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COMPARISON OF SIMULATION RESULTS AND FIELD MEASUREMENTS OF AN OPERATING RECOVERY BOILER

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ABSTRACT

A recovery boiler was operated using two sizes of black liquor firing nozzles while maintaining the same boiler load in each case. Temperature measurements were made using pyrometers to establish a vertical temperature profile within the furnace for both cases. The boiler was then simulated for both conditions using a computer-based model of the furnace to predict general combustion behavior. Simulations showed that differences in reduction efficiency for the two firing conditions can be attributed to greater amounts of organics striking the bed region for the case with larger nozzles. A simplified energy balance was used to predict heat release. The heat release profile was then compared to the mill temperature data showing good agreement and providing qualitative validation for the modeling technique.

INTRODUCTION

The purpose of this study was to use current recovery furnace modeling capabilities to explain observations of mill trials for two different firing modes of an operating boiler. One black liquor firing scheme used 15 guns with smaller nozzles (3/4" nominal ID), the other had 11 guns with larger nozzles (1" nominal ID). An effort was made to maintain the same load in both cases, yet significantly higher reduction efficiency was observed for the larger nozzle case, and pyrometry measurements showed a different temperature profile. Traditional recovery boiler design calculations cannot clearly explain these observations, so it was of interest to simulate black liquor combustion in the furnace using an advanced three-dimensional model.

There are numerous references in the literature to recovery boiler model development and simulation results (1-11). This is the first comparison of simulation results with boiler mill trials for different black liquor firing schemes. Recently, researchers have proposed a black liquor combustion model based on laboratory combustion experiments which includes both fundamental heat and mass transfer theory as well as empirically determined model parameters (12). This model is the basis for the recovery boiler simulation used in this work.

This paper first describes the mill trials and results for the Kaukas Boiler at both firing conditions. The computational modeling methodology is then described followed by a comparison of simulation results and mill data.

RECOVERY BOILER FIELD TESTING

The boiler studied in this work was the Ahlstrom 2700 tds/day recovery boiler at the Kaukas, Finland mill. The two operating conditions were 15 smaller 3/4" splash-plate nozzles and 11 larger 1" splash-plate nozzles operated at flow rates that yielded the same overall load to the boiler. Black liquor properties and firing conditions were very similar in both cases.

The pulp mill and boiler manufacturer jointly conducted full-load recovery boiler testing using the two different nozzles to determine which size gave the better performance at design loads. During testing thorough measurements were taken to document boiler operation for the two different firing strategies. Pyrometry measurements were taken at the air port levels and at the bullnose to determine the approximate vertical temperature profiles for both cases. In addition, standard recovery boiler heat and material balance calculations were done to compute the "expected" exit flue gas temperatures.

Approximate boiler dimensions and air distribution levels for the unit are given in Table 1.

Table 1. Air Distribution and Boiler Dimensions

Base Dimensions (m)	12.5 x 12.5
Height to Bullnose (m)	35
Liquor Gun Level (m)	6
Primary Air (%)	32
Secondary Air (%)	51
Tertiary Air (%)	17

Data showing average operating conditions for both mill trials is shown in Table 2. Mean droplet diameter was calculated based on the work of Empie et al. (13)

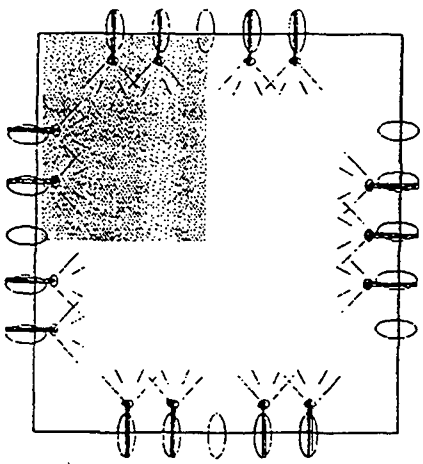
Table 2. Operating Conditions for the Two Mill Trials

	Case A	Case B
Number of Liquor Guns	15	11
Nozzle Orifice ID (mm)	22	27
Black Liquor Flow (kgds/s)	29.3	29.1
Firing Temperature (°C)	123.5	124.0
Firing Solids (%)	71.6	73.1
Mean Droplet Size (mm)*	2.62	3.25

* Calculated

The locations of black liquor guns are shown for Case A and Case B in Figures 1 and 2.

