Paper V

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Particle Size Distribution of Black Liquor Sprays with A High Solids Content in Recovery Boilers

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ABSTRACT

This study deals with fuel injection in kraft recovery boilers used in pulp mills. Black liquor is sprayed into the furnace of a recovery boiler through large splashplate nozzles. The drop size and drop size distribution of black liquor sprays have a major impact on the operation of a recovery boiler. When they are entrained by upwards-flowing flue gas flow, small droplets form carry-over and cause the fouling of heat transfer surfaces. Large droplets hit the char bed and the walls of the furnace without being adequately dried.

In this study, the drop size of black liquor with a high solids content was measured for two types of industrial-scale splashplate nozzles. The mass flow rate was varied between 4.3 and 6.1 kg/s and the spraying temperature was varied between 130-135°C. The excess temperature above the elevated boiling point (EBP) varied between 14-18°C.

The drop size and drop size distribution of black liquor sprays were measured by an image-analysis-based method. Although the spray consisted of spherical and non-spherical particles, it was assumed that non-spherical particles would form spherical droplets. Four theoretical drop size distributions were compared by the method of least-square difference.

The square-root normal distribution was slightly better compared to the log-normal, Rosin-Rammler, and normal distributions. The median diameter of equivalent spheres varied from 5 to 11.6 mm, when the square-root normal distribution was adapted. The span of drop size distribution was roughly 1.2. The volume median diameters were remarkably higher than those detected earlier for black liquor with lower solids content.

Keywords:

particle size distribution, spray, black liquor, recovery boiler

NOMENCLATURE

A	[m^2]	cross-sectional area of nozzle exit
D	[mm]	drop diameter
$D_{V0.5}$	[mm]	volume median diameter
q(D]	[ ]	differential distribution function
q	[ ]	parameter of Rosin-Rammler distribution function
$\dot{m}$	[kg/s]	mass flow rate
s	[ ]	standard deviation
s*	[ ]	normalized standard deviation
ΔT_e	[°C]	excess temperature, $T_{\text{black liquor}}$ -T_{EBP}
T_{BPR}	[°C]	boiling point rise, T_{EBP} – 100°C
T_{EBP}	[°C]	elevated boiling point, the boiling point of black liquor at 101 kPa
u*	[ ]	dimensionless velocity
u_s	[m/s]	sheet velocity
u_p	[m/s]	velocity at the nozzle exit
V	[m^3]	volume
ΔV	[ ]	volume fraction
v(D)	[1/m]	differential volume distribution
X	[ ]	parameter of Rosin-Rammler distribution function
x	[ ]	volume fraction
Δ	[ ]	relative span factor
ρ_{BL}	[kg/m^3]	density of black liquor

INTRODUCTION

Kraft recovery boilers convert the spent liquor from the pulping process to energy and chemicals. The spent liquor, known as black liquor, consists of lignin, pulping chemicals, and water. The dry solids content of black liquor is 60-80%. Chemicals are recovered into the char bed, which is formed on the bottom of the furnace. Energy from flue gases is recovered by heat exchangers in the upper parts of the furnace and utilized as steam or electricity. The boilers are very large; the cross-section of a modern boiler is 11 m x 11m or even more, and they may be up to 80 m high.

Black liquor is the sixth most important fuel in the world, according to Reeve (1993). The dry solids content of black liquor has increased in recent years in order to increase the capacity of recovery boilers and reduce emissions. The change in the properties of black liquor has led to changes in the spraying practices used within recovery boilers. There are only a few experimental studies concerning high solids content black liquor spraying, in spite of its importance as a fuel. The study of Helpiö and Kankkunen (1996) was carried out with black liquor with a solids content of below 70%. They measured drop size in a vertical spray test chamber, using nozzles with diameters of 15 and 22 mm. More recently, in a study by Loebker and Empie (2001), high-viscosity corn syrup was used as a model fluid. They used a splashplate nozzle with a diameter of 9.5 mm and measured drop size with an image analysis system.

