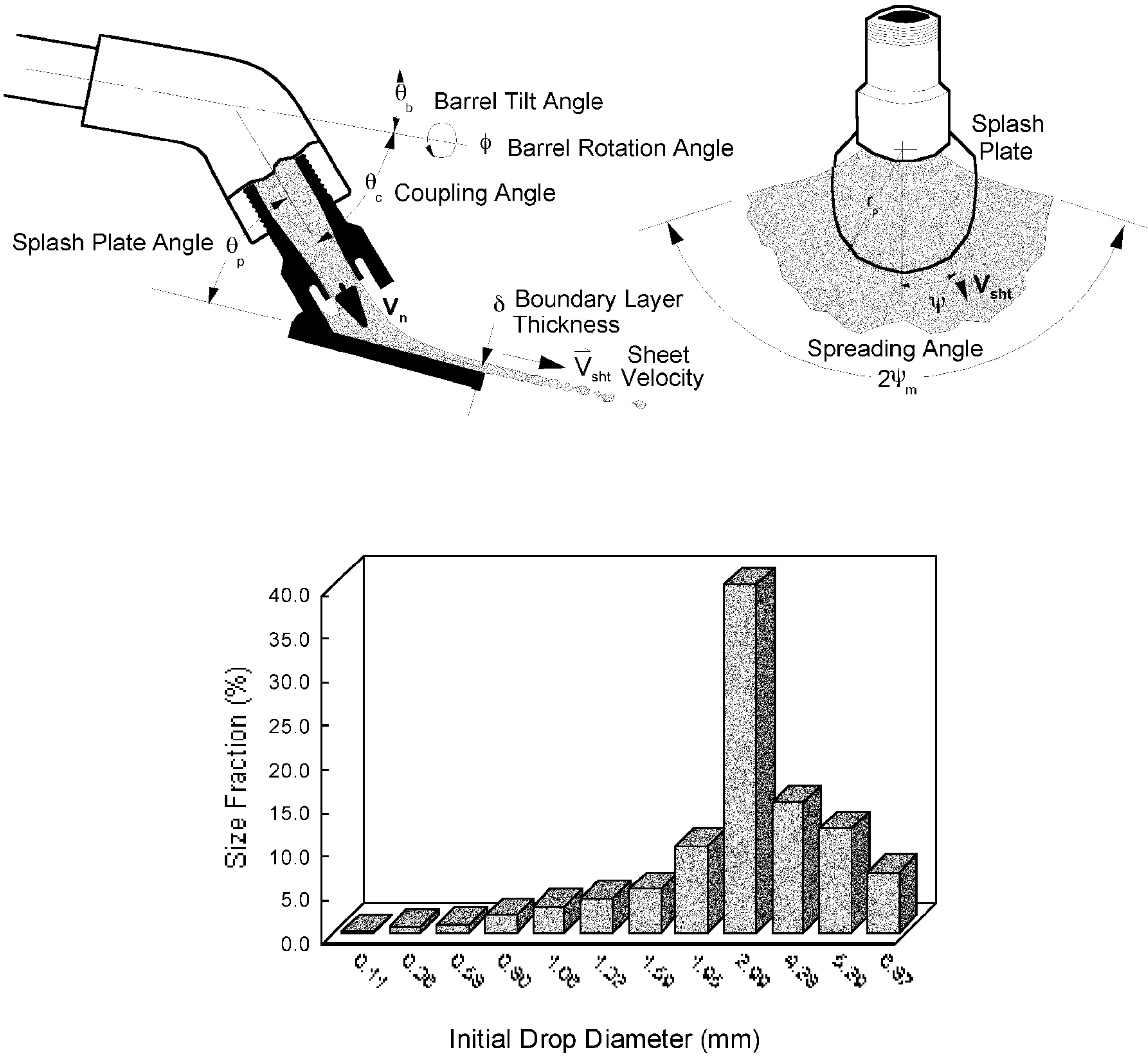

Figure 4. Black liquor flow and drop size distribution leaving splash plate nozzle.

