KRAFT BLACK LIQUOR DELIVERY SYSTEMS

Project 3657-2

Final Report

to the

U.S. DEPARTMENT OF ENERGY

February 1995
INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
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INSTITUTE OF PAPER SCIENCE AND TECHNOLOGY
Atlanta, Georgia

KRAFT BLACK LIQUOR DELIVERY SYSTEMS

Project 3657-2
Final Report

A Progress Report
to the
U.S. DEPARTMENT OF ENERGY

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ABSTRACT

An improved spray nozzle for black liquor injection into kraft recovery boilers has been sought which is expected to result in obtaining a controlled, well-defined droplet size distribution. An environmentally sound experimental spray facility capable of delivering black liquor at normal firing temperatures has been operated at the Institute of Paper Science and Technology to help achieve that goal. Previous work showed that black liquor sprays have a characteristic size distribution which is determined by the fluid mechanical forces breaking up the spray sheet issuing from the nozzle. Recent work has centered on applying vibratory assist as an independently-controlled force on the sheet breakup process in an attempt to change the drop size distribution. Results are presented which feature vibratory assist applied in the axial direction.
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EXECUTIVE SUMMARY

The research work described in this report represents the results of a six-year project designed specifically to develop the optimum black liquor delivery system for the current recovery boiler. Black liquor obtained from normal mill operation was used in this study.

The primary objectives of the research program have been:

* To develop laboratory equipment and methods for quantitatively studying commercial black liquor nozzle designs when spraying kraft liquors at typical operating conditions;

* To quantify droplet size distribution, velocity, and mass distribution for commercial nozzles spraying kraft liquors at typical boiler feed conditions;

* To develop techniques currently envisioned for improving the control of black liquor spray droplet size distribution with commercial nozzles; and

* To extend current liquor spraying technology by testing several fundamentally different, but commercially viable, delivery systems.

Success with this program should yield benefits in increased thermal efficiency and process productivity, as well as have potential for improvements in equipment design and process control. Coupled with the recovery boiler modeling project currently under way at IPST, the potential value of these programs to the industry is approximately $93MM/year for increased thermal efficiency and $240MM/year for increased productivity.

It was apparent from the work on standard commercial nozzles that gaining any degree of control over drop size distribution is going to require some external force, independent of the viscous, momentum, and surface tension forces which naturally control the droplet formation process. The concept of vibratory assist was visualized as a way to provide an independently-controlled means of influencing the sheet formation/breakup process. Application of vibrations transverse to the plane of the sheet was ineffective. Vibration in the direction of flow (i.e., axial pulsation) was expected to be more effective for reducing the randomness of the sheet breakup process.
Two nozzle designs featuring axial vibratory assist were conceptualized, fabricated, and tested with the black liquor spray apparatus. The more promising design could pulse the liquor flow by interrupting the flow at frequencies up to 450 Hz. Reliable operating characteristics were demonstrated. Results showed a dependence of median drop size on pulsation frequency, with a maximum occurring in the range of 220-260 Hz; the distribution width did not change. The implication of these results is that operating in the 220-260 Hz range will reduce the fraction of small droplets formed, which should result in reduced entrainment/carry-over rates in the recovery boiler without changing any of the normal process operating parameters, such as temperature, solids, or flow rate.
Black Liquor Delivery Systems Final Report

1.0 INTRODUCTION

The most important unit operation employed in the recovery cycle of the kraft pulping process is combustion of black liquor in the recovery boiler. This step is initiated by spraying the concentrated liquor through one of several types of commercial nozzles, the most common being the splashplate, the V-jet, and the swirl cone. Black liquor issues from the nozzle as a thin sheet, which subsequently breaks up into droplets. These droplets then go through the sequential processes of drying, pyrolysis and gasification, combustion, reduction, and smelt coalescence \[1\]. The rates at which these physical and chemical processes occur are highly dependent upon the size and size distribution of the droplets formed from the spray. The smaller the droplet, the greater the surface area per unit mass of liquor and, hence, the greater the rates of heat and mass transfer between the liquor particles and the furnace gases. While this is desirable for increasing recovery boiler capacity, it is offset by higher entrainment and carry-over in the upward flowing turbulent gas stream. Inevitably, the result is accelerated fouling of the relatively cool boiler tubes and more rapid plugging of the steam-producing section of the boiler.

To achieve increases in both black liquor throughput for recovery boiler-limited mills and recovery boiler energy efficiency, control of not only median droplet size, but also the width of the size distribution must be improved. Existing recovery boiler nozzles have been designed with two primary objectives – deliver production rates of liquor in a drop size range which gives acceptable combustion and reduction rates and efficiencies, and deliver the liquor reliably with minimal nozzle and boiler plugging. Any improvements which provide incremental capacity, while maintaining high efficiencies, will require better control of the size distribution.

Whether or not a narrower distribution should be the goal for an improved black liquor spray technology is still an open question. Too narrow a size distribution might not allow for a proper balance between suspension burning and burning on the char bed. It seems more likely that a drop size distribution having a reduced fraction of the finer sizes would enable increased capacity without increasing carry-over, while maintaining high combustion and reduction efficiencies.

The mass flow distribution of liquor within the furnace firing zone is not known and will not be in the near future because of the extreme difficulty of taking measurements in this turbulent, particulate-laden, corrosive, inaccessible, high temperature region. Characterization is best achieved through mathematical modeling using computational fluid dynamics and
fundamental kinetic and transport rate data.

The key to successfully modeling the recovery boiler furnace zone is to start with an accurate understanding of black liquor nozzle performance. Drop size and size distribution data are, of course, paramount. With regard to spatial distribution, it is also important to know not only the total angle of the spray sheet produced initially by given nozzle and liquor flow conditions, but also how the mass flow of black liquor varies with angular position within the sheet.

The ultimate answer will come from diagnostic tests on an operating recovery boiler. Regardless of what results are generated, both calculated and experimental, the bottom line is that some degree of operator control over drop size must be established so that the desired drop size distribution can be delivered to the firing zone of the recovery boiler.

1.1 OBJECTIVE

This research program was initiated as an applied effort to identify the optimum black liquor delivery system for the kraft recovery boiler and to present it to the industry in a timely fashion. Because it is not known what are the preferred spraying conditions for optimum recovery boiler operation, the fundamental objective was to develop ways to control the formation of black liquor droplets such that, once the optimum conditions are actually known, the specified drop size and size distribution can be obtained and the optimum achieved. The recovery boiler modeling program currently under way at IPST may ultimately be the best way to establish what are the preferred operating conditions for optimum operation.

1.2 DELIVERABLES

This research effort has delivered the following:

   a) A test facility capable of quantitatively assessing the performance of commercially viable spray systems while processing kraft black liquors at typical furnace feed conditions.

   b) The best commercial spray delivery system available with current technology.

   c) An appraisal of the technical viability of a fundamentally different black liquor delivery system.
1.3 BENEFITS

The objective of this program was viewed as delivering the tools which will help to realize the benefits of several other research activities in the black liquor area. Primary among these is the fundamental recovery boiler modeling research currently underway at IPST under DOE sponsorship. This basic work will determine the optimum black liquor droplet size and velocity distribution to maximize effective use of the furnace volume. Development of a system to achieve this desired liquor distribution was an objective of the present program. Potential benefits from this applied study have been projected in previous reports on this project; they are reproduced verbatim from last year's report in Table 1.1 below [2].