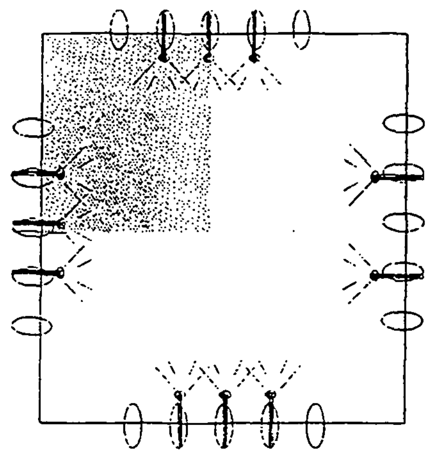
Front



Rear

Figure 1. Black Liquor Gun Locations for Case A (15 Gun).

Front



Rear

Figure 2. Black Liquor Gun Locations for Case B (11 Gun).

A standard industrial pyrometer was used to measure temperatures at the secondary, tertiary, and bullnose levels to establish an approximate temperature profile for both cases. From previous work (14) it is estimated that the temperature measurements with this pyrometer represent gas at distances roughly two meters into the furnace. Although the measurements are inaccurate for single absolute temperature measurements, they provide a good estimate of differences between the two mill trials. Pyrometry measurements and reduction efficiencies for the two cases are shown in Table 3.

Table 3. Mill Trial Results and Measurements

	Case A	Case B
Secondary Level Temp. (°C)	1012	1099
Tertiary Level Temp. (°C)	942	996
Bullnose Level Temp. (°C)	896	948
Reduction Efficiency (%)	92	96

These results show that a higher reduction efficiency was achieved in Case B by using fewer guns with larger nozzles. Standard recovery boiler heat transfer calculations based on similar combustion profiles predicted equal temperatures at the bullnose level. This is inconsistent with the pyrometry results unless a different heat release pattern with combustion higher in the furnace existed in Case B. This scenario would be counterintuitive since the mean droplet size was larger in Case B. A full three-dimensional simulation was desirable to explain higher exit furnace temperatures with larger black liquor drop sizes accompanied by greater reduction efficiency.

MODELING THE BOILER

Computer modeling of the Kaukas recovery boiler was done in two stages: 1) computational fluid dynamics (CFD) flow-field model, and 2) black liquor in-flight combustion model. The first part of the model focused on obtaining a flow pattern for the gases in the furnace. The second part involved predicting combustion behavior for the two firing conditions of 15 smaller nozzles (Case A) and 11 larger nozzles (Case B). The same flow field was used for both combustion simulations. The two main issues that we wanted to examine in the modeling effort were: 1) explain why improved reduction efficiency was observed in Case B, and 2) explain how the exit flue gas temperature could be higher for Case B at the same time.

CFD Flow Model

The initial phase of modeling was an isothermal CFD model of the gas flow in the furnace combustion zone below the bullnose. This modeling work was done at Ahlstrom Machinery in Varkaus, Finland, using FLUENT, ver. 4.01, on an HP Apollo workstation. Two planes of symmetry were used so that maximum resolution of grid nodes was available to describe individual secondary and tertiary air ports. This resulted in a flow field description of one quarter of the furnace. A nonuniformly spaced, Cartesian grid was specified, and an appropriate step bed was used as a boundary at the base of the furnace geometry.