BASE CASE MODELING RESULTS

The purpose of modeling the base case (existing operation) was to evaluate the current operation of the boiler and verify the results with observations and data obtained under actual conditions. Results of this modeling could then be used to diagnose potential operational and design deficiencies and correct these with the most cost-effective changes. The arrangement of air and liquor guns is shown in **Figure 5a**.

The results of this modeling identified a strong upward flow region in the center of the furnace and a downward flow region near the side walls. This result is typical of units operating with secondary air introduced from more than two walls, and is the result of opposing air jets colliding in the center of the furnace and deflecting upward (**Figure 6a**). Regions of high upward velocity correspond to areas of high carryover and high temperature. Recirculating flow patterns as predicted by the model were confirmed by observations of downward flow at the liquor gun ports. The base case model also showed that spacing of the tertiary air ports was too close to allow jets to penetrate the furnace without interference (**Figure 7a**), making the tertiary less effective at breaking up and redistributing the strong central core. This resulted in the high gas temperature and vertical velocity shown in the modeling results in **Figures 8a and 9a**. Observations of the upper furnace confirmed brighter gases on the left hand side wall at the tertiary air level. Upward flow in the left rear corner impinges on the underside of the bullnose and is redistributed to the right side of the boiler as it enters the superheater. The mill reported the build-up of deposits in this region as predicted in the model.

Predictions of mechanical entrainment (carryover) leaving the furnace correspond to the areas showing the highest upward velocities in the furnace as shown in **Figure 10a**. The location of the highest mechanical carryover observed in the unit corresponded to the locations predicted by the model.

Based on the results of the base case, it was decided that changes in operation and/or design would be investigated as a means to improve furnace operation. The goal was to recommend changes in operation and design to the existing air system that would eliminate gas flow imbalances, reduce carryover, and improve cleanability of the boiler.

UNIT OPTIMIZATION THROUGH MODELING

Modeling included investigation of nine different operation and air system arrangements. Alternative locations for air ports, damper positions and liquor firing strategies (suspension/wall drying) were evaluated relative to the improvement versus cost of modification. Results of the model case representing the recommended changes and the improvement to operation are included in this paper.

The base case results were used in selecting the alternatives investigated in the study. Changing the damper settings within the secondary air system (see **Figure 5b**) required no hardware change to the unit, and effectively eliminated the imbalances in the lower furnace, resulting in a reduction in mechanical carryover. Complete redesign of the secondary air system was studied, but provided little additional benefit to that of simple operational changes to the existing design.

Additional investigation suggested that an alternative arrangement and operation of the tertiary air system would improve boiler operation further by increasing the penetration of the tertiary air into the furnace. By reusing the existing hardware, the changes to the tertiary air system required moving four existing air ports, leaving three in the same position and adding three air ports (see Figure 5b). This arrangement permitted operation with essentially a 3-2 interlaced tertiary air system and reduced the interference of air jets. The five additional air ports allow for higher tertiary air flows (up to 30% of total air) to be added without interfering with the interlaced ports at higher boiler loads or increased tertiary air flows.

Liquor gun arrangement was also optimized to improve liquor distribution and minimize piling near the center of the char bed.

Comparison of the results of base case with the installed optimized case is shown in Figures 6-10. Secondary air jets penetrate about 70% across the furnace and vortices are created between pairs of opposing jets to promote mixing (**Figure 6b**). The distribution of vertical velocity at the liquor gun elevation is significantly more uniform (Figure 8b). The new arrangement of tertiary air ports reduced jet interference and improved flow stability in the upper furnace. The flow and temperature distribution in the upper furnace is balanced side-to-side and more uniform at the furnace exit (**Figures 8b and 9b**). Predicted gas temperatures were reduced by 44C (80F) at the furnace exit (Figure 9b). Predicted carryover was reduced to less than 20% of that predicted by the base case operation (**Figure 10b**).

