BLACK LIQUOR SPRAYING

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INTRODUCTION

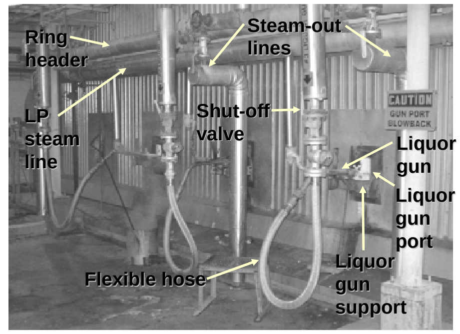
Spray droplet size and spray distribution are key variables in controlling black liquor droplet combustion, char bed combustion, smelt reduction, entrainment, and carryover. Black liquor sprayed into recovery furnaces should ideally form droplets small enough to dry and partially pyrolyze before reaching the char bed, but large enough to avoid being entrained in the furnace gas flow. Droplets about 2 to 4 mm in diameter are usually considered the proper size for good recovery boiler operation. The impact of nozzle design, fluid properties, and operation on black liquor trajectory, droplet size, and spray distribution will be presented below, and the dramatic impact of flashing on nozzle performance will be discussed.

The nozzle itself is only one component of the black liquor delivery system. The delivery system starts at the heavy black liquor storage tank. The delivery system includes black liquor pumps, mix tanks for precipitator dust and makeup chemicals, a ring header that surrounds the boiler, connecting pipes and hoses, liquor guns, and finally, liquor nozzles.

The elements which are particularly important are the ring header, the piping to the individual liquor guns, the shutoff valves, the flexible hose, the liquor gun, and the nozzle. **Slide 3** shows a photograph of the arrangement of these elements on a recovery boiler.

Slide 3

Black Liquor Guns



Slide 4 lists the key parameters that control black liquor spray. Process variables are determined by the mill processes outside of the recovery boiler. Operating parameters are usually within the control of boiler operator, but may be limited by the boiler design.

Slide 4

Key Parameters for BL Spray

Process Variables
- **Liquor dry solids**
- **Liquor elevated boiling point**
- **Physical properties (density, viscosity, etc)**
- **Liquor burning characteristics (swelling)**

Operating Parameters
- **Number and arrangement of guns**
- **Tilt or oscillation of gun barrels**
- **Nozzle type and size**
- **Firing temperature**
- **Liquor flow rate and pressure**

Slide 5 lists the key variables that characterize the black liquor spray.

Slide 5

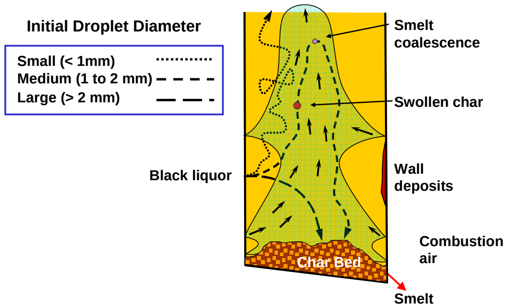
Spray Characteristics

- **Median droplet diameter**
- **Droplet size distribution**
- **Spray velocity**
- **Flow distribution**

Slide 6 illustrates the importance of droplet size on the particle trajectory. The largest drops (> 2mm) are influenced by the initial velocity of the spray and gravity; these particles deposit on the furnace walls and char bed after partial drying and pyrolysis.

Slide 6

Impact of Droplet Size on Trajectory



The smallest drops (< 1mm) have the greatest aerodynamic drag and are swept upward by the gases rising in the furnace; these particles are known as carryover and they deposit on the tubes of the convection pass and potentially plug the boiler. Intermediate size drops (1 to 2 mm) burn in suspension as the swollen particles are swept upward by gas flow, but then fall to the char bed after smelt coalesces into a dense molten smelt particle.

The objectives of black liquor spraying are summarized in **Slide 7**. The first objective is to control droplet size to achieve a mass median diameter of 2 to 4 mm. Droplet size should be large enough to minimize particle carryover and small enough to dry the liquor before it reaches the char bed. Droplet size also determines the amount of burning that occurs in suspension versus that which occurs on the char bed. A decrease in droplet size will cause an increase suspension burning and reduce the amount of char delivered to the bed, and reduce the height of the char bed.