In the present study, high solids content black liquor spraying was studied for the first time. The applicability of these results was increased in a number of ways, compared to earlier measurements. The black liquor used in the tests was taken directly from the ring header of an operating recovery boiler. Test nozzles were installed in a horizontal position, which is the nozzle position in an operating furnace. The nozzles used were industrial-scale nozzles, thus eliminating the need for dimensional analysis when utilizing the measured spray properties for an operating boiler. In addition, advanced spray characterization methods were available. Thus, it was possible to obtain new experimental results for black liquor spray characteristics.

The spraying temperature was well above the boiling point of the liquor, which resulted in heavy flashing in some cases. Spray characteristics were measured almost simultaneously in the test chamber and in the furnace environment with a furnace endoscope. It is not possible to measure drop size and size distribution in the furnace and therefore they were measured in the test chamber. Spray formation was observed to be similar in the spraying chamber and furnace, and therefore the spray characteristics measured in the test chamber are assumed to be applicable to furnace conditions, as proposed by Miikkulainen *et al.* (2002b). Secondary atomization in the furnace is not expected because of the high viscosity of the particles and relatively low velocity and gas density in the furnace.

It is important to be able to describe the drop size distribution of a fuel spray exactly. Inaccurate description leads to poor chances of optimizing combustion. Most fuels produce unburned particles and emissions if the spray contains large droplets. Therefore, small drop sizes are desirable. In the case of a recovery boiler, small black liquor droplets are carried up by the gas flows from the lower furnace into the convective heat transfer section. This phenomenon is known as carry-over and it leads to the fouling of heat transfer surfaces, while simultaneously reducing chemical recovery through the char bed process. Large drops cool down and harmfully increase the size of the char bed. Therefore, both small and large droplets are of paramount importance.

Optimal spraying parameters can be chosen only if the drop size is known with sufficient accuracy. Probability density functions enable the drop size distribution to be estimated so that the spraying parameters can be varied in a controlled way. This study presents the results of experiments to determine the best drop size distribution function for black liquor spraying within varying spraying parameters.

EXPERIMENTAL

Nozzles

Two widely-used industrial-scale nozzles were used in these tests. The pipe diameters of Nozzles A and B were 27 mm and 28 mm, respectively. The splashplate cuts off the nozzle pipe exit area of Nozzle A. The splashplate of Nozzle B was located at a distance of 20 mm from the nozzle exit. The splashplate angles α for Nozzles A and B were 23° and 36°, respectively. The nozzles are presented schematically in Figure 1.

A-type splashplate nozzle, d_p = 27 mm **B-type splashplate nozzle, d_p = 28 mm**

Figure 1: Splashplate nozzles of types A and B

Black Liquor

The spray experiments were carried out at a modern pulp mill with continuous cooking and liquor heat treatment. In the test series presented here, the dry solids content of the softwood black liquor varied between 75% and 78%. The spraying temperature was 130-135°C. The excess temperature above the atmospheric boiling temperature of the black liquor was 14-18°C. The properties of the softwood black liquor used in the tests are presented in Table 1. Direct steam injection before the ring header was used to adjust the temperature of the black liquor.

Table 1: Properties of Black Liquor

Properties	Values
Solids Content	75-78%
Density	1440-1450 kg/m^3
Viscosity	110-160 mPa·s
Boiling point	116-119°C
Spraying temperature	130-135°C
ΔT_{EBP}	14-18°C

Black liquor spraying tests were carried out over a period of one month. Whenever possible, the test situation was adjusted according to the needs of the boiler operators. Sometimes the temperature or solids content of the black liquor changed a little during a test series. These series were repeated whenever possible.

A black liquor sample was taken daily and the dry solids content of all samples was determined at the KCL Laboratory. The viscosity, boiling point, and chemical analysis for each sample were determined by KCL.

The viscosity was analyzed at three temperatures and for varying dry solids contents. The viscosity measured at temperatures of 110°C, 130°C, and 160°C is presented in Appendix 1. An equation was developed which enabled the viscosity at any temperature and solids content to be calculated. In these tests, the viscosity varied between 110 and 160 mPa·s. The atmospheric boiling point of black liquor was approximately 116-119°C, depending chiefly on the solids content. The measured boiling point of the liquor is presented in Appendix 1.