PERFORMANCE IMPROVEMENT RESULTS

Comparative results of the modeling indicated that changes to the secondary air system operation would provide a significant improvement to the side-to-side imbalances in the furnace. Reducing the interference in secondary air jets was investigated after modeling and before making any hardware change by alternately opening and closing dampers at the secondary air zone.

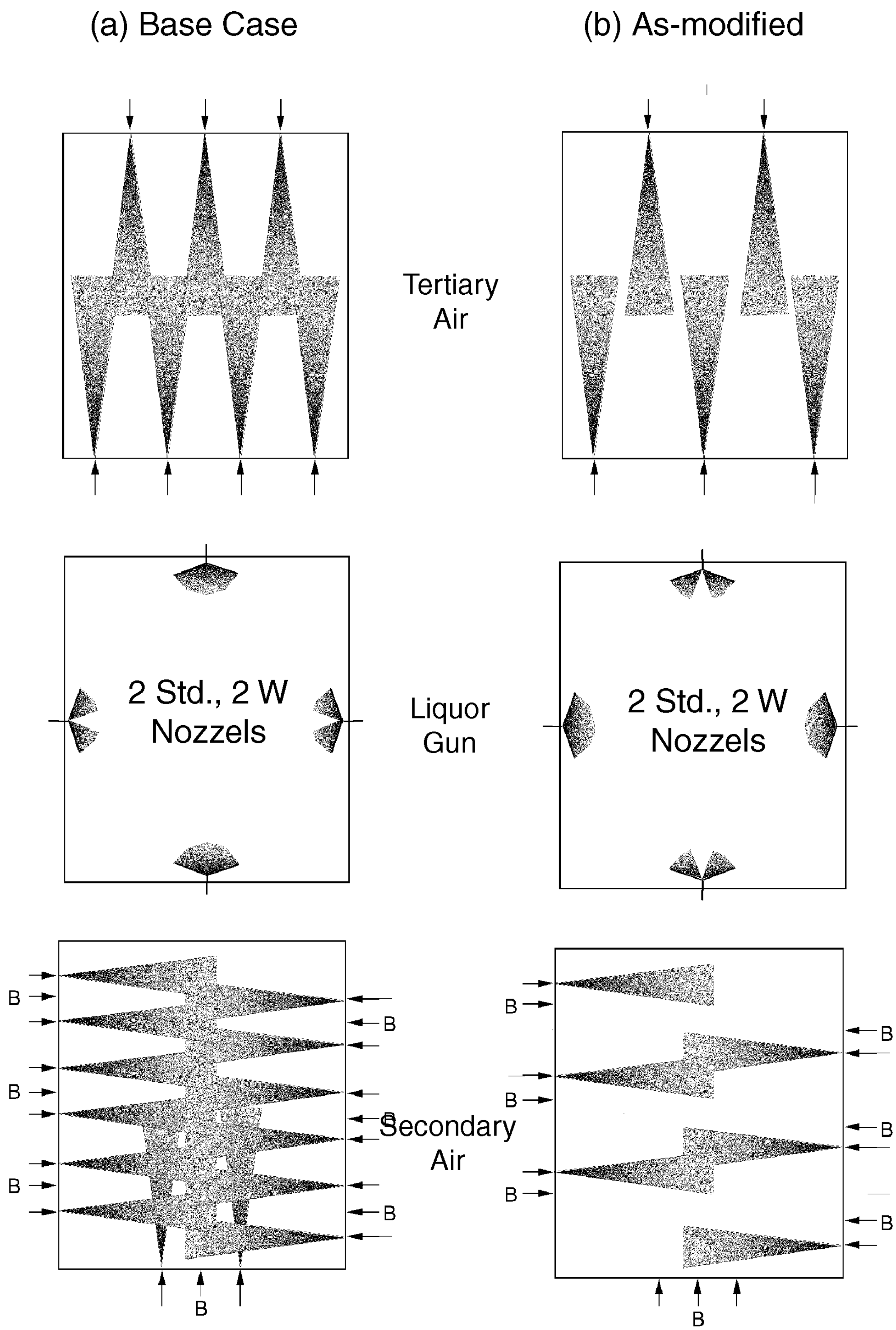

Figure 5. Arrangement of air and liquor guns (a) before optimization, (b) after optimization.

