Flow and pressure drop characteristics of black liquor nozzles

T. M. Spielbauer and T. N. Adams

Black liquor nozzles like the B&W splashplate and the CE U-type and V-type should be insensitive to routine fluctuations in viscosity, solids contents, and temperature.

Black liquor is the by-product of the wood pulping process. It consists of an aqueous solution of the organic material removed from digested wood along with the spent inorganic cooking chemicals used in the digestion process. Black liquor is burned in large process units called "recovery boilers" to recover the inorganic chemicals and to recover the energy in the organic material. Black liquor is introduced into the recovery furnace through a set of nozzles often referred to as "liquor guns."

Several aspects of black liquor nozzles are currently under intensive study (*1, 2*). The main thrust of these studies is to control the black liquor droplet size for optimizing combustion. These studies complement numerous field tests of alternative nozzles carried out by individual mills, where less precise but immediate and practical results are obtained. The proper selection of nozzle size and number depends on a knowledge of the flow and pressure drop characteristics of these nozzles.

In the mill situation, black liquor nozzles are connected through rigid gun extensions and flexible hoses to ring headers that encircle the recovery boiler. These ring headers are typically 15 cm (6 in.) in diameter, while the connections to the individual nozzles are 2.5-5 cm (1-2 in.) in diameter. Reasonable engineering calculations of flow and pressure drop characteristics in these lines are possible if the black liquor viscosity is known. However, the geometries of the various types of nozzles have made the calculation of the pressure drop across them less certain.

Our purpose here is to present data on the flow and pressure drop characteristics of black liquor nozzles. We will (a) describe the three most common types of black liquor nozzles and show the range of their usual operation, (b) describe the spray facility where the flow/ΔP data for the nozzles were taken, (c) present the available data for four nozzles, and (d) discuss the data in terms of the fluid mechanics of nozzle flow.

Spielbauer is a graduate student, and Adams is a professor at The Institute of Paper Science and Technology, 575 14th St., N. W., Atlanta, Ga. 30318.

Black liquor nozzle description

Babcock & Wilcox splashplate nozzle

Splashplate-type nozzles are widely used for black liquor spraying. The basic arrangement is a straight tapering nozzle section that causes the black liquor flow to impinge on a flat or slightly curved plate at an angle of approximately 45°. The flow flattens into a broad fluid sheet which subsequently breaks into ligaments and droplets after leaving the plate. A diagram of a typical black liquor splashplate nozzle from the Babcock and Wilcox Co. (B&W) is shown in **Fig. 1**. Two of these nozzles were used in taking the data.

One nozzle will be referred to as a B&W 12-49, while the other is a B&W 15-52. The first two digits in this nozzle designation refer to the nozzle exit diameter measured in thirty-seconds of an inch. The diameter for the first is 12/32 in. (0.375 in. or 0.95 cm), while the second is 15/32 in. (0.469 in. or 1.19 cm). The second two digits in this nozzle designation refer to the angle at which the fluid exiting the nozzle orifice strikes the splashplate. The jet from the first nozzle impinges on the splashplate at a 49° angle. Due to practical test considerations, these nozzles were selected from the small end of the spectrum of nozzle sizes used in commercial service.

For all the nozzle types, the flow/ΔP characteristics will be presented in terms of flow coefficients that are used in equations of the form:

$$\Delta P = C_f (1/2) \rho V_n^2 \qquad (1)$$

where

ΔP = pressure drop across the nozzle, Pa

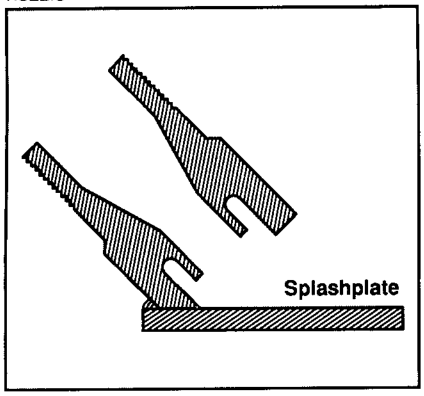
C_f = flow coefficient, unitless

ρ = fluid density, kg/m³

V_n = fluid velocity at the minimum flow area, m/s.