The predicted flow field is characterized by velocity magnitude contours and vector plots in Figures 3-7. Figure 3 shows secondary level air jet penetration using velocity magnitude contours. A similar plot shows air jets at the tertiary level in Figure 4. It is evident from these figures that there is considerable interaction of the secondary air jets. Figures 5 and 6 show velocity vectors at the secondary and tertiary levels which show swirl patterns in the flow field. Figure 7 shows velocity vectors at the liquor gun level which indicates that a central core has developed where highest upward flow components are in the center of the furnace. Upward velocities dissipate with distance up the furnace.

The CFD results presented here will have limited accuracy. Some of the recognized limitations in this study are: isothermal flow, k-e turbulence model, step bed vs. smooth bed, large aspect ratios for some cells, and only a partial simulation of the overall boiler geometry. However, for the purposes of this study, only an approximation of the true flow field is needed since we are looking for differences in black liquor combustion due to a variation in firing practice. Our assumption is that the CFD-generated flow field is a reasonable approximation of the actual flow and that only minimal differences in the gas phase flow exist between firing with either 15 guns or 11 guns.

Black Liquor Combustion Model

In-flight black liquor combustion behavior was simulated at the Institute of Paper Science and Technology on an IBM RS-6550 workstation. The flow field predictions were imported into an independent full furnace geometry and were fixed for combustion calculations. Combustion simulations were done by projecting the CFD flow field predictions of a quarter furnace to a full furnace geometry through mirror images to allow asymmetric placement of liquor guns. The simulated gun arrangements followed the locations used in mill tests.

The black liquor combustion model used in this work is based on descriptions of the four stages of black liquor combustion: 1) drying, 2) pyrolysis, 3) char burning, and 4) inorganic smelt reactions. Heat and mass transfer relationships are used to predict the rates at which each of the combustion stages occur. Heat transfer calculations are based on a single, film resistance model for the individual black liquor drops. The trajectories of drops are determined by a force balance using a coefficient of drag relationship and are influenced by swelling characteristics of the black liquor and gas flow patterns within the furnace. These trajectories dictate where mass and energy are exchanged between the gas and droplet phases and whether the droplets become entrained or fall to the char bed.

Black liquor mass flow as a function of angle within the spray sheet was specified according to a parabolic distribution (15). Gun firing angle into the furnace was at a slight downward angle of 10° with respect to horizontal.

SIMULATION RESULTS

The in-flight black liquor combustion model predicts mass transfer rates in three-dimensional space for three stages of black liquor combustion: 1) evaporation, 2) pyrolysis, and 3) char burning. The model also predicts where black liquor mass, including inorganic portions, strikes the furnace boundaries, i.e. walls, bed and carryover.

Improved Reduction Efficiency

The biggest difference between the two firing patterns was the black liquor mass striking the bed. Tables 4 and 5 summarize the fate of black liquor in the two cases. Almost twice as much uncombusted organic volatiles and char mass lands on the bed in the Case B (11 larger nozzles). In addition, more inorganic material landed on the walls in Case A. These simulation results help to explain the higher reduction efficiencies observed in the mill trials in the case of larger nozzles. It is recognized that some uncombusted char is needed for good bed operation to help reduce sulfate to sulfide. If we combine the pyrolysis and char masses into a single organics term, roughly 82% of the organics burned in-flight in Case A versus about 70% burned in-flight in Case B. About 13% of the organic mass landed on the bed in Case A and versus about 27% to the bed in Case B. The remainder in each case landed on walls.