The increased thermal efficiency value for the industry is approximately $93 million/year; the incremental value of a 1% increase in process productivity for the industry is estimated at $240 million/year. These estimates reflect savings increments above the state-of-the-art recovery boiler technology that is available.

<table>
<thead>
<tr>
<th>Table 1.1 Benefits from Proposed Research</th>
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<tbody>
<tr>
<td><strong>Goals:</strong></td>
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<tr>
<td></td>
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<td></td>
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<td></td>
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<tr>
<td><strong>Targets:</strong></td>
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<tr>
<td><strong>Element</strong></td>
</tr>
<tr>
<td>Increased fired per cent solids</td>
</tr>
<tr>
<td>Reduced flue gas temperature</td>
</tr>
<tr>
<td>Reduced carbon in smelt</td>
</tr>
<tr>
<td>Reduced sootblowing steam</td>
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<tr>
<td>(Total)</td>
</tr>
</tbody>
</table>

2. Increased process productivity

Incremental production 1% 400

Industry Value:

1. Increased thermal efficiency

$5.1 \times 10^5 \text{Btu/adt} \times 60 \times 10^6 \text{adt/yr} = 3.1 \times 10^{13} \text{Btu/yr}$

$3.1 \times 10^{13} \text{Btu/yr} \times $3.00/10^6 \text{Btu} = $93,000,000/yr

2. Increased process productivity (1%)

$60 \times 10^6 \text{adt/yr} \times $400/adt \times 0.01 = $240,000,000/yr

-3-
Thermal efficiency and process productivity goals are not independent. The recovery boiler is often the bottleneck in the entire pulping process. Thermal efficiency is often sacrificed for high productivity. Hence, thermal efficiency and productivity increases may not be realized simultaneously. On the other hand, the recovery boiler is the only pulp mill operation which can often claim that improved unit productivity will result in increased millwide productivity.

The in-place capital investment in recovery boiler technology is so large (>10 billion) that radical changes, expansions, and replacements will be rare for the foreseeable future. Barring a significant departure from the kraft process in the near term, the industry will be firing black liquor in conventional recovery boilers well beyond the year 2000.

1.4 SUMMARY OF PREVIOUS RESULTS

1.4.1 Experimental

Black liquor was sprayed continuously through commercial nozzles using a heated, recirculating pump-around loop system [2]. The central component of the system was a spray chamber which served the dual purpose of providing a visible spray pattern while containing and storing the liquor inventory. The front and rear walls contained 1.5 m x 1.2 m tempered glass windows to allow back-lighting and videotaping of the liquor spray sheet and droplets. The side of the chamber had an opening for the spray nozzle which was oriented to deliver the liquor sheet in a horizontal trajectory parallel to the windows. Images of the black liquor spray pattern and breakup into droplets were obtained using a Xybion ISG-250 high-speed video camera, in combination with a Tracor-Northern TN-8500 image analyzer. Additional details are contained in refs.[2-7].

A two-stage Moyno pump circulated the liquor from the spray chamber through a spiral heat exchanger for temperature control, then through a Brookfield viscometer and back to the chamber. Correlations of liquor solids with viscosity and temperature enabled on-line control of liquor solids. The system had the capacity to deliver up to 150 L/min (as measured by a Foxboro magnetic flowmeter) of liquor to the nozzle at 650 kPa (80 psig). Because of odor control considerations, the spray chamber was operated under a slight negative draft. An ID fan drew air in through eight adjustable dampers, after which this gas flow, plus any volatiles coming from the liquor spray, were pulled through a carbon absorber (provided by Westvaco Corp.) before being exhausted to the atmosphere.

-4-
The three nozzles used predominantly in this work were a Babcock & Wilcox (B&W) 12/45 splashplate, a Spraying Systems Co. (SS) 11/65 V-jet, and a Combustion Engineering (CE) swirl cone. Each type is widely used for black liquor spraying (cf. ref.[5] for additional detail). Video recordings of the spray pattern were made at different positions and distances from the nozzle. From the visual analysis of the videotape, it was apparent that the solids concentration of the black liquor had a strong effect on droplet formation. At low solids (50%), the majority of the drops were spherical, but at high solids (70%), most of the images were large, irregularly shaped drops connected to strings and filaments.

Several drop size distribution models were tested to fit the experimental data; the best one was the square root-normal distribution. It was shown that the ratio of the standard deviation to the square root of the mass median diameter had a constant value of 0.2, and therefore, only one parameter was necessary to characterize the square root-normal distribution for black liquor.

Samples of sprayed liquor were collected by using two different types of patternators. The first arrangement used a single box with a large 7.6 cm x 7.6 cm opening. This collected samples from the V-jet nozzle at a distance of about 84 cm from the nozzle. A second patternator was constructed for the B&W splashplate nozzle. Nine 2.5 cm x 2.5 cm sampling boxes were arranged on a half-circle frame at 20° intervals. The radial distance from the nozzle to the front edge of each box was fixed at 11.5 cm. The sampling boxes cut the liquor sheet into sections which could be collected simultaneously for a fixed time and accurately weighed to determine the mass flux at the nine different angles (cf. ref.[3] for additional detail).

1.4.2 Mechanism of Droplet Formation

In the black liquor spraying process, the bulk fluid issues from the nozzle orifice and is converted into a fluid sheet, which subsequently breaks up into drops. Both a wave mechanism and a perforation mechanism have been postulated as the first step in the breakup of the sheet [8,9]. These both lead to the formation of cylindrical strands of fluid, which then form droplets according to jet breakup theory. The common denominator of the two mechanisms is that aerodynamic, inertial, viscous, and surface tension forces will be active in the ultimate droplet formation process. The balance of these forces is governed by fluid dynamics, subject to the random disturbances present in all systems. The inevitable result is a characteristic distribution of drop sizes. Spielbauer and Aidun discuss this in greater detail [8,9].
1.4.3 Drop Size Distribution

The range of droplet sizes in most commercial sprays is very broad, with more than two orders of magnitude between the smallest and largest diameter. Mathematical description of droplet sizes in a spray is most often presented in the form of a statistical distribution function. Because for most sprays the droplet diameter was not distributed in the manner of a normal, or Gaussian, curve, several alternative distribution curves were considered. Included were the Log-Normal, Square Root-Normal, Upper Limit Log-Normal, and Rosin-Rammler. For pressure atomizers and two-fluid atomizers, the Square Root-Normal distribution was recommended [10]. Previous research on black liquor sprays was correlated according to the Square Root-Normal distribution [11].