The second objective of spraying is to distribute the liquor spray uniformly over the plan area of the furnace and char bed. The amount of liquor hitting the walls should be minimized, but can not be completely eliminated. The goal is to create a uniform symmetrical bed shape that maximizes the area for heat transfer and chemical conversion of char and smelt on the surface of the bed.

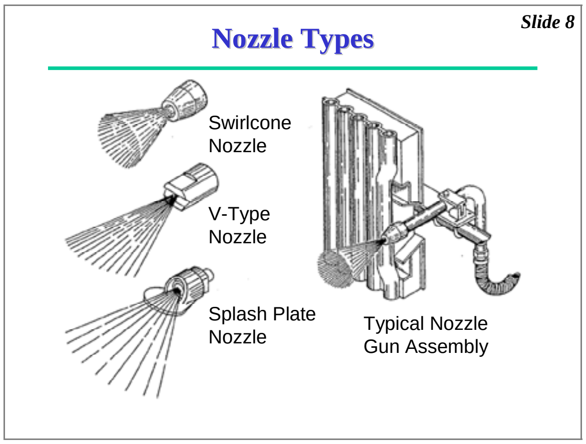
Slide 7

Objectives for Effective Spraying

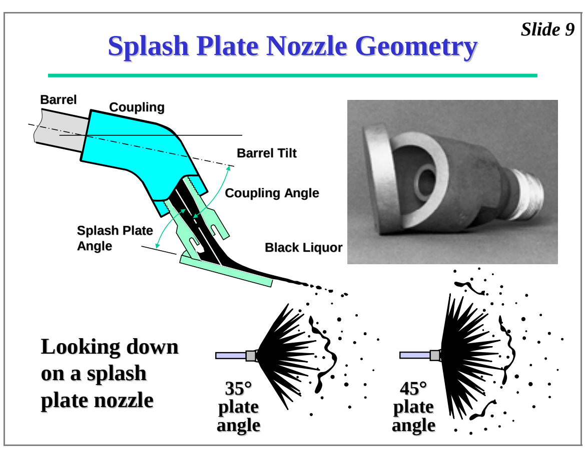
- **Control droplet size (2 to 4 mm)**
  - **Minimize particle carryover**
  - **Deliver mostly dry liquor to bed**
  - **Control height of char bed**
- **Distribute liquor spray**
  - **Minimize liquor on furnace walls**
  - **Create a uniform symmetrical bed shape**

BLACK LIQUOR NOZZLES

Slide 8 shows three basic types of black liquor nozzles and a schematic of the liquor spray from each nozzle. The purpose of any nozzle is to spread out the flow of black liquor and form a sheet of liquid that breaks up into coarse drops. The spray distribution will be determined by the specific nozzle type. In general, the flat sheet from a splash plate nozzle follows the angle of the splash plate itself. For a swirlcone and a V-type nozzle, the sheet follows the nozzle axis. However, in all cases the sheet spreads out in a flat or conical geometry. This pattern, along with the liquor velocity, sets the initial distribution of the liquor ligaments and drops into the furnace.

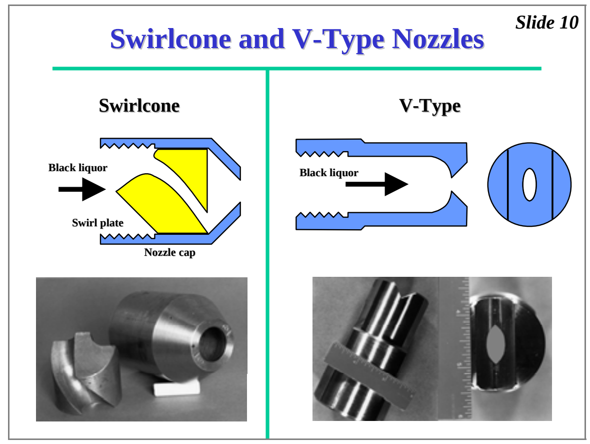


Slide 9 shows a schematic of a splash plate nozzle along with a photograph. The splash plate nozzle consists of a flat plate of rounded cross-section attached at an angle to the end of a pipe. Black liquor flows through the pipe and, when it exits from the end of the pipe, it strikes the flat face of the plate at an angle of approximately 45°. The flow is turned and flattened into a sheet of liquid.