The characteristic flow velocity for the nozzle is evaluated at the minimum flow area. The minimum flow area is easy to identify for the B&W splashplate nozzle

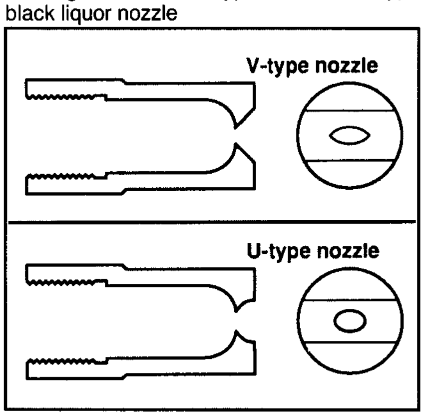
1. Diagram of a B&W splashplate black liquor nozzle



I. Typical dimensions and flows for B&W splashplate nozzles

	SI units	*Engineering units*
Nozzle exit diameter	1.9-3.2 cm	0.75-1.25 in.
Operating pressure	124-330 kPa	18-48 psi
Nozzle exit velocity	13.7-24 m/s	45-80 ft/s
Black liquor viscosity	0.05-0.25 Pa•s	50-250 cp
Reynolds number	1400-21,000	1400-21,000

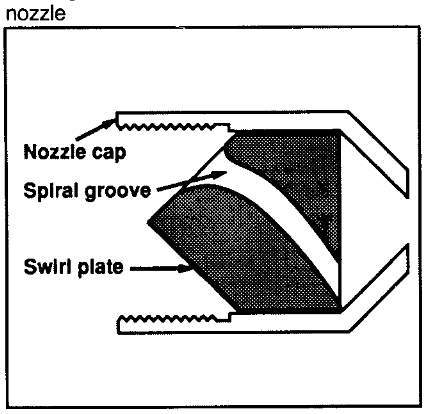
2. Diagram of a CE V-type and a CE U-type black liquor nozzle



II. Typical dimensions and flows for CE swirl cone, V-type, and U-type nozzles

	SI units	*Engineering units*
Minimum nozzle diameter	1-1.9 cm	0.4-0.75 in.
Operating pressure	82-125 kPa	12-18 psi
Nozzle velocity	9-11 m/s	30-37 ft/s
Black liquor viscosity	0.03-0.15 Pa•s	30-150 cp
Reynolds number	810-9405	810-9405

3. Diagram of a CE swirl cone black liquor nozzle



III. Fluid properties and operating conditions for the nozzle flow/ΔP tests

	Black liquor		*Corn syrup*	
	SI units	*Engineering units*	*SI units*	*Engineering units*
Specific gravity	1.35-1.39	1.35-1.39	1.38	1.38
Dry solids	66-69%	66-69%	73%	73%
Temperature	92-117°C	198-243°F	25-94°C	77-201°F
Pressure	21-502 kPa	3-73 psi	41-646 kPa	6-94 psi
Flow	0.5-2.5 L/s	7.5-40 gal/min	0.3-2.3 L/s	5-36 gal/min
Viscosity	34-140 mPa•s	34-140 cp	160-1238 mPa•s	160-1238 cp
No. of data points	37	37	108	108

because it is the exit area, but it is less straightforward for some of the other nozzles.

The flow coefficient is related to the other commonly used parameter for characterizing the flow/ΔP relationship for nozzles—the discharge coefficient, C_D. The discharge coefficient is used in the equation:

$$Q = C_D A (2\Delta P/\rho)^{1/2} \quad (2)$$

where

Q = volume flow rate, m³/s

A = flow area, m²

C_D = discharge coefficient, unitless.

so that:

$$C_f = 1/C_D^2 \quad (3)$$

A sharp-edged orifice has a C_D of approximately 0.6, while a flow nozzle has a C_D near 1.0. This results in a range for C_f from 1.0 to 2.8.

The flow coefficient is the sum of contributions from inertial acceleration and viscous losses. The inertial acceleration term is the difference in velocity head between the entrance and the minimum flow area. The inertial acceleration term will be unaffected by the specific condition at the nozzle entrance if the initial velocity head is much smaller than the velocity head at the minimum flow area. The velocity head is given by:

$$h_v = 1/2\ V^2 \tag{4}$$

where

h_v = velocity head, m^2/s^2

By continuity:

$$A_e V_e = A_n V_n \tag{5}$$

where

A_e = flow area at the entrance, m^2

V_e = velocity at the entrance, m/s

A_n = minimum flow area of the nozzle, m^2.

so that for circular cross sectional areas:

$$h_{ve}/h_{vn} = (D_n/D_e)^4 \tag{6}$$

where

D_e = diameter at the entrance, m

D_n = diameter at the minimum flow area, m.