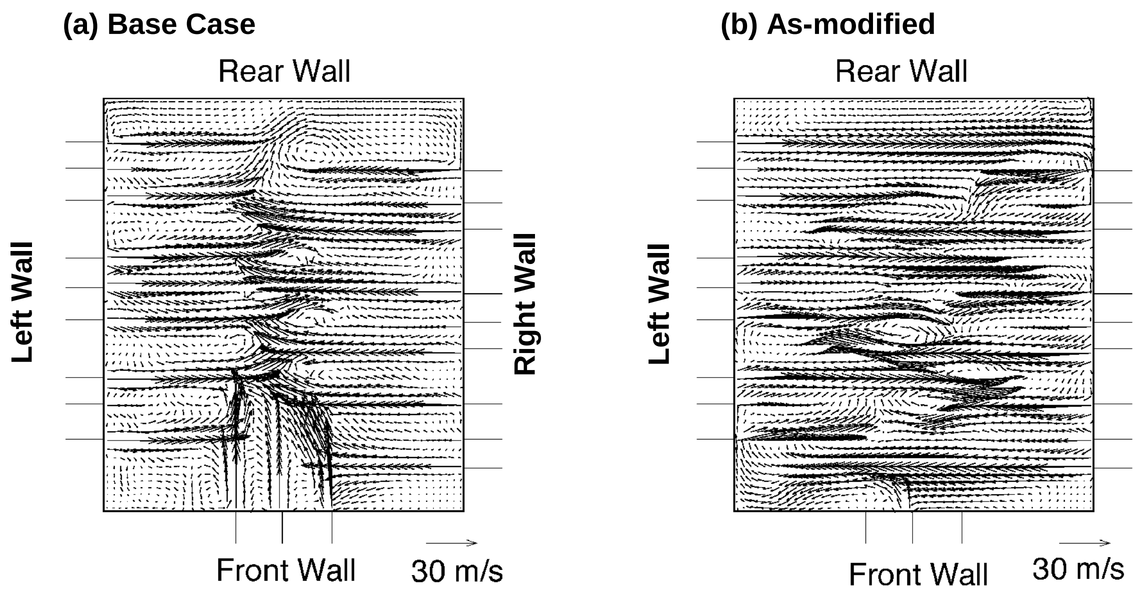

Figure 6. Velocity vectors at secondary air elevation (a) before optimization, (b) after optimization.