The sheet leaves the plate and breaks up into droplets. Impingement of the flow on the plate causes the flow to fan out through an angle of 120° to 180°. Larger splash plate angles spread the black liquor out through a wider angle.

Slide 10 shows schematic diagrams and photographs of a swirlcone nozzle and a V-type nozzle.



Though the appearance of the swirlcone nozzle is quite different, the droplet formation process is similar to that for the splash plate. Black liquor flows down a barrel to the nozzle. Just ahead of the nozzle is a block or swirl plate with spiral grooves which cause the flow to rotate as it flows along the walls of the nozzle cap. A short distance downstream is the circular nozzle exit. The rotating hollow flow exits from the nozzle in the form of a conical sheet of black liquor. This conical sheet of liquor breaks down by the same mechanism as the flat sheet from the splash plate nozzle.

The V-type nozzle consists of a cylindrical tube topped with a hemisphere that has been cut across the tip with a V-shaped channel. Liquor flows at relatively low velocity to a point just ahead of the nozzle exit opening and then is accelerated and discharged in a flat sheet.

The typical size, operating conditions, and black liquor droplet size for the different nozzles is summarized in **Slide 11**.

Slide 11

BL Nozzle Operating Conditions

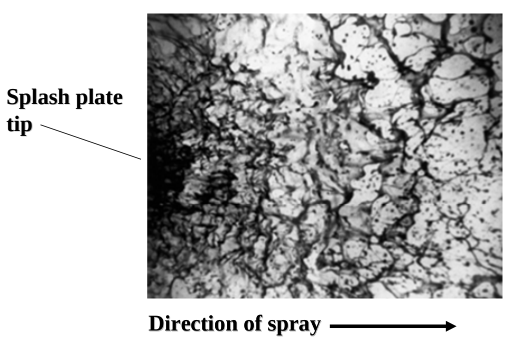
	Splash Plate	Swirlcone & V-type
Orifice size, in.	0.7 – 1.25	0.4 – 0.75
Pressure, psi	15 – 45	12 – 18
Flow, GPM	25 – 75	20 – 40
Median droplet size, mm	2 – 4	2 - 4

DROPLET SIZE DISTRIBUTION

Slide 12 shows a stop-action picture of a black liquor spray with the characteristic initial formation of ligaments followed by droplet formation.

Slide 12

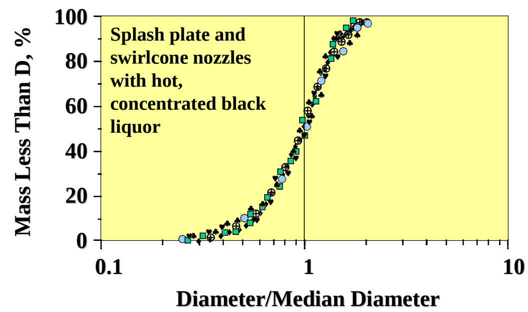
Black Liquor Spray Breakup



There have been several investigations of black liquor nozzles and spray size distribution. **Slide 13** shows data from one of these studies for a wide range of operating conditions using hot, concentrated black liquor. The droplet size distribution is normalized to the median droplet diameter.

Slide 13

Spray Size Distribution for BL Nozzles



Within experimental error, the size distribution is identical for all nozzle types and black liquor properties. This means that for all current black liquor nozzles, only the median size can be changed by nozzle geometry and operating conditions. Once the conditions have been set for a particular median droplet size, the breadth of the distribution is fixed. Selection of nozzle type and size should only be based on such factors as the flow rate, median droplet size, or spray distribution rather than on the breadth of the size distribution.

Data from black liquor spray studies has been used to develop correlations for median droplet size as a function of operating conditions. **Slide 14** shows one of these correlations.