For the B&W splashplate nozzle, the entrance diameter is approximately 1.8 times the nozzle diameter, so that:

$$h_{ve}/h_{vn} = (1/1.8)^4 = 0.095 \tag{7}$$

The entrance velocity head is less than 10% of the nozzle exit velocity head, so the flow coefficient will be insensitive to specific inlet conditions.

The viscous term for fully developed pipe flow is expressed in the form:

$$\Delta P = (1/2)\rho\ V^2\,(L/D)\,(C/Re_n) \tag{8}$$

with

$$Re = \rho\ V D/\mu \tag{9}$$

where

V = local average velocity, m/s

Re = Reynolds number

μ = fluid viscosity, Pa·s

L/D = pipe length-to-diameter ratio

C,n = constants.

Characteristic dimensions and flows for the B&W splashplate nozzles are presented in **Table I**, which shows a range of 1400–21,000 for Reynolds number. Using an upper limit for Reynolds number of 2000 for laminar flow, we see that the flow regime for the B&W splashplate nozzle spans the range from laminar flow to turbulent flow.

Equation 8 is specifically for fully developed flow. Fully developed flow only occurs when the pipe length-to-diameter ratio, L/D, is fairly large. The usual range for fully developed turbulent flow is an L/D greater than 10, while L/D must be greater than 100 for many laminar flow situations. For the B&W splashplate nozzle, the L/D is only approximately 4.3, and most of this length is tapering. Therefore, the fully developed flow equation for viscous loss is not directly applicable to this nozzle or to the other black liquor nozzles. For this reason, an *a priori* calculation of flow-pressure drop characteristics of black liquor nozzles would be quite difficult.

Combustion Engineering's V-type and U-type nozzles

V-type and U-type nozzles are widely used in spray applications. Combustion Engineering (CE) offers both types for black liquor service. **Figure 2** presents a diagram for each type. The nozzle consists of a cylindrical passage capped with a hemisphere. A V-shaped or U-shaped notch is cut diagonally across the cap, producing an approximately elliptical nozzle opening. The opening in the V-type nozzle has a narrower aspect ratio and sharper corners than the U-type. The opening for the U-type is closely approximated by a true ellipse, while the V-type is somewhat less so. The area and equivalent circular diameter for each are given by:

$$A_u = (\pi/4)\ b\ c \tag{10}$$

$$D_u = (b\ c)^{1/2} \tag{11}$$

$$A_u = 0.9\ (\pi/4)\ b\ c \tag{12}$$

$$D_u = 0.95\ (b\ c)^{1/2} \tag{13}$$

where

A = nozzle exit area, m^2

D = equivalent circular diameter, m

u, v = subscripts for U-type and V-type nozzles

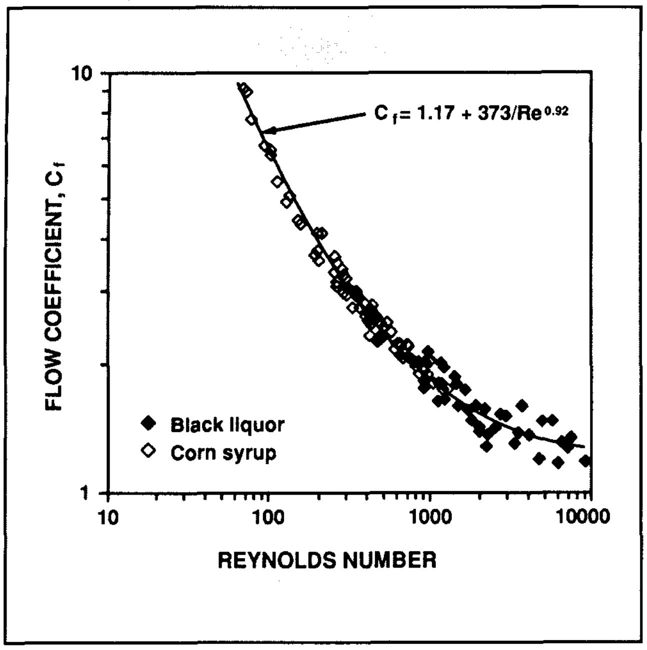
b, c = major and minor axis dimensions, m.