The statistical distribution models listed above were examined in this work, with the Square Root-Normal distribution best fitting the drop size data [3]. Use of the Square Root-Normal distribution allowed each of the experimental size distribution curves to be represented by just two parameters, the median diameter, $D_m$, and the standard deviation, $\sigma$. Because $\sigma$ tended to increase as $D_m$ increased, it was useful to define a normalized standard deviation, $\delta$, as $\sigma/\sqrt{D_m}$. This latter parameter was a better measure of the width of the size distribution because it removed the effect of the magnitude of the median diameter.

The data showed that the normalized standard deviation ($\delta$) was essentially constant for a given nozzle. This reduced the Square Root-Normal distribution to a one-parameter model, namely, the median drop diameter.

Examination of the drop size data for all three types of nozzles with several different black liquors over various combinations of solids concentration, temperature, and nozzle pressure gave a $\delta$-value of $0.20 \pm 0.03$. This relationship is valuable in predicting drop size distribution in that once $D_m$ is known, $\sigma$ can be calculated, along with the entire distribution.

That $\delta$ is invariant may be rationalized through the basic laws of mass and momentum conservation. What is essential to the drop formation process is the balance between viscous, inertial, pressure, and surface tension forces present in the system. These are dependent upon fluid properties, flow velocities, and nozzle design, i.e., the fluid mechanics of the system. There are no independently applied forces to change or upset the naturally occurring balance. This would imply that changes in drop size distribution, both in shape and width, must come from a nozzle design that features some independent external force, such as vibratory assist.

-6-
1.4.4 Flow/Pressure Drop Characteristics

Flow rate/pressure drop characteristics for the three nozzle types were correlated from a standard mechanical energy balance using the following equation:

\[ \Delta P = C_f \left( \frac{1}{2} \rho_L v_n^2 \right) \]  

where:
- \( \Delta P \) = pressure drop (Pa)
- \( \rho_L \) = liquor density (kg/m\(^3\))
- \( v_n \) = nozzle velocity (m/s)
- \( C_f \) = flow coefficient

The flow coefficient is a function of the type of spray nozzle. Pressure drop across the nozzle was assumed to be equal to the gauge pressure at the nozzle inlet because the outlet of the nozzle was at atmospheric pressure. For high temperature operation where the liquor was above the boiling point temperature, it was found that \( \Delta P \) must be based on the difference between the inlet pressure and the vapor pressure of the black liquor.

The explanation for this is that the minimum pressure in the nozzle occurs near the outlet at the vena contracta. The pressure at this point cannot drop below the vapor pressure of the black liquor. The result is that the nozzle exit pressure is maintained at the vapor pressure for temperatures above the boiling point.

A test series with the B&W splashplate, CE swirl cone, and SS V-jet nozzles was completed, using a 3x3x3 matrix (solids of 50, 60, and 70%; viscosities of 270, 90, and 30 cP; and nozzle pressures of 204, 307, and 410 kPa (15, 30, and 45 psig). Pressure vs. flow rate correlations were derived as a function of Reynolds Number. For the three tests at high viscosity and low pressure, the flow rate was too low to produce sheet breakup. Another three tests at 70% solids and low viscosity could not be completed because the heat exchanger did not have the capacity to heat liquor to well over the boiling point (130°C) in a single pass.

For the three splashplate nozzles tested (B&W 12/45, B&W 15/52, and Tampella 18) at various run conditions, \( C_f \) was correlated with Reynolds number according to the following equation \( (r^2= 0.91) \):

\[ C_f = 1.35 + 371 \text{ Re}^{-0.9} \]
For the SS V-jet nozzles (V-11/65, -21/65, -24/65), the corresponding correlation (Reynolds number based on nozzle hydraulic diameter) was:

\[ C_f = 1.06 + \frac{66.4}{Re} \quad (3) \]

For the CE V-jet nozzle (V-15), the flow coefficients were significantly higher (about 20%) than for the SS V-jets. Therefore, unlike the splashplate correlation, eq. (3) does not apply universally to all V-jet nozzles.

For the CE swirl cone (Sw-12), the flow coefficient was independent of Reynolds number and had an average value of 1.12.

1.4.5 Droplet Diameter

Background

Bennington and Kerekes [12] were the first to report on the size and size distribution of droplets from black liquor nozzles. The orifice diameter for their nozzle was only 0.7 mm, and resulting drop sizes were about one-tenth those from typical recovery boiler nozzles. Nonetheless, the distribution of drop sizes about the median was similar to those found in this study. They noted that the size distribution about the mean was primarily a function of the mechanism for sheet breakup. Spielbauer et al. [13] noted the same result using more typical black liquor nozzles. Hence, the basic mechanism of sheet breakup appears to be invariant and leads to a characteristic size distribution.

Effect of Spraying Conditions

Drop size measurements were correlated with physical and operating parameters (e.g., viscosity, density, surface tension, temperature, nozzle pressure, and nozzle design) by using appropriate dimensionless groups and the ratio of the median drop diameter to the nozzle diameter. The dimensionless groups chosen were Reynolds number, Euler number, and Schmidt number; Weber number and Ohnesorge number would have been of interest, but because these feature surface tension which could be neither varied nor measured, these groups were not considered. The three dimensionless groups are defined in order below:

\[ Re = \frac{D_n v_n \rho_l}{\mu_l} \]
\[ Eu = \frac{g_c P_w}{(v_n \rho_l)^2} \]
\[ Sc = \frac{\mu_l}{(\rho_l D_w)} \]
where: \( D_n \) = nozzle diameter (m)  
\( v_n \) = nozzle exit velocity (m/s)  
\( \rho_L \) = liquor density (kg/m\(^3\))  
\( \mu_L \) = liquor viscosity (kg/m\(^s\))  
\( g_c \) = gravitational constant  
\( P_w \) = vapor pressure of water (kg/m\(^2\)/s\(^2\))  
\( D_{wl} \) = diffusivity of water in liquor (m\(^2\)/s)

Each of the dimensionless groups can be related to various physical forces. Reynolds number represents the ratio of inertial to viscous forces; Euler number is the ratio of pressure to inertial forces and would characterize the process of water escaping the liquor sheet in the form of vapor, resulting in the formation of perforations. The Schmidt number relates mass and momentum transfer, characterizing the process of water molecules diffusing through the boundary layer at the gas-liquid interface surrounding the liquor sheet.