Slide 14

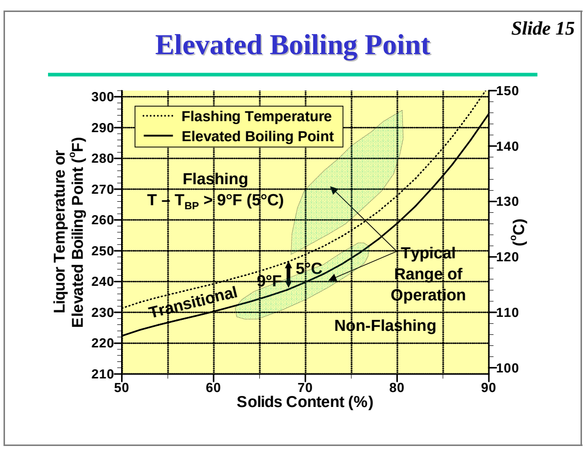
Median Droplet Size

$$D_{median} = 0.290\, K_L K_N \frac{D_n^{1.23} S^{0.62}}{Q^{0.23} T^{0.14}}$$

- **Splash plate, swirlcone, and V-type nozzles**
- **D_{median} = median droplet diameter**
- **K_N, K_L = nozzle and liquor constants**
- **S = liquor dry solids (weight fraction)**
- **T = liquor temperature, °C (non-flashing)**
- **D_n = nozzle diameter, m**
- **Q = volume flow rate, m³/s**

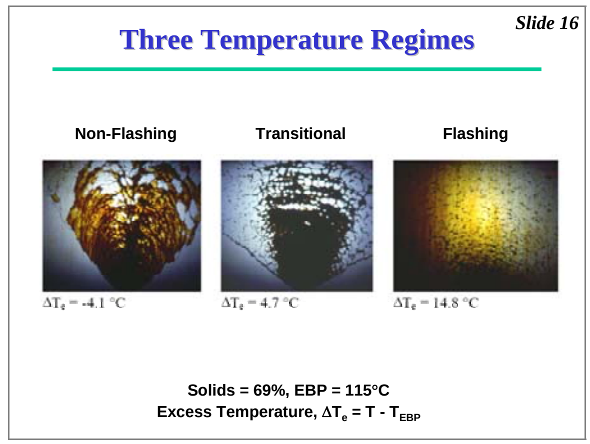
The study involved three types of nozzles (splash plate, swirlcone, and V-type) and eight different liquors operating at non-flashing conditions in a cold test chamber. The constant K_N varies ±10% for different nozzles and the constant K_L varies ±10% for most liquors. The dependence on nozzle diameter is approximate. Therefore nozzles which are much larger than the 0.35 in (0.9 cm) diameter used in this study should not be expected to follow this relationship very accurately.

Slide 15 shows the elevated boiling point of black liquor as a function of liquor dry solids. The boiling point increases with liquor dry solids, and can vary by several degrees for different liquors with the same dry-solids. It is common practice to control the liquor temperature at or near the elevated boiling point. Higher temperature ensures that the liquor is not too viscous and that it can be pumped through the delivery system without excessive pressure drop. Higher temperature (lower viscosity) is also needed for effective droplet breakup. Typical liquor firing temperatures are 230-290°F (110-143°C) corresponding with dry solids of 65 to 80%.



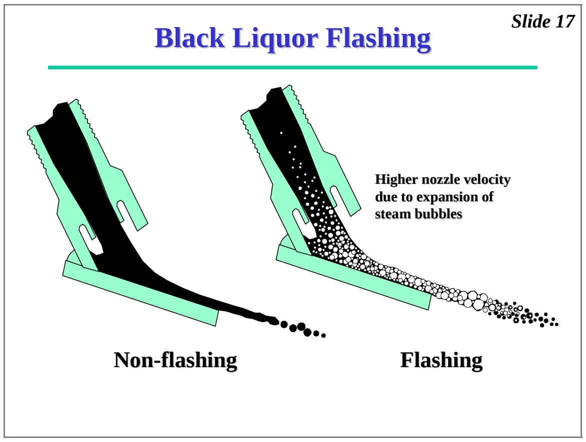
Slide 15 also shows the range of temperatures and solids which flashing occurs, and the transition region between non-flashing and flashing conditions. The transition is approximated by an offset of about 9°F (5°C), which varies for different liquors and different nozzles.