We used a CE U-type nozzle for which the major and minor axis dimensions were 13.5 mm and 9.1 mm (0.53 in. and 0.36 in.), which is equal to a circular nozzle diameter of 11.1 mm (0.44 in.). For the CE V-type nozzle used, the major and minor axis dimensions were 18.3 mm and 8.3 mm (0.72 in. and 0.33 in.), equal to a circular nozzle diameter of 11.7 mm (0.46 in.).

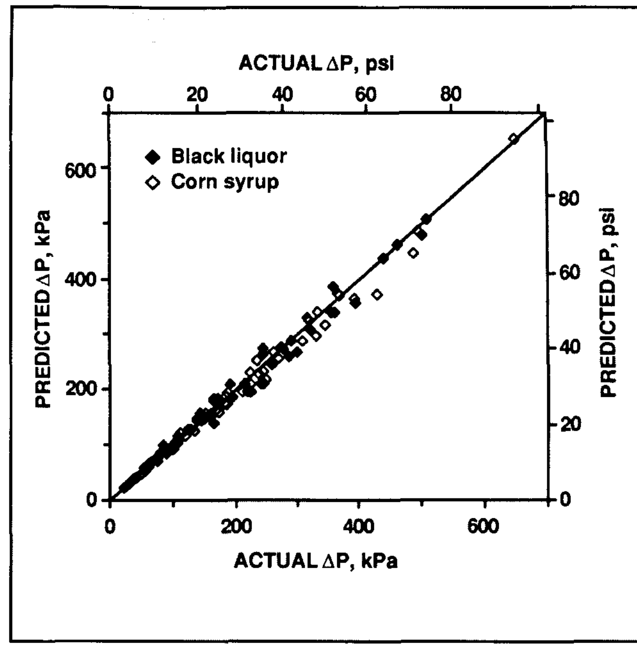
For both the U-type and the V-type nozzle, the entrance diameter is more than twice the nozzle exit diameter. As with the splashplate nozzle, the flow/ΔP characteristics will be insensitive to the initial flow conditions at the nozzle entrance.

V-type and U-type nozzles have not been in black liquor service as long as the splashplate or the other common nozzle, the swirl cone. However, values of dimensions and flows for current practice with V-type and U-type nozzles should be similar to those for the swirl cone. Typical values are presented in **Table II**.

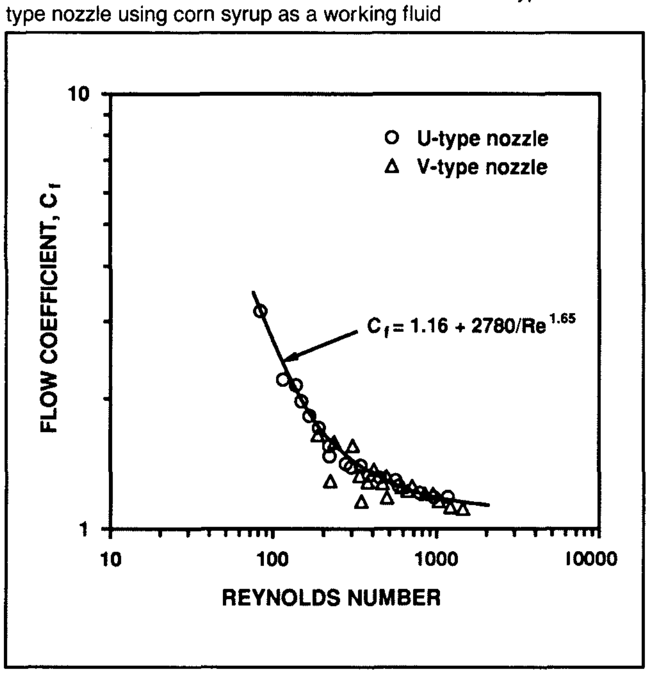
4. Flow coefficient data and correlation for two B&W splashplate nozzles using black liquor and corn syrup