Taking two groups at a time and relating them to the droplet/nozzle diameter ratio, two correlations for the swirl cone nozzle emerged with \( r^2 \)-values above 0.95:

\[
\frac{D_m}{D_n} = 0.64(Re)^{-0.14}(Eu)^{0.09}
\]  
(4)

\[
= 0.10(Eu)^{0.16}(Sc)^{0.09}
\]  
(5)

For the V-jet:

\[
\frac{D_m}{D_n} = 0.73(Re)^{-0.12}(Eu)^{0.11}
\]  
(6)

\[
= 0.14(Re)^{0.17}(Sc)^{0.08}
\]  
(7)

In terms of discrete physical parameters, these reduced to:

\[
D_m = 1.68(D_n)^{0.86}(v_n)^{-0.32}(\rho_L)^{-0.25}(\mu_L)^{0.14}(P_w)^{0.09}
\]  
(4a)

\[
= 0.10(D_n)(v_n)^{-0.32}(\rho_L)^{-0.25}(\mu_L)^{0.09}(P_w)^{0.16}(D_{wl})^{-0.09}
\]  
(5a)

and:

\[
D_m = 1.67(D_n)^{0.88}(v_n)^{-0.34}(\rho_L)^{-0.23}(\mu_L)^{0.12}(P_w)^{0.11}
\]  
(6a)

\[
= 0.14(D_n)(v_n)^{-0.35}(\rho_L)^{-0.25}(\mu_L)^{0.08}(P_w)^{0.17}(D_{wl})^{-0.08}
\]  
(7a)

where \( D_m \) and \( D_n \) are in millimeters. If the diffusivity of water in black liquor is estimated from the Wilke-Chang correlation [14], which shows a reciprocal dependence upon viscosity, then
equation (5a) gives an effective viscosity exponent of 0.25.

The functional dependencies exhibited in equations (4a), (5a), (6a), and (7a) give interesting interpretations. Droplet diameter decreases as both velocity and density increase. Both are related to the kinetic energy of the liquor issuing from the nozzle, implying the greater the energy that is dissipated, the smaller the drop size. It is interesting to note the relative insensitivity of \( D_m \) to liquor physical properties, with the exponents in equations (4a)-(7a) generally in the 0.1 to 0.3 range. The apparent stronger dependence on nozzle diameter is artificial, since nozzle diameter was not varied for these correlations. (Data were obtained for different diameter splashplate nozzles, and these are reported below.)

The only operating parameters that were varied significantly within the data base for the above correlations were velocity and temperature. Hence, a correlation of the diameter ratio in terms of these two parameters was established:

\[
\frac{D_m}{D_n} = \kappa v_n^\alpha T^\beta
\]

where \( T \) is in °C, and the empirical values for \( \kappa, \alpha, \) and \( \beta \) are given in Table 1.2 [3]. The exponents for velocity are about the same as reported above based on dimensionless groups; the temperature exponents can then be expected to represent the combined temperature effects embodied in density, viscosity, and vapor pressure. The basic conclusion that drop size decreases weakly as temperature increases is consistent with the limited data of Bennington and Kerekes [12].

### Table 1.2 - Constants in Equation (8)

<table>
<thead>
<tr>
<th>TEST</th>
<th>( \kappa )</th>
<th>( \alpha )</th>
<th>( \beta )</th>
<th>( r^2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.30</td>
<td>-0.312</td>
<td>-0.194</td>
<td>0.894</td>
</tr>
<tr>
<td>2</td>
<td>4.51</td>
<td>-0.426</td>
<td>-0.407</td>
<td>0.820</td>
</tr>
<tr>
<td>3</td>
<td>2.61</td>
<td>-0.436</td>
<td>-0.264</td>
<td>0.679</td>
</tr>
<tr>
<td>4</td>
<td>0.69</td>
<td>-0.338</td>
<td>-0.092</td>
<td>0.929</td>
</tr>
</tbody>
</table>

**Effect of Nozzle diameter**

In mill recovery boilers, typical nozzle diameters range from 1 cm up to 3 cm. Since most of the laboratory testing was done with diameters at the low end of this range, it is important to determine how the mean drop size will change with increasing
nozzle diameter. Data were obtained for splashplate nozzles of three different diameters (9.5, 11.9, and 18.0 mm) at 84°C and pressures of 238 and 342 kPa (20 and 35 psig) with 56% solids black liquor. Linear regression of the data yielded:

\[ D_m = 0.24 \times D_n^{0.162} \]  

(9)

where \(D_m\) and \(D_n\) are in centimeters [2]. The relatively low value of the exponent in eq. (9) indicates that drop size is not strongly dependent on nozzle diameter. An increase in nozzle diameter from 1 cm to 3 cm would only increase drop size by a factor of 1.2.

**Effect of Black Liquor Type**

Black liquor properties vary from mill to mill and from day to day within the same mill, depending upon wood furnish and pulping conditions. These variations can impact recovery boiler operation through changes in the liquor swelling and burning characteristics.

To determine the effect of black liquor variability on drop size, five different mill black liquors were obtained from four different kraft pulp mills. Three were softwood liquors (Georgia), one hardwood (Michigan), and one a 50/50 mixture (Alabama). Each liquor was tested with two different nozzles (CE swirl cone and B&W splashplate), two nozzle pressures (238 and 342 kPa), one solids level (60%), and two viscosities (60 cP and 200 cP).

An analysis of variance (ANOVA) was used to determine significant effects of spraying conditions, including possible interactions. Of the variables studied, nozzle type, nozzle pressure, and liquor viscosity were all statistically significant (99% confidence limit) in their effect on drop size. The change in drop size with liquor type was not statistically significant, even at the 90% confidence limit; neither were any interactions. The most important variable was nozzle type. The effects of viscosity and nozzle pressure mirrored the previous results. In addition, the drop size distribution continued to fit the Square Root-Normal distribution law with a normalized standard deviation of 0.2.

**Effect of Temperature**

The effect of drop diameter on temperature has been reported above to vary by the -0.1 to -0.4 power. As black liquor temperature was raised continuously, there was a temperature
(designated the transition temperature) above which the spray droplet size decreased by more than 20%. At the same time, changes were observed in the shape and direction of the spray pattern. For both the V-jet and splashplate nozzles, the normally flat spray sheet opened up into an oval-shaped cone; also, with the splashplate nozzle, the central plane of the spray sheet moved away from the plane of the splashplate. The angle of this deviation was not measured, but it was estimated to be 20°-40°. These effects were observed to be reversible as temperature was lowered continuously to a value below the transition value.

Both of these changes can be attributed to vaporization of water. The physical effects of flashing can be analyzed by considering the flow of black liquor through the nozzle. Although the specific designs of the nozzles are quite different, they are similar in that the black liquor flows through a restriction before the spray issues from the nozzle. As the liquor flows through the restriction, its velocity increases, and its pressure decreases. The pressure at the inlet of the nozzle is higher than the vapor pressure of the liquor, and hence, single phase flow prevails at this point. As the liquor flows through the nozzle orifice and its pressure decreases, a point is reached where the vapor pressure exceeds the line pressure and vaporization occurs, resulting in a reduced fluid density and an increased velocity.

Since drop size was reported above to decrease as velocity increases, a spray from this two-phase flow emerging from the nozzle above the transition temperature would be expected to have a smaller diameter. The change(s) in shape and/or direction of the spray sheet above the transition temperature with a splashplate nozzle can result from the flashing steam contributing a component of momentum normal to the plate and, therefore, to the original plane of the spray.

The transition temperature was estimated to be several degrees above the atmospheric boiling point of the liquor and was dependent upon the dissolved solids content of the liquor. In this work, the transition temperatures were observed to be about 5°C above the atmospheric boiling point at 60% solids and about 9°C at 70% solids.