Slide 16 shows the effect of flashing on the spray from a splash plate nozzle. The break-up of the liquid sheet is affected dramatically when flashing occurs. Droplet size is much smaller under flashing conditions. In this illustration, the excess temperature $\Delta T_e = T - T_{EBP}$ is used to quantify the degree of flashing.



Slide 17 shows a schematic representation of the effects of flashing on black liquor spray formation. Within the delivery system, the liquor starts at a pressure higher than one atmosphere in the ring header. The pressure decreases due to frictional losses in the piping system as the liquor approaches the nozzle orifice. The liquor pressure reaches the ambient pressure (typically 1 atm) at the nozzle orifice. If the liquor is fired at or below its elevated boiling point, no water can evaporate within the enclosed piping system. As the liquor temperature is raised above the elevated boiling point, evaporation within the delivery system can occur. With modest increases of only a few degrees above the elevated boiling point, the rate and impact of the evaporation would be very modest. Any evaporation or bubble

formation would only occur at the nozzle orifice. As liquor temperature is raised further, evaporation can occur at higher and higher pressures at locations upstream of the nozzle. This evaporation, or flashing, has a very pronounced effect on flow and droplet formation.



Slide 18 shows an example set of spray conditions that will be used to illustrate changes in key operating parameters. At these conditions, the liquor is slightly above the elevated boiling point.

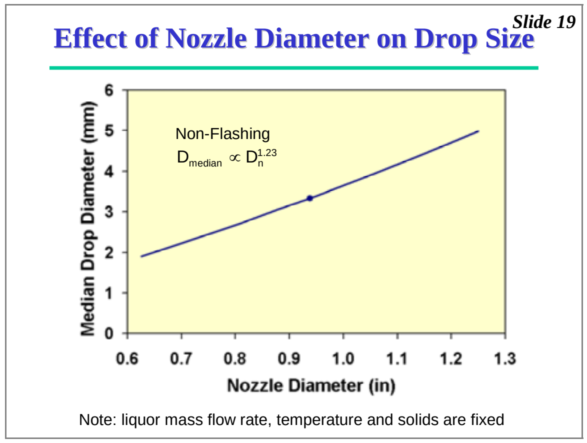
Slide 18

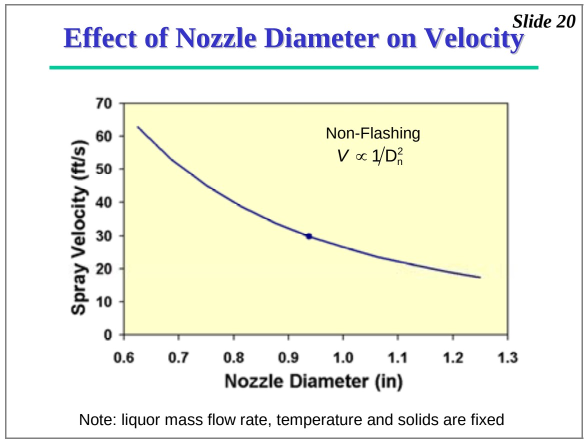
Example Nozzle Spray Conditions

- **Splash plate nozzle**
- **Nozzle diameter – 30/32 in (24 mm)**
- **Solids content – 70 %**
- **Temperature – 245°F (118°C), transitional**
- **Volume flow rate – 74.5 gpm (4.7 l/s)**
- **Liquor pressure – 16.4 psig (1.13 bar)**

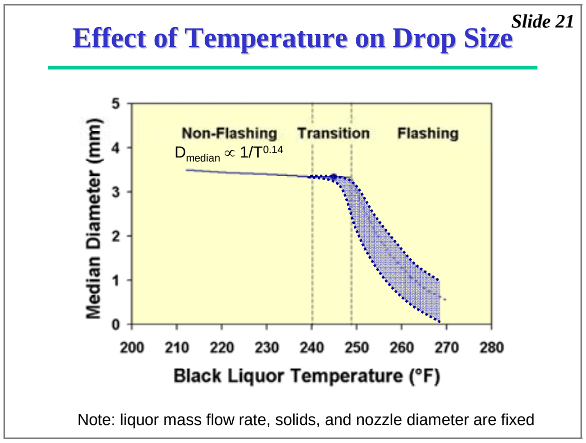
- **Median droplet diameter – 3.3 mm**
- **Spray velocity – 30 ft/s (9.1 m/s)**