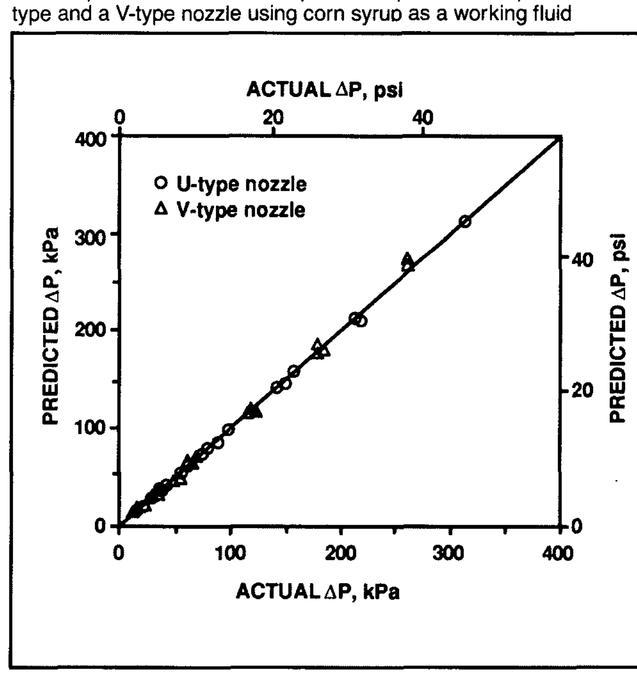
5. Comparison of actual and predicted pressure drop for two B&W splashplate nozzles using black liquor and corn syrup



6. Flow coefficient data and correlation for a CE U-type and a V-type nozzle using corn syrup as a working fluid



7. Comparison of actual and predicted pressure drop for a CE U-type and a V-type nozzle using corn syrup as a working fluid



Combustion Engineering swirl cone nozzle

Swirling conical spray nozzles are also widely used in spray applications. Combustion Engineering has used a swirl cone nozzle for black liquor service extensively. Only in the past several years have the V-type and U-type nozzles been offered as an alternative. **Figure 3** shows a diagram of a CE swirl cone nozzle. It consists of a pipe with a conical cap that contains a circular exit orifice. Immediately behind the cap is a plate or block which contains two spiral grooves that impart swirl to the flow. This combination results in a swirling conical spray pattern from these nozzles.

The geometry for these nozzles results in a minimum flow area at the grooves in the swirl plate. For a typical black liquor nozzle in mill service, the diameter of the exit orifice is 2.5 cm (1 in.) while the equivalent circular flow area dimension for the grooves is only 1.9 cm (0.75 in.). The groove area is the appropriate one to use to characterize the flow/ΔP behavior of these nozzles.

As with the other black liquor nozzles, the entrance dimension is more than twice the minimum flow dimension, so the inlet conditions will not affect the flow/ΔP

characteristics of CE swirl cone nozzles. The swirl cone nozzle contains a tapered section, and its length-to-diameter ratio is similar to the splashplate nozzle. The general impact of viscous losses would be expected to be similar to that of the splashplate nozzle. The typical dimensions and flow characteristics are the same as for the V-type and U-type nozzles given in Table II.

Spray facility description

The experimental facility used to obtain the data reported here was constructed at the Institute of Paper Chemistry in Appleton, Wis., (now the Institute of Paper Science and Technology in Atlanta) to study the spray characteristics of black liquor nozzles (*1*). The flow loop consists of a 1.9-m^3 (500-gal) storage tank, fluid preparation and pumping systems, and a spray booth. The spray nozzle being tested is located at the top of the spray booth and sprays the working fluid down into a catch tank at the bottom of the booth. The pressure, temperature, and flow of the fluid are measured immediately ahead of the nozzle. The fluid viscosity can be measured either off-line in the laboratory using a benchtop viscometer from Brookfield Engineering Labs., Stoughton, Mass., or continuously in a by-pass line located ahead of the spray nozzle using a Brookfield on-line viscometer. Viscosity data along with all other data around the flow loop are continuously recorded using a digital data acquisition system.