Since the transition temperature \( (T_{tr}) \) is the liquor boiling point at some elevated pressure, it should be predictable in the same way that the atmospheric boiling point of black liquor is [7]:

\[
T_{tr} - T_{bp} = (K_{tr} - K_{bp}) \frac{S}{(100-S)}
\]  \hspace{1cm} (10)

The value of \( K_{tr} - K_{bp} \) was 4°C; typical values of \( K_{bp} \) range from 10° to 15°C [15].
Using an average drop size calculated for temperatures above and below the $T_r$, the ratio of the median diameters above and below the transition temperature was 0.82. Applying this result to recovery boiler operation, a hypothetical 20% decrease in median drop diameter would mean that, for the same liquor mass flow, the number of drops would be doubled and the surface area increased by about 30%.

In addition to measuring the median drop size, the standard deviation of the Square Root-Normal distribution was also calculated for each test. Previous work at temperatures below $T_r$ showed that the normalized standard deviation ($\delta$) was essentially invariant at 0.20 (±0.03). For temperatures above $T_r$ in this work, the average value for $\delta$ was 0.19, signifying essentially no change in $\delta$ and leaving the Square Root-Normal distribution model as a one-parameter model.

1.4.6 Mass Flow Distribution in Liquor Sheet

The sheets of liquor that issued from splashplate and V-jet nozzles were characterized with respect to distribution of mass flows within the total spray angle ($\theta$), defined as the angle bounded by the left and right outer edges of the spray sheet. A maximum mass flux occurred at the spray centerline which coincides with the nozzle axis. The mass flux exhibited a dependence on angular position ($\phi$, defined as the angular position in the spray sheet measured with respect to the centerline of the splashplate), decreasing in magnitude out to the edge of the sheet ($\pm \theta/2$). At the very outer edge was a thick, slow-moving rim; just inside the spray angle the mass flux was larger than expected, while just beyond it the flux was essentially zero.

The total spray angle increased with operating pressure until it reached a maximum value; above this point, the spray angle decreased slightly with increasing pressure. Viscosity had a strong influence on the spray angle, with increasing viscosity causing a reduction in the spray angle. The spray angle for the splashplate was much wider than for the V-jet and approached 180° at high flow rates and low viscosities. The SS V-jet nozzle is classified as a 65° nozzle by the manufacturer, and the measured spray angle values approached this value at high flows and low viscosities.

In order to quantify how the mass flow varied with angular position in the spray sheet, it was necessary to define a mass flow factor (MFF) as the ratio of the measured flow at a given angular position to the average flow over the total spray angle [3,16]. Because each sampling box had a fixed width, the measured mass flow represented an average over the angle, $\Delta \phi$. Hence, the MFF becomes the ratio of the mass flux into the box at
angle \( (\phi \pm \Delta \phi/2) \) to the mass flux averaged over the spray angle, \( \theta \).

From visual observations of the liquor sheets, one could see that there was a central core in the angular range from \(-15^\circ < \phi < 15^\circ\) having a relatively uniform flow rate. Outside this region, the flow rate dropped off steadily to the outer rim.

A correlation of MFF as a function of angular position \( (\phi) \) was developed for predicting mass flow distribution for a nozzle under specified operating conditions. Although either a linear or a parabolic dependence would have produced a reasonable curve fit of the measured MFF profile, the linear correlation was judged unsuitable because the slope of the "curve" at \( \phi = 0 \) has a discontinuity, whereas the experimental curve was continuous in this region. The parabolic correlation satisfied this criterion at the centerline, and hence, it was used to represent the data.

If the MFF is expressed in the form:

\[
MFF = P - Q \phi^2
\]  

the constants \( P \) and \( Q \) can be approximated, knowing the MFF at \( \phi = 0 \) and at some other angular position, \( \phi(1) \). Hence, at \( \phi = 0 \), \( MFF = P \); at \( \phi = \phi(1) \), \( MFF = MFF(1) \) and \( Q = (P - MFF(1))/\phi(1)^2 \). It can be shown further that the model predicts \( \theta = (12(P-1)/Q)^{1/4} \) [16]. Modeling the mass flux profile as a parabolic function of angular position, with the maximum flux at the centerline, predicted the mass flux at the sheet centerline to be 1.5 times the average flux for the entire sheet cross section at the same radial distance from the tip of the nozzle. Model predictions of both the centerline flux and the full spray angle agreed to within 10\% of the experimental values for the splashplate nozzle. These results should provide useful input to mathematical models of the combustion processes occurring in kraft recovery boilers.

1.4.7 Alternative Commercial Nozzles

Commercially available spray nozzles from different commercial applications, ranging from spray coating to aerial application of pesticides for agricultural crops, were evaluated for their use with black liquor. Common commercial nozzle types not presently used with black liquor include: sonically assisted atomizers, two-phase atomizers, rotary disc atomizers, and full-cone nozzles. All but the last one are generally designed to provide fine droplets (under 100 microns) and thus were eliminated from consideration.

The nozzles we chose to test were the Bete Spiral R, Bete Whirl R, and Delavan Raindrop R. All are basically full-cone
nozzles with design features (internal or external) that give a tangential velocity component to the liquor flow; all are claimed to give coarse, uniform conical sprays.

Comparison tests were run on the three alternative nozzles, along with the standard B&W 12/45 splashplate, CE swirl cone, and SS F-12 V-jet [2]. Operating conditions were 75°C/60% solids (220 cP viscosity) and 89°C/56% solids (70 cP); nozzle pressures of 238 and 342 kPa (20 and 35 psig) were used.

Examination of the median diameters for the four sets of experimental conditions showed that the only nozzle to give a significantly different diameter was the Delavan Raindrop. It gave values 50-80% greater than the average of the other five nozzles. All six nozzles fit the square root-normal distribution, and all six gave the usual value for the normalized standard deviation of 0.20 ± 0.02.

Hence, the only alternative commercial nozzle to have shown any promise was the Delavan Raindrop. In this case, the size distribution was essentially shifted to the right, but with the same relative size distribution; the implication is that the fraction of small droplets (i.e., the ones that tend to be carried over in the recovery furnace) will be lower for the Raindrop, relative to a standard black liquor nozzle operating at the same conditions. Just how the recovery boiler would respond to combustion of a "Raindrop spray" is unknown at this point.

1.4.8 New Nozzle Concepts

A task was undertaken to develop new nozzle concepts in an effort to gain some degree of control over drop size and size distribution. One constraint always kept in view was that any new conceptual nozzle had to be easily implementable and very reliable. This latter limitation recognizes the need for the recovery boiler to remain on-line around the clock 350 days a year. One approach was to consider physical modifications to an existing splashplate nozzle which would change the nature of the sheet coming off the splashplate to reduce the randomness of the breakup process. A second approach was to employ the principle of vibratory assist and apply it to an existing splashplate or V-jet nozzle.