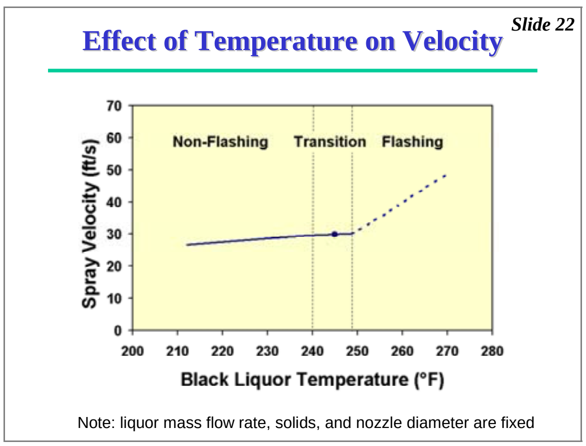
Slides 19 and 20 show the effect of nozzle diameter on median droplet size and spray velocity (assuming that liquor temperature, flow rate, and solids are fixed). The selection of nozzle size is important for establishing the right droplet size and the trajectory of the spray. However the operator cannot be expected to change the nozzle size to respond to subtle changes in bed size and carryover.





Slides 21 and 22 shows the effect of temperature on median droplet size and spray velocity (assuming nozzle diameter, flow rate and solids are fixed). Below the elevated boiling point, temperature has a relatively minor effect on the spray. As the liquor temperature is raised several degrees above the boiling point there is a consistent, and dramatic change in spray characteristics. With temperatures significantly above the elevated boiling point, there is a substantial decrease in spray droplet size compared to non-flashing conditions. There is also a corresponding large increase in spray velocity. These changes strongly affect spray trajectory, droplet burning, and droplet entrainment. It is a common practice to use liquor firing temperature as the key operating variable to control the median droplet size and height of the char bed. This strategy works more effectively for firing high solids black liquor than for low solids.

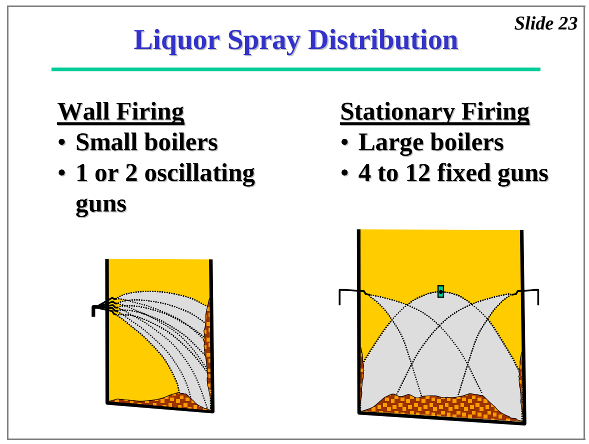




SPRAY DISTRIBUTION

Slide 23 shows two basic strategies for spraying black liquor. ***Wall firing*** was commonly practiced in many early boiler designs and is still used on some small boilers with liquor dry-solids of 68% or less. One or two oscillating liquor guns are located in the center of the furnace wall. The guns are continuously tilted up and down, and rotated, spraying liquor in a figure eight pattern to cover a wind band of the walls above the hearth. The objective is to distribute the liquor on the walls of the boiler where it can dry out before it falls to the char bed.

The second basic strategy known as ***stationary firing*** is now more commonly practiced on large recovery boilers with liquor dry-solids of 68% or more. Black liquor is sprayed into the furnace with 4 to 12 fixed guns, to achieve drying of liquor spray in suspension with hot gas rising from the furnace hearth. The objective is to minimize the amount of liquor sprayed on the walls, control droplet size to minimize carryover and distribute partially dried liquor and char over the bed.