Equipment

The experiments were carried out in the spray test chamber presented in Figure 2. The main dimensions of the spray test chamber alone were 5.5 m x 3 m x 2 m. The facility for the liquor gun and endoscope insertion extended the length to 10 m. The width of the first section of the chamber, where the nozzle was located, was 120 cm. The last section, where the drop size measurements took place, was 60 cm wide. The chamber was equipped with windows which enabled the spray height to be measured. Another window was used to ensure the right spray location for the drop size measurement. The spray width was restricted by spray separation baffles, so that only a narrow undisturbed part of the spray was allowed to reach the drop size measurement chamber. The nozzle was located horizontally to ensure close similarity to spraying in a furnace. Odorous gases were drawn away through the end wall and the top of the chamber. Substituting air entered the chamber through the liquor gun hole. The temperature in the chamber was 60-80°C. The black liquor was returned, after dilution, to the recovery cycle.

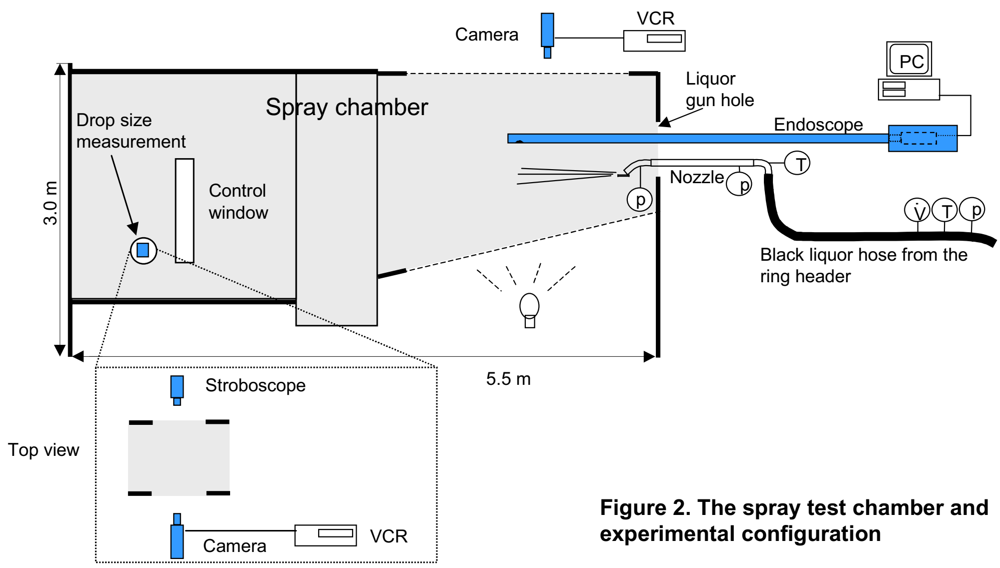


Figure 2. The spray test chamber and experimental configuration

The furnace endoscope was used to compare the spray properties in the test chamber and the furnace. The furnace endoscope was located 0.3 to 0.5 m above the splashplate nozzle. This air-cooled endoscope tube was approximately 3 m long; there was a high-shutter-speed CCD camera at one end of the tube and a prism for a right-angle view at the other. To make it possible to get a picture of the spray break-up mechanism, a black-and-white high-shutter-speed CCD camera was located in the roof structure of the spray test chamber.

The velocity measurements at the spray centerline were based on the triple-exposure mode of the camera and on the image-analysis system. In order to calculate the spray velocity, the trajectory of the spray had to be determined. In addition, the shape and the length of the black liquor sheet were measured and the sheet break-up mechanism was determined. These results are reported by Miikkulainen *et al*. (2002a) and Miikkulainen *et al*. (2002b).

The drop size and shape were determined by a system based on a video camera and image analysis. The video camera was used to record the spray at a measurement distance of 4 meters from the nozzle. The drop size and shape were assumed to be fixed at that distance.