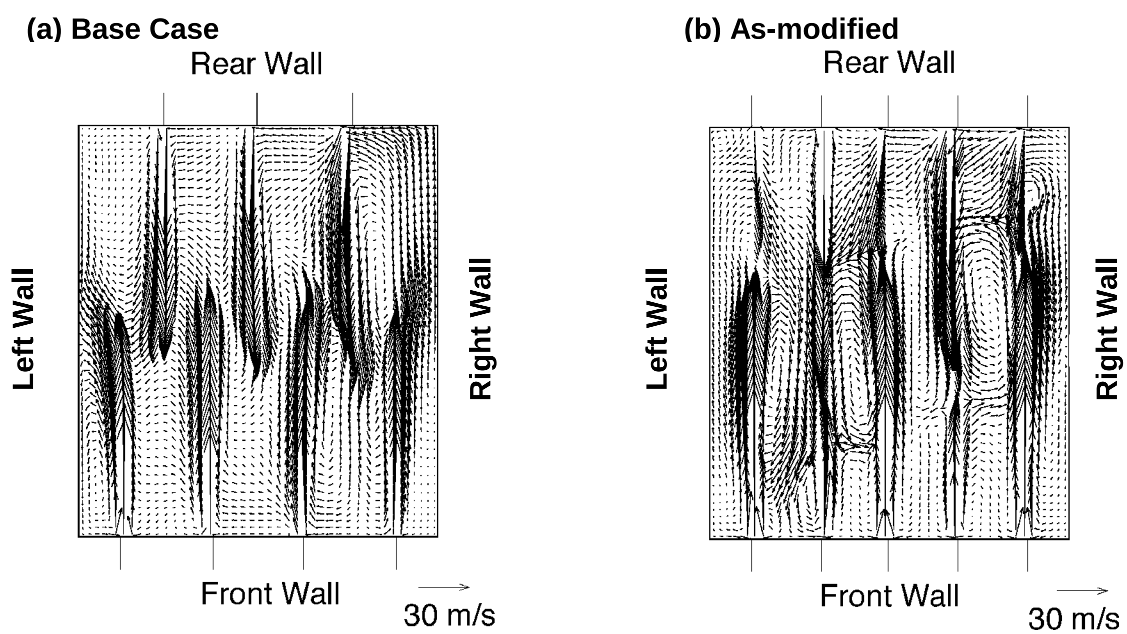

Figure 7. Velocity vectors at tertiary air elevation (a) before optimization, (b) after optimization.