After leaving the liquor nozzle, the spray distribution in the boiler is determined by the trajectories (or flight paths) of many droplets (of varying size) as they fall under the influence of gravity and aerodynamic drag. As shown previously in **Slide 6**, the actual droplet trajectory can be strongly influenced by the gas flow pattern in the furnace and by the dramatic changes in droplet size and density as they go through the stages of burning in the furnace. The gas flow in recovery boiler furnaces is often channeled flow with high velocity peaks and recirculation zones. The trajectories of different size droplets can be very different, with small droplets entrained and carried out of the furnace, large droplets going directly to the char bed, and intermediate droplets taking a complicated route through burning and smelt coalescence before going to the char bed.

Direct observation of droplet trajectories and burning in a recovery furnace is extremely difficult, at best. In the past decade computational models for the flow and combustion in recovery boiler furnaces have been developed. Results from these models have been favorably compared observable conditions in recovery boilers and they have become useful tools for design and optimization of recovery boilers. They are particularly good at showing the sensitivity of boiler operation to changes in air system and liquor spraying. They also can show the interaction of various parameters on boiler operation. Recently some of the complexity of these computational techniques has been relaxed to yield a model that predicts the trajectory and deposition of black liquor sprays within a recovery boiler furnace. The full description of this model is given in the paper *“Black Liquor Spray Calculator”* listed in the section **Further Reading** below.

Slide 24 describes how this calculator can be used and **Slide 25** gives some basic information about one particular recovery boiler that will be used as an example here. The results described below are only specific to this recovery boiler, but they demonstrate the utility of this approach and indicate the relative impact of several operating changes.

Slide 24

Predicting Spray Distribution and Deposits

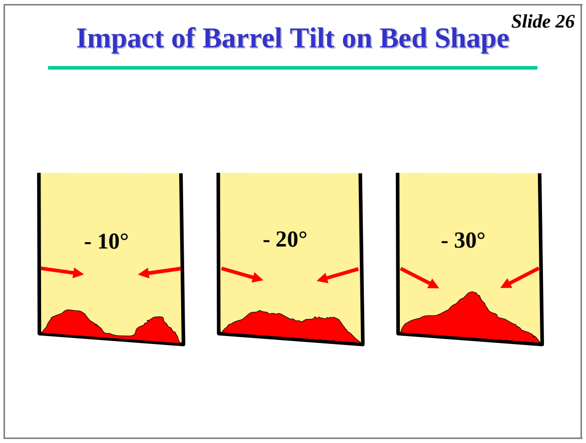
- **Based on computational analysis of the trajectories of large drops**
- **Useful for sensitivity studies**
- **Useful for initial optimization**
- **Examples for one particular boiler**
  - **Demonstrates sensitivity to operating parameters**
  - **Can show interactions between parameters**

Slide 25

Recovery Boiler Used in Examples

Floor dimensions	31.5 x 28.4 ft (9.6 x 8.7 m)
Firing method	Stationary firing
Number of guns	4, one at center of each wall
Barrel tilt	- 20° (median)
Nozzle size	#38 (38/32 inches or 1 $^{3}/_{16}$”)
Splash plate angle	49° (median)
Liquor dry solids	65.8%
Liquor temperature	220°F (104.4°C) non-flashing

Slide 26 shows the impact of barrel tilt angle on the char bed shape for the example boiler. These three char bed shapes are familiar to almost every recovery boiler operation at one time or another. Though the specific impact of barrel tilt on bed shape is almost certainly not correct for every recovery boiler, the results indicate that barrel tilt is probably the right parameter to adjust if char bed shape is the only issue being addressed. Applying the spray calculator to the specific geometry and operation of a specific boiler would be a good option if char bed shape is a chronic problem.



Slide 27 shows the impact of nozzle size on black liquor deposition in the furnace for the example boiler. The total black liquor flow was constant in these calculations so the larger nozzle resulted in lower liquor velocity at the nozzle, larger median droplet size and higher deposition rates of liquor near the center of the char bed.

Slide 28 shows the impact of splash plate angle on black liquor deposition in the furnace of the example boiler. Splash plate angle has multiple effects on the liquor spray. Here the higher angle spreads the liquor more to the periphery than the center of the char bed. Slides 27 and 28 make it clear that more than one parameter can influence the char bed deposition rate, and that optimization will depend on the interaction of several parameters.