Modified Splashplate Nozzles

Conceptually, one way to reduce the randomness of the sheet breakup process would be to modify the smooth, flat surface of the splashplate in such a way that the liquor sheet is no longer uniform, but has defined zones of alternating thick and thin cross-section in the flow direction. In this way, the sheet
would initially tend to break at the thin spots, which would be governed by how the sheet thickness was perturbed by the surface characteristics of the modified splashplate. Hence, the initial breakup would no longer be random. Of course, subsequent breakup of the resulting individual "jets" into droplets would still be governed by fluid mechanical forces and the randomness that those forces introduce.

Six different modified splashplates were designed, fabricated, and tested in the black liquor spray chamber [2]. All the geometric modifications to the splashplate surface proved ineffective. One which used multiple cylindrical pegs mounted around the splashplate periphery and normal to the splashplate surface gave a 25% reduction in median diameter, with a 0-30% increase in the width of the distribution; both effects are undesirable.

**Dual Splashplate Nozzle**

It was hypothesized that a bimodal drop size distribution might be attractive in that the smaller size would tend to burn in flight while the larger size would fall to the char bed prior to combustion. An attempt was made to generate a spray with a bimodal size distribution by configuring two splashplates back-to-back, each with its own liquor flow [2]. The liquor feed was divided into two branches, each having a control valve to adjust the flow through its branch. By using different diameter nozzles and different pressure drops in the two branches, two different sheet velocities, and hence two different drop size distributions, were thought to be obtainable. Interaction of the two parallel liquor sheets coming off the splashplates could be varied by providing a spacer between the splashplates. By design, the spacer could not only control the distance between the sheets coming off the plates, but also the angle between the sheets. The sheets could readily be made to converge or diverge, thereby maximizing or minimizing the degree of sheet interaction. Naturally, each branch functioned like a typical splashplate nozzle, and hence, operational reliability of the dual splashplate concept was not a concern.

Results showed that if there was sheet interaction, a larger median drop size resulted in comparison to a single splashplate nozzle; size distribution widths were the same for both cases. If there was little or no sheet interaction, drop size and size distribution were unchanged from the single nozzle case. Under the conditions run, no bimodal drop size distributions were detected.

**Vibratory Assist**

A number of studies have been carried out regarding the
stability of thin liquid sheets moving in a gaseous environment. Inviscid theories of two-dimensional wave growth predict that, in the initial stages of growth, an optimum frequency exists where the growth rate is a maximum. Viscous theory, on the other hand, predicts the absence of a wave of maximum growth rate except at low velocities. Crapper et al. [17] have claimed that dominant waves seen on a sheet must be of a frequency imposed by some external force. Hence, the role of vibratory assist is to obtain growth rates of low amplitude waves at any distance from the nozzle orifice. Crapper and Dombrowski [18] suggested that drop size may be affected by both nozzle amplitude and frequency. Since these factors may depend upon natural frequencies in the apparatus, drop sizes in industrial settings could well turn out to be different from those given by the same nozzle in the laboratory.

Vibration of the liquor flow can be done either in-line with or normal to the flow. The resulting waves in the liquor sheet issuing from the nozzle should be in the dilational and sinuous modes, shown in Figs. 2.1 and 2.2, respectively [2]. Conceptually, the dilational mode would be expected to give a narrower drop size distribution, since the breakup of the sheet into ligaments should occur at the points of minimum thickness. These are not randomly placed because of the vibrations imposed on the system. The subsequent breakup of ligaments into drops will still be a random event. On the other hand, the sinuous wave mode maintains a constant sheet thickness, implying that sheet breakup will still be a random phenomenon going to ligaments, which then randomly break up into drops.

The sinuous mode was examined first because it was easier to accomplish experimentally. A splashplate nozzle was vibrated in a direction normal to the plane of the plate by a two-knobbed cam rotating with a motor shaft. Vibrational frequency was varied from 0 to 93 Hz. Splashplate displacements were about 0.1 and 0.2 mm. Using a black liquor flow rate of 12 gpm with liquor viscosities ranging from 75 to 150 cP, no significant changes in median drop size or normalized standard deviation were recorded. We did, however, observe that vibrations caused the liquor sheets to break up sooner than without vibration. The higher vibrational amplitude did form liquor bands whose width decreased with increasing frequency.

An alternative mode of generating transverse waves was examined using an air-driven vibrator. Frequencies up to 130 Hz were tried with the splashplate nozzle operated at the same conditions as for the cam-driven nozzle. Results showed a significant effect on the liquor sheet, the drop size, and size distribution. Bands of liquor formed whose width was inversely proportional to the vibrational frequency. The bands broke into smaller pieces just like sheets formed with no forced vibrations, resulting in a relatively broad range of drop sizes. Relative to
Figure 2.1  VIBRATORY ASSIST

Dilational Wave Generation

- Wave-like Disturbances to Upper and Lower Surfaces of the Sheet Are Out of Phase

- Vibration in Direction of Liquor Flow (i.e. Pulsation of Liquor Flow)

Figure 2.2  VIBRATORY ASSIST

Sinuous Wave Generation

- Wave-like Disturbances to Upper and Lower Surfaces of the Sheet Are in Phase

- Vibration in Direction Normal to Plane of the Sheet
the zero vibration case, the median diameter for 70 to 110 Hz on average was 20% higher, and the normalized standard deviation was 24% higher. No trend was observed with increasing frequency. Hence, this did not appear to be a promising route toward obtaining a more controlled drop size distribution.

The dilational wave mode was examined by imposing axial vibrations (i.e., pulses) on the liquor flow. This mode is very difficult to accomplish experimentally, as evidenced by the lack of activity reported in the literature. We conceptualized, designed, built, and tested an apparatus to mechanically pulse the liquor flow to a commercial V-jet nozzle under controlled conditions of vibrational frequency and amplitude [2].

A key feature of the method used to pulse the flow was that the operator could positively control the amplitude and frequency of vibration, not relying on a "spring constant" which most other mechanical vibratory methods do. Also, larger amplitudes could be accomplished than what are normally achieved with traditional acoustic or pneumatic vibrators.

Testing with axial vibratory assist using the pulsed flow mode described above was carried out with 62% solids black liquor flowing through a 3/8-inch V-jet nozzle at 73°C and 8 gpm. Liquor viscosities ranged from about 100 to 160 cP. Frequencies up to 147 Hz were run with a maximum variation in the liquor flow to the nozzle orifice of ±20% of the mean [2].

Compared with the zero vibration case, median drop diameters and normalized standard deviations for the vibratory runs were not significantly different. When the normalized standard deviation (6) values were correlated linearly with frequency, a small positive coefficient resulted, implying the distribution width increased with frequency. This is counter to the result that was expected. Unfortunately, equipment limitations precluded going to greater frequencies and amplitudes of flow variation with this design.