Three fluids were used in taking the data—two kraft black liquors and a corn syrup. One of the liquors was obtained from a kraft mill in the Southeast, and the other liquor was obtained from a kraft mill in the Midwest. Corn syrup was selected as another working fluid for these nozzle tests because it has a solids content and viscosity similar to black liquor at typical mill firing conditions. Corn syrup is also known to be a Newtonian fluid over a wide range of shear rates. The Newtonian viscosity measured by the Brookfield instruments was sufficient to characterize black liquor and corn syrup viscosity at the relatively low shear rates in these nozzles. The range of fluid properties and operating conditions used in these tests are presented in **Table III.**

In addition to these data, three data points were used from work on a B&W 12-49 splashplate nozzle by the B&W Alliance Research Center (*3*). These data were taken with a midwestern kraft black liquor at 53% solids and 25°C (77°F).

Data for the four types of nozzles

Splashplate nozzle data

Data for the two B&W splashplate nozzles on pressure drop, flow rate, viscosity, and nozzle geometry were used to calculate the maximum velocity, the nozzle Reynolds number, and the flow coefficient. Shown in **Fig. 4** is a plot of flow coefficient as a function of Reynolds number. The pattern shown is typical of many flow situations where C_f decreases smoothly with increasing Reynolds number until a constant value is reached. Flow coefficient correlations are usually for a single flow element of uniform dimensions. This is not exactly analogous to the situation of the more complex splashplate nozzle. The curve in Fig. 4 would apply only to nozzles that are geometrically similar to the B&W splashplate nozzle. Geometric similarity would count on the similarity of nozzle length-to-diameter ratio and on the similarity of the taper from the entrance to the exit. The flow would also have to disengage from the nozzle exit before striking the splashplate.

The data in Fig. 4 have been correlated with a simple two-term equation, resulting in an overall flow coefficient which is equal to a constant term plus a term that is a function of Reynolds number. The correlation is:

$$C_f = 1.17 + 373/Re^{0.92} \quad (14)$$

A plot of the predicted ΔP based on Eqs. 1 and 14 vs. the actual measured ΔP for the splashplate nozzle is shown in **Fig. 5**. The fit of the data is quite good. The black liquor data are differentiated from the corn syrup data in this figure. The data fit and the data scatter are very similar for the two fluids (actually four fluids because three black liquors were used). Not readily apparent in this figure is that the three black liquors (two fired hot and one fired cold) are also very similar to each other.

U-type and V-type nozzle data

The pressure drop data for the CE U-type and V-type nozzles are plotted in **Fig. 6** in a manner similar to the splashplate nozzle data. There is very little difference in the flow coefficient between the CE U-type and V-type nozzles. The same general pattern can be seen for the flow coefficient as a function of Reynolds number as was seen for the splashplate nozzle with one key difference—the curve is displaced to lower Reynolds numbers. This difference is not too surprising, considering the geometric differences between the splashplate and the U-type and V-type nozzles. The entry section of the U-type and V-type is very large compared to the nozzle orifice, so the velocity head is quite low. Viscous losses in these nozzles would be appreciable only at low Reynolds numbers.

The data in Fig. 6 have been correlated in a manner similar to that for the splashplate nozzle. The best fit flow coefficient correlation is:

$$C_f = 1.16 + 2780/Re^{1.65} \quad (15)$$

A plot of the predicted ΔP based on Eqs. 1 and 15 vs. the actual measured ΔP for the U-type and V-type nozzles is shown in **Fig. 7**. Data for these nozzles were taken only with corn syrup. The comparison in Fig. 7 is quite good.

Discussion

The data and correlations presented for the two types of black liquor nozzles reveal some important practical results for both the mill application of these nozzles and for the laboratory study of black liquor sprays.

Comparing the usual operating conditions for the B&W splashplate nozzle given in Table I to the data in Fig. 4, we see that black liquor viscosity is not an important parameter in this nozzle's flow characteristics. The flow coefficient for this type nozzle at the lowest practical Reynolds number of 1400 is only about 1.65, and above this Reynolds number it quickly decreases to the constant value of 1.17. Furthermore, the viscous loss term constitutes only 29% of the overall flow coefficient at the most extreme practical operating point, so we would expect the flow coefficient to be nearly a constant for the broad range of routine mill operations. The flow characteristics would therefore be nearly independent of black liquor viscosity, temperature, and solids. This would contribute to the insensitivity of these nozzles to normal fluctuations in mill operating conditions and would make operating pressure a good indicator of black liquor flow (though ring header pressure would have to be corrected to nozzle pressure drop).