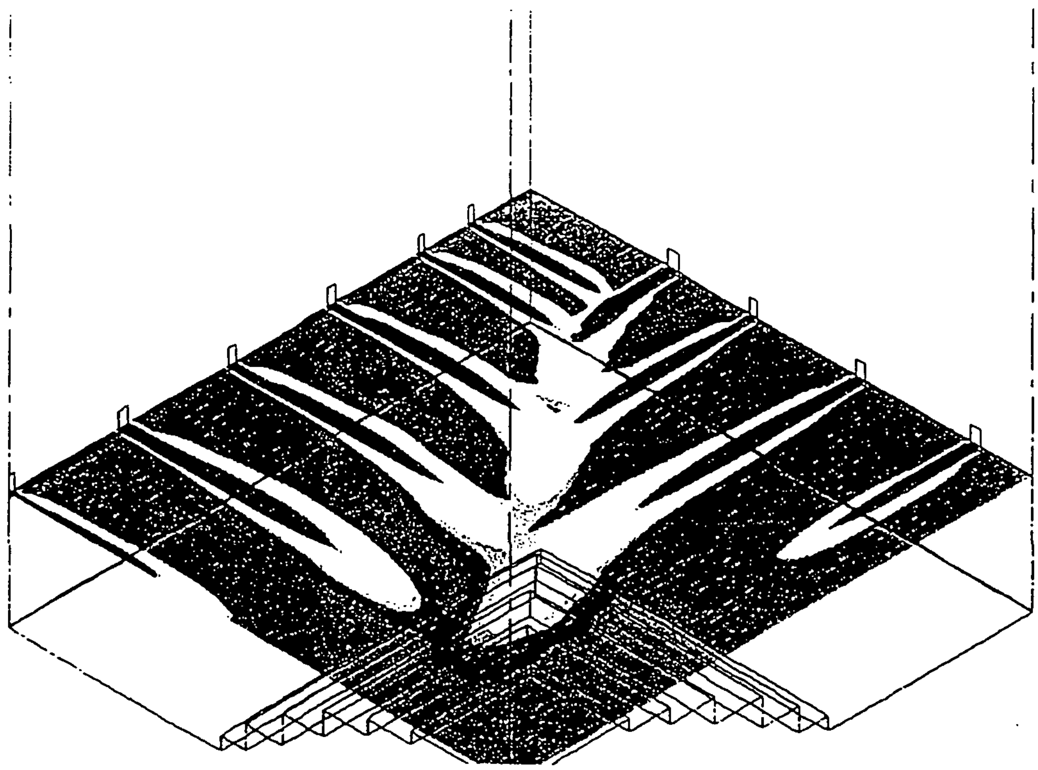


Figure 3. Velocity Magnitute Contours of the Quarter Furnace Geometry at the Secondary Air Port Level.