Dielectrophoresis

An alternative concept which has potential for influencing drop size distribution in black liquor sprays may use the phenomenon of dielectrophoresis where an electric field is positioned around the spray sheet to alter the direction of flow of the neutral, but polarizable droplets that are formed. By exerting an independently controlled force on the droplets that will be proportional to drop diameter, it may be possible to cause collisions of the smaller drops with larger ones, resulting in coalescence. Electrostatic forces have been used to encourage coalescence in emulsions since the beginning of the 20th century.
Coalescence is known to occur as particles or droplets moving at different velocities collide. Dielectrophoresis enhances this tendency by providing a force of attraction between two polarized droplets.

This concept, if successful, should reduce the fraction of fine droplets and result in a size distribution skewed toward the larger sizes. If a drop size distribution can be achieved having a reduced percentage of the fine fraction, then entrainment/carry-over rates in the recovery boiler should be decreased, thereby making room for a capacity increase. Improvements in energy recovery efficiency would also be expected from reduced sootblowing requirements.

Dielectrophoresis is the movement of an uncharged particle in a nonuniform field, by virtue of the dipole induced on the particle by the field [19]. The dielectrophoretic force on a droplet will be proportional to droplet volume, field strength, field gradient, and difference in dielectric constants between the droplet and the gas space through which it is flowing. Typically, field strengths of 10 kV/m are required for dielectrophoretic forces to be significant.

Since the force of an isolated dipole is toward the higher field strength for both polarities of field, both AC and DC fields produce dielectrophoretic motion. In a DC electric field, the dielectrophoretic force is normally much lower than the electrophoretic force, but there is no net electrophoretic motion in an AC field. Hence, an AC field can be used to make independent observations of dielectrophoretic effects.

Generation of a nonuniform field can be accomplished by any number of electrode configurations. Of course, parallel plates are excluded because the resulting field is uniform. Our initial choice of electrode configuration which could be mounted in the black liquor spraying apparatus consisted of three rods, contained in each of two parallel planes, spanning the lateral area of the spray sheet and providing a nonuniform field for practically all of the drops that form.

With this geometry, two operating modes were possible. In the first case, the spray was positioned equidistant between the two planes of electrodes. Droplet migration toward both planes was expected, in principle. Only the drops exactly equidistant from the two electrode planes would not experience a nonuniform field, and hence, they would not be subject to the dielectrophoretic force. In the second arrangement, the electrode planes were both on one side of the spray sheet. The electric field lines of force were more nonuniform for all droplets, and hence should have provided a stronger dielectrophoretic force on all drops in the spray.
An exploratory test employing dielectrophoresis was conducted at 38°C using 48% solids black liquor flowing at 12.6 gal/min from a SS 15/65 V-jet nozzle. At these conditions, the liquor viscosity was 130 cP.

The tests were performed both with the spray sheet centered between the two electrode planes and with both electrode sets to one side of the sheet. In both configurations, the closer electrode set was about 9 inches from the center of the spray sheet. Direct current voltages of 3.0 and 5.0 kV were applied between the electrode sets, yielding a maximum field strength of about 10 kV/m.

The voltage limitation in our system was determined by the cutoff current for the power supply. The electrodes were encased in insulating PVC tubing, but this did not prevent current flow for voltages above 5 kV. The key parameter here is the "spark-gap voltage" which, for a given dielectric medium between electrodes of known spacing, is the maximum voltage possible before breakdown occurs. For 5 kV with air as the dielectric, the minimum allowable distance separating the electrodes is 1-2 mm. With black liquor droplets effectively increasing the dielectric constant of the medium between the electrodes, the minimum separation distance is significantly increased. Hence, higher field strengths with this electrode configuration did not appear to be possible.

Drop size determinations using dielectrophoresis conditions showed no significant effect of field strength on drop size or size distribution for field strengths up to 10 kV/m, the maximum field strength allowed before dielectric breakdown occurred. Hence, it did not appear that drop size distribution could be significantly altered by this route.

2.0 RESULTS FROM YEAR SIX

2.1 Axial Vibratory Assist - Interrupted Flow Design

An alternative mode of achieving vibratory assist in the axial direction is to use flow interruptions rather than pulsations. Our initial design reported previously [20] was unreliable mechanically and limited in frequency of pulsation to under 30 Hz. Above this frequency, the rotating tube was subject to binding and seizure. An improved design enabled higher pulsation frequencies with improved operability and reliability. This was accomplished by positioning all holes in both the rotating and stationary pipes at the same axial position. The rotating cylinder contains two or more holes at a fixed axial position, while the outer pipe section contains two outlets, diametrically opposed at the same axial position. In the first design, the sets of holes were axially displaced.
As with the first design, one outlet on the outer pipe is connected to the nozzle orifice, while the other outlet is connected to a recycle line. Black liquor is fed to the inner cylinder which is rotating at a rate set by a drive motor assembly. Liquor flows out to the nozzle or to the recycle as dictated by whether or not the holes in the rotating inner cylinder line up with a hole in the stationary outer pipe. In general, when liquor flows to the nozzle orifice, it does not to the recycle; and vice versa. Leakage through the annular space between the rotating and stationary bodies is minimized by providing a tight clearance between the bodies.

The net effect of this concept is to provide an interrupted flow to the nozzle orifice while not deadheading the black liquor pump. The frequency of interruption is determined by the angular rotation speed provided by the drive assembly. The amplitude of the pulses created in the flow to the nozzle is determined by the relative sizes of the holes and the liquor pressure. Additional pairs of holes could be drilled in the rotating cylinder to increase the frequency of spray interruption.

A Disclosure of Invention has been filed covering a nozzle to give a pulsed black liquor flow by the flow interruption mode described above.

For vibratory assist to work effectively, it must be done at the proper frequency and amplitude of pulsation; otherwise, the natural frequency of the sheet will dominate, giving a normal distribution of drop sizes. An estimate of the required vibrational frequency was calculated from wave theory, assuming that the sheet breaks up into discrete uniform bands with no interactions between adjacent bands [2]. For typical values of the black liquor process parameters, a minimum vibrational frequency of 240 Hz was predicted. There is no easy way to estimate the desired amplitude because it is related to complicated stability theory.

2.2 Axial Vibratory Assist - Interrupted Flow Results

Testing with axial vibratory assist using the interrupted flow mode described above (cf. Fig. 2.3) was carried out with 62% solids black liquor flowing through a 3/8-inch V-jet nozzle at 73°C and 8 gpm. Liquor viscosities ranged from about 100 to 160 cP. The distributor design was machined so that liquor flowed to the nozzle orifice 1/4 of the time (3/4 time going to recycle). The frequency range extended from 0 Hz up to 450 Hz; liquor solids and temperature (: viscosity) were held constant.