The same comments would be true for the CE U-type and V-type nozzle. Though the operating Reynolds number range for these nozzles is generally lower, the flow coefficient curve is also shifted lower. At the lowest practical Reynolds number of 810, the viscous term contributes little to the flow coefficient. Again, in the broad range of practical mill operations, the flow characteristics of the U-type and V-type nozzles would be insensitive to black liquor viscosity, solids, and temperature.

Though data are not available for the CE swirl cone nozzle, its geometric parameters indicate that the flow characteristics should be similar to those for the B&W splashplate nozzle shown in Fig. 4. Viscous losses will be more important for this nozzle than for the other nozzles. The general operating conditions for the swirl cone are given in Table II. Comparing the operating conditions to the likely flow characteristics reveals a significantly greater likelihood of sensitivity of this nozzle to routine liquor property fluctuations and settings. Data will be required to confirm this speculation.

An additional practical result from these tests is black liquor's apparent similarity to other fluids. Though black liquor viscosity can change dramatically with solids and temperature, as well as from liquor to liquor, its flow characteristics at a given viscosity are apparently the same as other fluids at the same viscosity and density. As well, in comparing black liquor under the highest shear rates for normal flow conditions to a fluid known to be Newtonian, there is no apparent effect of black liquor's known complex rheology at high shear rates (*4, 5*). This result is mainly because the actual shear rates are relatively modest compared to those required for black liquor to show non-Newtonian rheology. This supports the validity of using simple fluids such as corn syrup for calibration and other purposes in studies of black liquor sprays. The use of such fluids eases experimental procedures and extends the range of experimental conditions because the fluid is far easier to handle and characterize than black liquor.

Conclusions

Tests have been carried out on four black liquor spray nozzles using three black liquors and one corn syrup. B&W splashplate nozzles and CE U-type and V-type nozzles were studied over a range of operating conditions which spanned the range of routine pulp and paper mill operations. The following conclusions can be drawn from these tests:

1. The flow and pressure drop characteristics of black liquor nozzles follow a regular pattern with respect to a Reynolds number which is based on the minimum flow area.
2. Flow coefficient data for these nozzles can be correlated with a simple two-term fit. The first term represents inertial acceleration, and the second represents viscous loss.
3. For both types of nozzlės tested, the viscous loss term is only minimally important at the extreme lower end of the normal mill operating conditions. Thus, for most normal operating conditions, only the constant inertial acceleration term is important to the flow characteristics.
4. As a result of the constant inertial acceleration term, the B&W splashplate and the CE U-type and V-type nozzles should be insensitive to routine fluctuations in black liquor viscosity, solids, and temperature.
5. Due to the particular geometry of the CE swirl cone nozzle, its flow characteristics are likely to be much more sensitive to routine black liquor fluctuations, but additional nozzle flow data are needed to confirm this.
6. Comparison between the three black liquors and the corn syrup reveals that the low-shear Newtonian viscosity of black liquor characterizes this fluid well for flow studies.□

Literature cited

1. Kraft black liquor delivery systems, U.S. DOE Contract No. FC02-88CE40839, Adams, T. N., Grace, T. M., and Malcolm, E. W., Institute of Paper Chemistry, Appleton, Wis.
2. Black liquor droplet formation project, U.S. DOE Contract No. AC02-83CE40626, Stockel, I. H., University of Maine.
3. Spielbauer, T. M., Adams, T. N., Monacelli, J.E., and Bailey, R. T., 1989 TAPPI/CPPA Intl. Chemical Recovery Conf., TAPPI PRESS, Atlanta, p. 119.
4. Physical properties of kraft black liquors, U.S. DOE Contract No. AC02-82CE40606, Fricke, A. L., University of Florida.
5. Adams, T. N. and Frederick, W. J., Kraft recovery boiler physical and chemical processes, American Paper Institute, New York, 1988.

The authors gratefully acknowledge the support of the U.S. Department of Energy for the study of black liquor delivery systems. Nozzles used in the tests at the Institute of Paper Chemistry were generously donated by the Babcock & Wilcox Company and by Combustion Engineering, Inc.

Portions of this work were used by T.M.S. as partial fulfillment of the Ph.D. degree at the Institute of Paper Science and Technology.

Received for review April 19, 1990.

Accepted May 3, 1990.