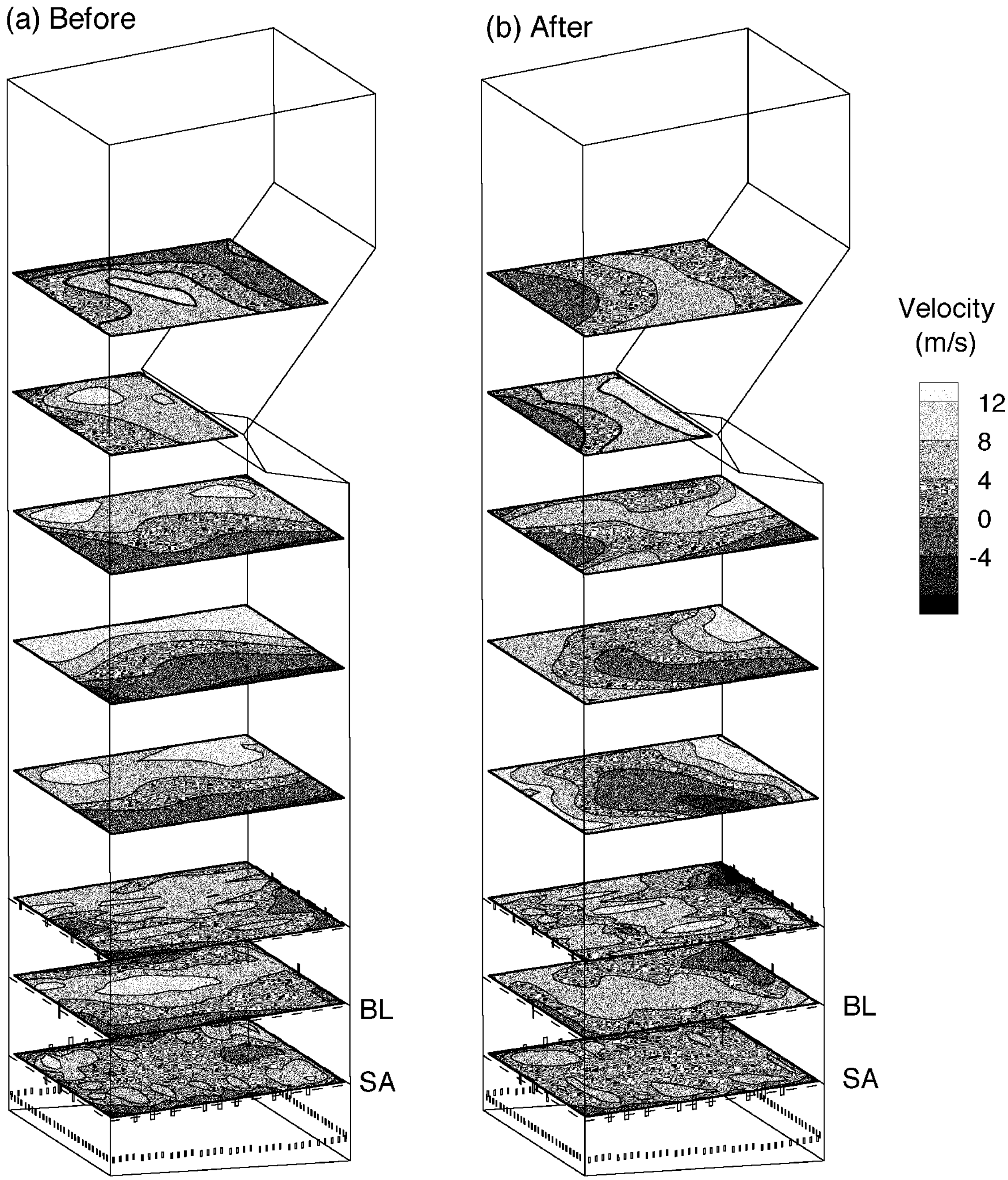

Figure 8. Vertical velocity at horizontal planes (a) before optimization, (b) after optimization.