Fig. 2.4 shows the effect of pulsation frequency on median drop size. The filled symbols represent actual data, whereas the unfilled symbols are median diameters calculated for no pulsation
Figure 2.3  AXIAL VIBRATORY ASSIST

Interrupted Flow Mode

Black Liquor In

Liquor to Nozzle

Liquor to Recycle
from previously reported correlations, at the same respective spraying conditions for each data point. The calculated zero pulsation curve is basically flat. Interestingly, median drop size with pulsation increased from 2.2 mm with no pulsation up to a maximum of 3.5 mm at 220 to 260 Hz, then decreased steadily to 2.5 mm at 450 Hz. The shape of the median drop diameter vs. pulsation frequency curve was nearly sinusoidal, supporting the expectation of harmonic behavior that should be characteristic of a vibratory process (cf. Fig. 2.4). Surprisingly, the normalized standard deviation of the drop size distribution did not show any significant variation with pulsation frequency (cf. Fig. 2.5).

Since one of our primary objectives was to be able to spray black liquor into a recovery boiler with minimal droplet entrainment and carry-over, it would seem intuitively obvious that the fraction of small drops in a spray should be minimized. Based upon the size distributions measured, we have calculated the fraction of drops in an individual spray at a given frequency that is smaller than 1 mm and 0.5 mm. Plotting the % Less Than 1 mm (or 0.5 mm) vs. Pulsation Frequency, the curve goes through a minimum in the frequency range where the maximum median drop sizes occurred (cf. Fig. 2.6).

The important question at this juncture is what do these results mean with regard to optimizing recovery boiler performance? A major operational concern is droplet carry-over, and we have not demonstrated any ability to narrow the drop size distribution which might result in reducing the fraction of small size droplets, thereby reducing carry-over. But narrowing the drop size distribution is not a necessity.

What we have shown is a way of increasing median drop diameter without changing the size distribution and doing this independent of the normal process operating parameters (e.g., temperature, pressure, % solids); the only quantity we have to change is pulsation frequency.

These results can be used to calculate the frequency dependence of the mass fraction of drops in a given spray that would be less than some small diameter, say 1 mm or 0.5 mm. Fig. 2.7 plots the % Less Than 1 mm (or 0.5 mm) vs. Median Drop Diameter and includes a calculated curve for a normalized standard deviation of 0.19. It graphically shows the benefits of being able to increase median drop diameter by pulsing the liquor flow and obtaining a spray with a reduced fraction of fine droplets. Results show that 4% of the drops would be less than 1 mm at zero pulsation (median drop diameter 2.2 mm) and about 1% at the 230 Hz condition which gave a median drop diameter of 3.5 mm. This may have interesting implications for reducing carry-over in recovery boilers; predictions using the IPST recovery boiler model currently being developed will be generated to confirm this desired result.

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Fig 2.4 Drop Diameter vs. Frequency - Tests 75 and 83

![Graph showing the relationship between drop diameter and pulsation frequency for Tests 75 and 83. The graph includes data points for each test and predictions at 0 Hz.]
Fig 2.5 Drop Diameter and Normalized Standard Deviation vs. Frequency - Test 83

- Median Drop Diameter (mm)
- Pulsation Frequency (Hz)
- Symbols:
  - Dm - Test 83
  - 10^-s/DM^-0.5 - Test 83
  - Strand fraction - Test 83
Fig. 2.6 Percent Less Than 1.0 mm vs. Frequency - Test 83
Fig. 2.7 Percent Less Than 1.0 mm vs. Median Drop Diameter - Test 83
3.0 CONCLUSIONS

1. Gaining independent control over drop size distribution in black liquor sprays from commercial nozzles will require an independently-controlled external force, such as vibratory assist.

2. Vibratory assist in the axial direction, as applied to black liquor spraying, was accomplished with two novel nozzle designs. The one achieving a pulsed flow by inducing periodic flow interruptions has shown some promise in changing the mean drop size without changing the normal process operating parameters. There may exist a harmonic frequency where a minimum of small size drops is made.

3. To what extent the drop size distribution should be narrowed or skewed to have a positive impact on recovery boiler performance is not known at this time. An estimate can be obtained by specifying different drop size distributions as input to the recovery boiler model currently being developed by the Institute of Paper Science and Technology and calculating the model predictions.

4. Median droplet size data from a B&W splashplate nozzle and a CE swirl cone nozzle showed a weak dependence on liquor velocity and fluid physical properties. The ratio of median droplet diameter to nozzle diameter was related to the product of Reynolds Number and Euler Number, each raised to an experimentally determined nonintegral power; similarly, Euler and Schmidt Numbers also correlated well. Both dimensionless correlations were broken down into a product of the individual physical parameters, each raised to an experimentally determined power. It was shown that the parameters which most strongly influenced mass median drop diameter were nozzle diameter, and liquor density and velocity. At high solids levels, liquor viscosity became important. When droplet diameter was empirically correlated with velocity and temperature raised to appropriate exponents, drop size was shown to decrease as either operating parameter was increased.

5. Several drop size distribution models were tested to fit the experimental data; the best one was the square root-normal distribution. It was shown that the ratio of the standard deviation to the square root of the median diameter has a constant value of 0.2, and therefore, only one parameter is necessary to characterize the square root-normal distribution for black liquor sprays.

6. As temperature was increased, drop diameter gradually decreased until a transition temperature was reached (5-9°C above the atmospheric boiling point, depending on % solids) where the drop size abruptly decreased by about 20%; the normalized
standard deviation for the drop size distribution remained unchanged at 0.2. This effect was accompanied by a noticeable change in the physical appearance of the spray. The normally planar spray sheet became oval in cross section, and for a splashplate nozzle, the central plane of the sheet came off the plate at a 20 to 40 degree angle, rather than at zero degrees. These phenomena were attributed to flashing at the nozzle.

7. Black liquor spraying characteristics were not sensitive to the type of liquor at the same viscosity. Median diameter was shown to depend most strongly upon nozzle type and pressure, along with liquor viscosity. A weak dependence upon nozzle diameter was also observed.

8. Measurements were made of the local distribution of liquor flow in the spray pattern as a function of the angle from the sheet centerline. Results for both the splashplate and V-jet nozzles showed the mass flow distribution to be parabolic, with the maximum mass flow at the centerline and decreasing with increasing angle. Limited analysis of drop size as a function of the angle from the sheet centerline showed no significant effect.

9. Consideration of alternative commercial nozzles uncovered none which featured improved control over median diameter and width of the diameter distribution. The Delavan Raindrop did give a coarser-than-normal spray, which gives it potential for producing sprays that result in reduced entrainment/carry-over rates in recovery boilers.

10. Configuration of a splashplate-type nozzle to give two parallel liquor sheets, which subsequently break up into two distinct droplet distributions, gave a larger median drop size than a single splashplate nozzle if there was sheet interaction. If there was little or no sheet interaction, drop size and size distribution were unchanged from the single nozzle case. Under the conditions run, no bimodal drop size distributions were detected.

11. Geometric modification of the surface of a splashplate nozzle to alter drop size and size distribution at near-normal spraying temperatures proved ineffective. However, using multiple cylindrical pegs mounted normal to the splashplate surface gave a 25% reduction in median diameter, with a 0-30% increase in the width of the distribution. These were attributed to the formation and breakup of multiple jets rather than a sheet of liquor.
4.0 REFERENCES


APPENDIX A - Papers Published