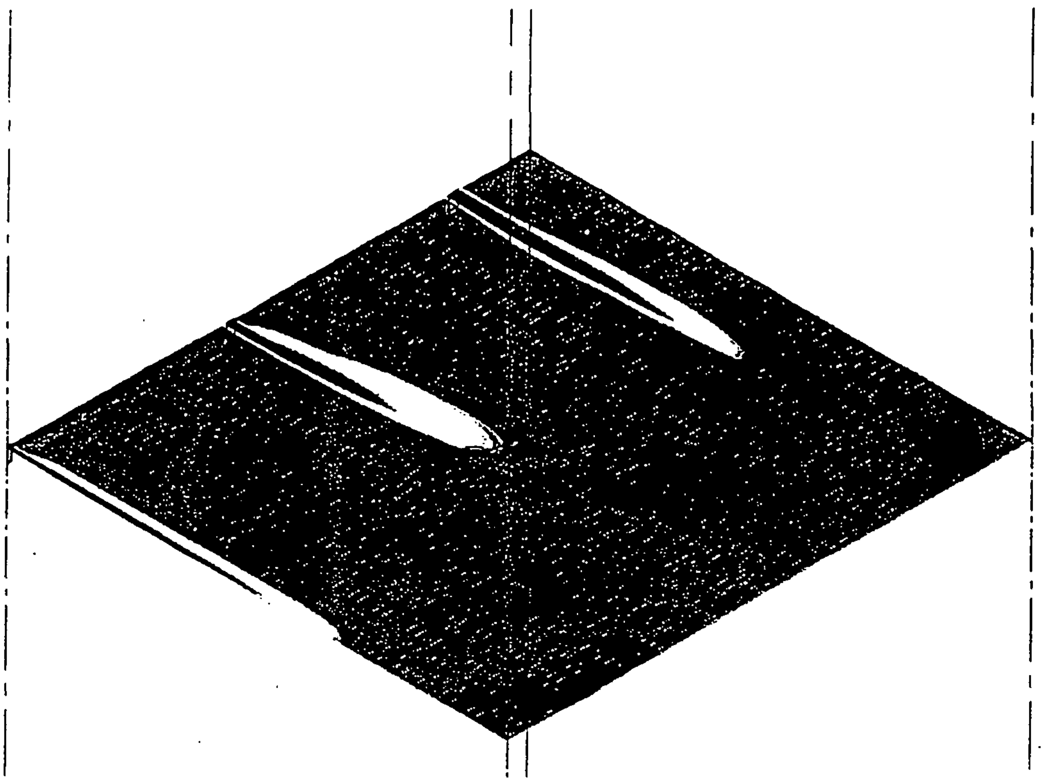


Figure 4. Velocity Magnitute Contours of the Quarter Furnace Geometry at the Tertiary Air Port Level.

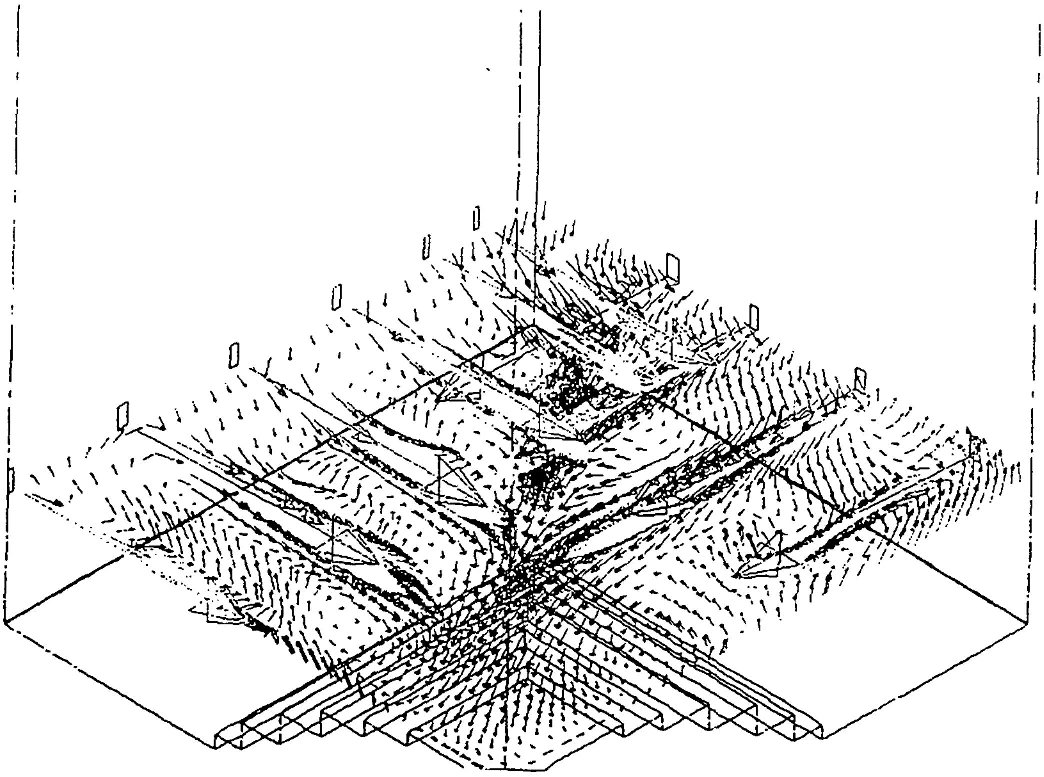


Figure 5. Velocity Vectors at the Secondary Level.