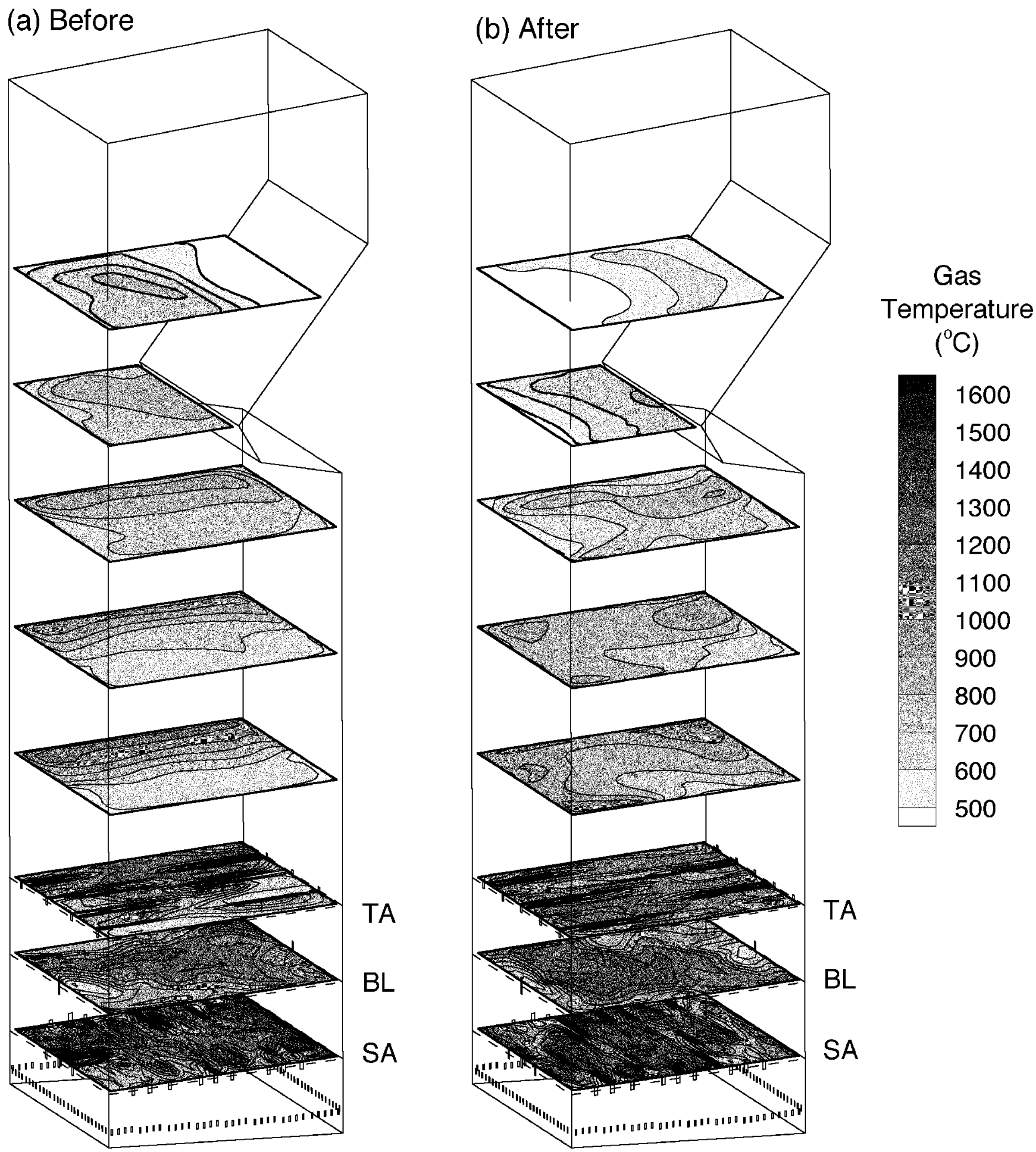

Figure 9. Gas temperatures at horizontal planes (a) before optimization, (b) before optimization.

Modeling of this arrangement led to the operational changes and verified its effectiveness at improving operation. The mill implemented these changes and immediate improvements were noted in unit operation. This simple experiment added significantly to the overall confidence that the proposed operational and hardware changes would be effective.