Slide 29 shows the impact of liquor flashing on the liquor deposition on the char bed. Flashing impacts both the median droplet size and liquor velocity at the nozzle. This results in very different deposition rates on the char bed under flashing and non-flashing conditions.

SUMMARY

Median droplet size and spray distribution have been characterized for a range of black liquor nozzle designs and operating conditions. Approximate correlations of the median droplet size are available for a few nozzles under non-flashing conditions.

One of the most important aspects of black liquor nozzle performance is the impact of flashing on spray droplet size. Flashing occurs whenever the liquor firing temperature is more than a few degrees above its elevated boiling point. Flashing decreases the median droplet size of the spray and increases spray velocity.

Spray distribution after leaving the black liquor nozzle is complex function of nozzle geometry and boiler operating conditions. Computational models are useful for examining the sensitivity of liquor spray deposition to boiler parameters and for initial optimization.

The implications for Kraft recovery boilers are summarized in **Slide 30**.

Slide 30

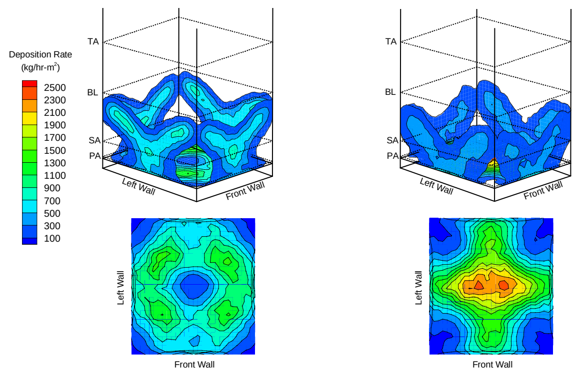
Implications for Recovery Boilers

- **Select nozzle type, number, arrangement, and barrel tilt for liquor spray distribution**
- **Select nozzle size for required flow, liquor pressure and median droplet size**
- **Recognize and control flashing**
  - **Flashing impacts spray velocity and droplet size**
  - **Stay above or below flashing temperature**
  - **If above, use temperature to control droplet size**

Slide 27

Impact of Nozzle Size

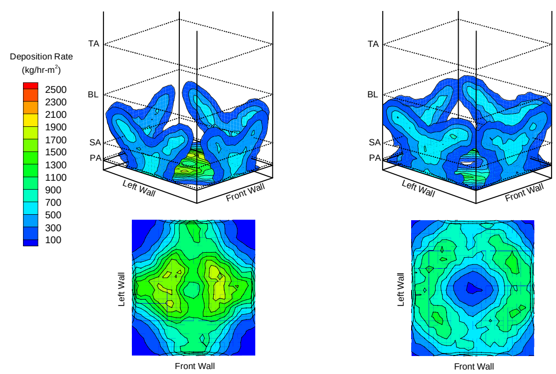
#34 nozzle **#40 nozzle**



Slide 28

Impact of Splash Plate Angle

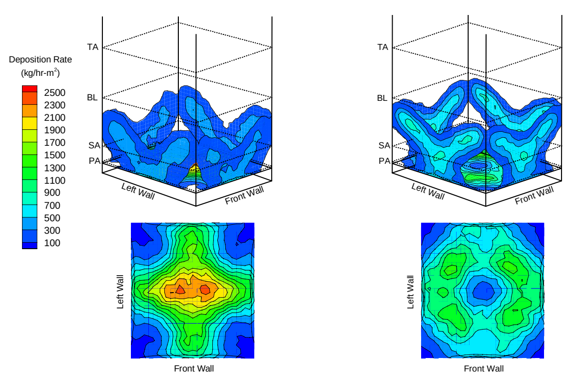
35° **49°**



Slide 29

Impact of Flashing

Non-Flashing **Flashing**



FURTHER READING

Kraft Recovery Boilers, Adams, T. N., Frederick, W. J., Grace, T., Hupa, M., Iisa, K., Jones, A. K., and Tran, H., T. N. Adams editor, TAPPI Press, Atlanta, GA, 1997.

"Black Liquor Spray Calculator", Viscardi, R.P., Wessel, R.A., Jorgensen, K.I., and Rivers, K.A., International. Chemical Recovery Conference, Charleston, SC, June 2004.