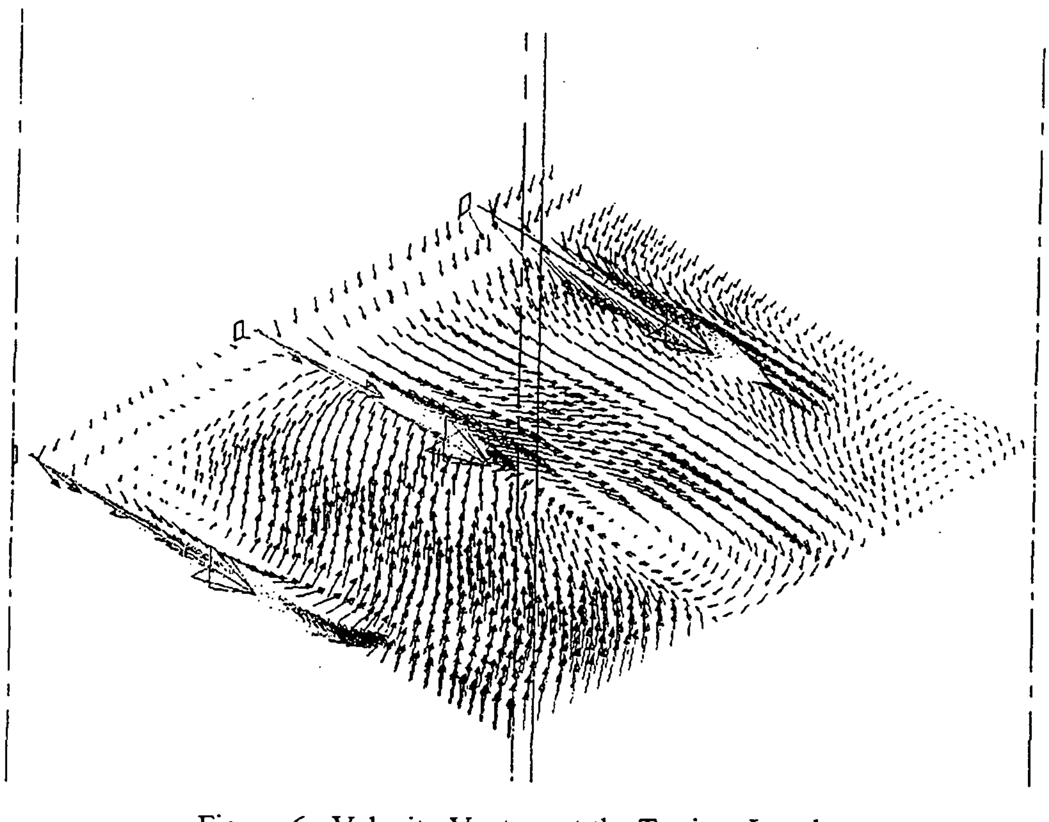


Figure 6. Velocity Vectors at the Tertiary Level.