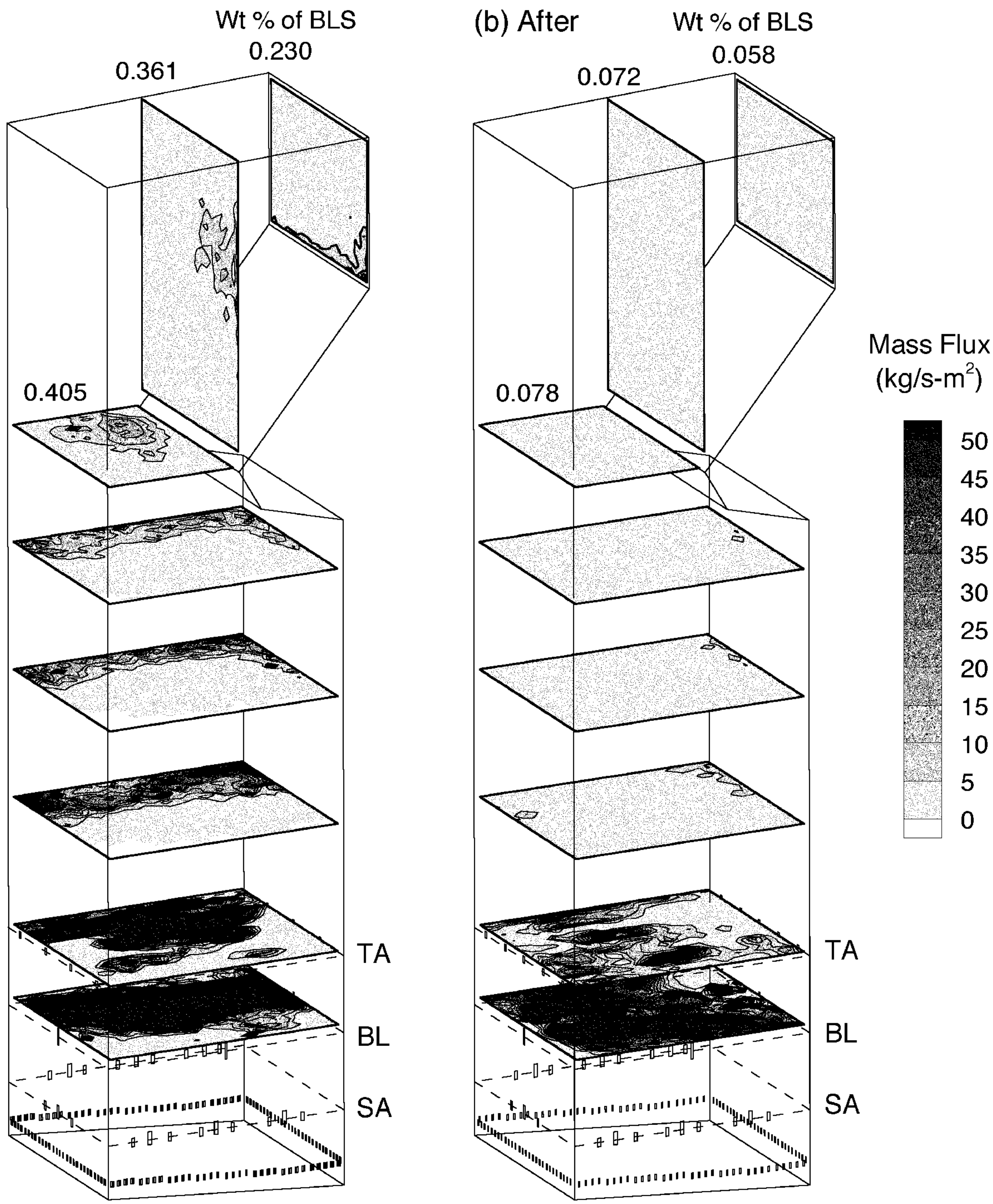

Figure 10. Mechanical carryover at selected planes (a) before optimization, (b) after optimization.

Modifications to the recovery boiler were completed in December of 1997. The unit was returned to service, and ran to the next scheduled outage which was six months later. Observations of the unit following modifications showed significant improvements. There was a significant reduction in the mechanical carryover seen in the upper furnace and superheater regions. Upper furnace color was much darker, very balanced and showed no visible carryover. This operation translated into a significant reduction in the superheater fouling rate. The deposits that did form were softer, less tenacious and were readily removed by the normal operation of the sootblowers. At the end of the first six months of operation, there was no evidence of any adverse fouling or plugging in the unit. Attemperator flow and steam temperature levelized at the design value of 440C (825F). The unit continues to operate on a six month scheduled outage basis and the performance continues to duplicate that of the first six months of post modification operation.

CONCLUSIONS

Post modification performance leaves no doubt that the major improvement in the unit performance relative to fouling was achieved. The contribution of each of the individual changes is more difficult to quantify. Modeling would predict that the major improvement was due to reduced carryover and improved furnace balance and stability. The superheater addition with lower downstream gas temperatures would predict less sintering and deposits that are easier to remove. Overall experience with reduced chloride concentrations in the liquor would predict reductions in the fouling rates and improved sootblower effectiveness. If one assumes the same carryover, fouling rates, and sootblower effectiveness, our functional modeling predicted that with the additional superheater surface, the attemperation at design steam temperature would cease after twelve (12) weeks of operation versus two (2) weeks without the surface addition <u>that was typical</u>. Experience shows that this is not the case. The unit attemperates at design steam temperature throughout the six month operating period with no evidence of residual fouling, indicating that design steam temperature could be maintained for even longer periods of time. This is good evidence that fouling rates have decreased and that physical properties of the ash have changed such that it is removable and equilibrium conditions can be achieved and maintained.

Our attempt to prioritize the individual changes would rate the air system modifications first due to the carryover reduction, the addition of surface second, and the reduction in chlorides a close third. The latter two combine to produce the more easily removed friable deposit permitting the achievement of equilibrium conditions.

Alternative arrangements studied helped to determine the most cost-effective changes, and input from operations aided in the selections of changes to consider. The results of the model provided the basis to train operations personnel how to operate the boiler to achieve the best performance.

Modeling the recovery boiler prior to hardware modifications allows designers and operators of recovery boilers a means to evaluate the alternatives collectively, and provides valuable insight into design and operation that was previously unavailable.

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Received for publication: July 13, 1999
Accepted: September 27, 1999
Presented at the 1999 TAPPI Engineering Conference

This paper was accepted for publication and abstracting in the July 2000 issue of TAPPI Journal.