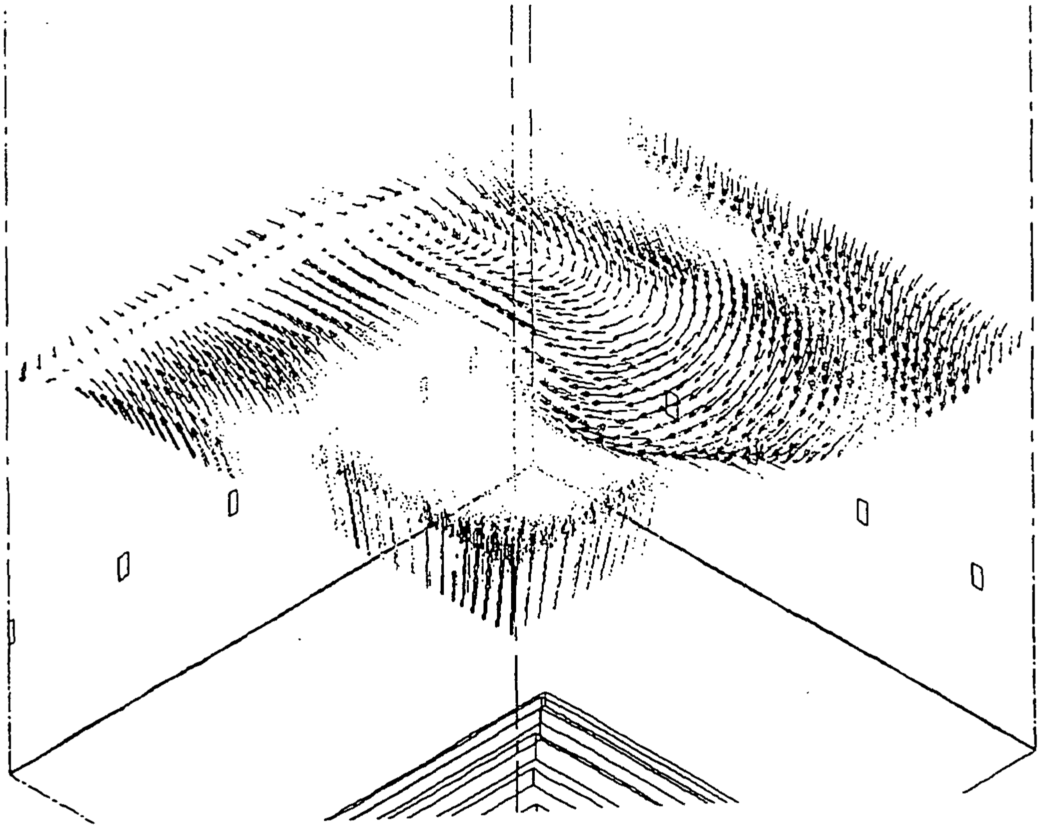


Figure 7. Velocity Vectors at the Liquor Gun Level.

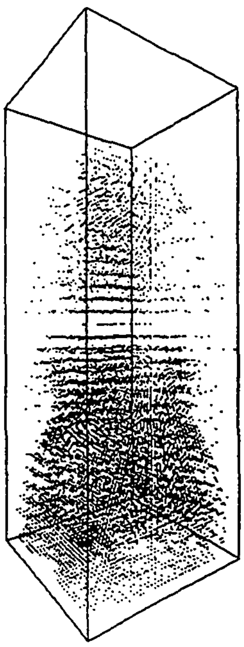


Figure 8. Char Combustion Locations for Case A.

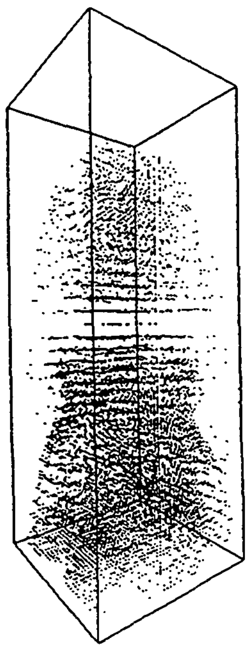


Figure 9. Char Combustion Locations for Case B.

Table 4. Final Fates of Black Liquor Mass in Case A.

	Water	Pyrolysis	Char	Smelt	Organic (total)
In-flight	0.98	0.85	0.70	0	0.82
Hit Walls	0.009	0.05	0.07	0.29	0.05
Carried Out	0	0	0	0.006	0
Hit Bull Nose	0	0	0	0.001	0
Hit Char Bed	0.01	0.10	0.23	0.70	0.13

Table 5 . Final Fates of Black Liquor Mass in Case B.

	Water	Pyrolysis	Char	Smelt	Organic (total)
In-flight	0.96	0.73	0.53	0	0.70
Hit Walls	0.006	0.03	0.06	0.22	0.04
Carried Out	0	0	0	0.004	0
Hit Bull Nose	0	0	0	0.0008	0
Hit Char Bed	0.04	0.24	0.41	0.77	0.27

Temperature Profile Differences

Figures 8 and 9 show three-dimensional views of mass transfer locations for evaporation, pyrolysis, and char burning for the 15 gun and 11, gun cases respectively. These graphics show that combustion patterns were qualitatively similar for both cases.

To give a better indication of heat release in the furnace, total organic mass release during both the pyrolysis and char burning stages was summed on a fractional mass basis. The resulting profiles of black liquor organic mass transfer are compared in Figure 10 for the two cases. The bimodal nature of the combustion pattern makes it hard to predict how temperature would be effected at the gun level. However, there was more combustion activity predicted higher in the furnace for the case with larger nozzles which would help to explain a persisting higher temperature for the case with larger mean drop size. Differences in gun locations may have contributed to the change in combustion profile.

Additional Insight

The Kaukas recovery boiler is a relatively large, modern boiler with a distance of 35 m from bed to bullnose. Because of this high furnace combustion zone, very little physical carryover was predicted in either the 15 gun or 11 gun simulations. The mill has experienced very little fouling, so this also qualitatively supports the model's predictions of minimal carryover.

CONCLUSIONS

Recovery boiler modeling techniques allowed a better understanding of observations made during mill trials.

Reduction efficiency improvement for the boiler firing with larger nozzles was shown to be the result of larger droplets and more uncombusted black liquor char directly to the bed.

A change in temperature profile resulted in higher temperatures for the exiting flue gas and was due to more combustion activity higher in the furnace for the larger nozzles.

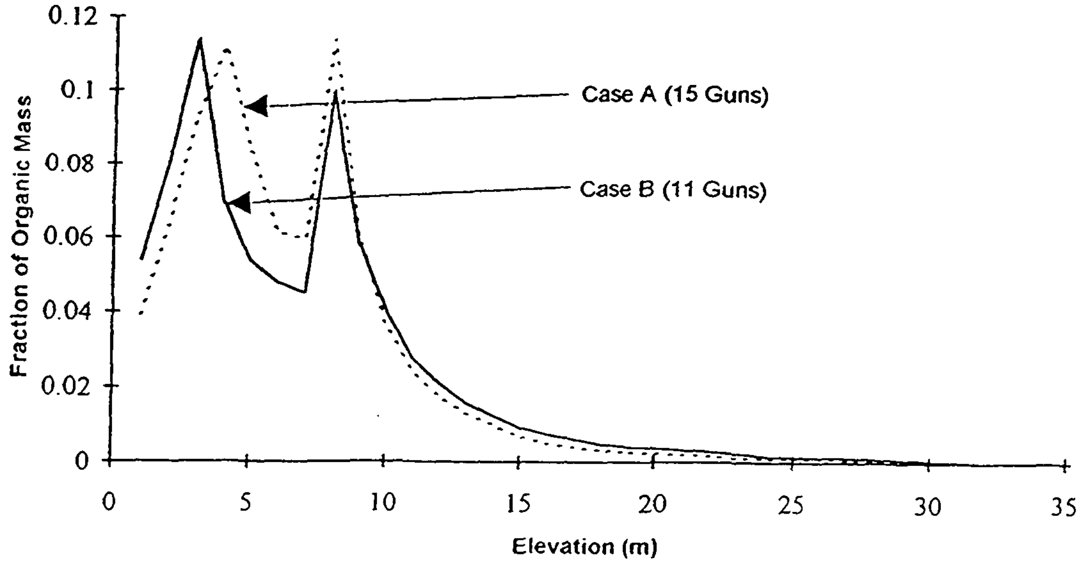


Figure 10. Release of Black Liquor Organic Mass versus Elevation in the Furnace.

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