The spray was lit by a stroboscope from the opposite side of the chamber, so that the droplets could be detected by a standard video camera without motion blur. The focal length of the optics was normally 102 mm. The optics gave reliable information concerning the mass median diameter and large particles, but inaccurate information about particles smaller than about 1 mm. In two high-magnification cases, the focal length of the optics was 250 mm, to facilitate the study the relevancy of the normal optics tests. Two example images obtained with normal optics are presented in Figure 3. The image size is 91x75 mm.

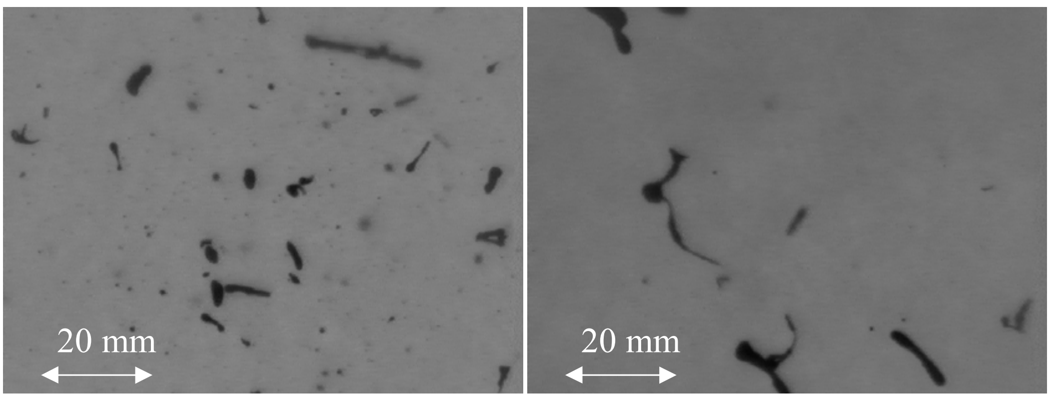


Figure 3. Particles in two spraying situations at a distance of 4 meters from the nozzle. High solids content black liquor 4.2 kg/s at a spraying temperature of 135°C (left) and 6.1 kg/s at a spraying temperature of 130.4°C (right).

Experimental Procedure

The black liquor was taken directly from the ring header of the recovery boiler. It was possible to measure the mass flow rate and temperature using the boiler instrumentation. The accuracy of the boiler instrumentation was verified with a calibrated mass flow meter. In addition, the temperature and the pressure in the nozzle pipe were measured by a separate data logger.

Three mass flow rates of 4.3 kg/s, 5.2 kg/s, and 6.1 kg/s were used in the tests to detect the effect of the mass flow rate on the size of the drops. Three temperatures were used in the tests to study the effect of temperature on the spray properties. The temperature range used was the maximum possible approved by the boiler operators. The temperature of the black liquor in the spraying chamber tests was normally equal to that of the black liquor sprayed into the recovery boiler. A 13-m insulated black liquor hose came from the ring header of the boiler. In the case of the lowest spraying temperature, the temperature control was achieved by laying the uninsulated metal hose in water-cooled vessels.

Each test session took 11 minutes. Ten minutes' worth of video material was available for analysis, and also 15,000 video images. Normally only 1500 frames were studied for each case. However, about 2500-10,000 particles could still be observed. Two high-magnification cases were studied with 15,000 frames in order to study the relevancy of the tests.

DISTRIBUTION FUNCTIONS

Normal distribution, log-normal distribution, and the square-root normal distribution function are mathematical distribution functions. The Rosin-Rammler distribution function is an example of an empirical distribution function. All these functions have been used to describe droplet size distributions.

Rosin-Rammler Distribution

The most commonly applied distribution function in the field of particle science is the Rosin-Rammler distribution. It is generally applied in the field of spraying as well. The Rosin-Rammler distribution function is defined by the equation:

$$q_{RR}(D) = qX^{-q}D^{q-1}e^{-(D/X)^q} \qquad (1)$$

where q is a measure of the uniformity of the spray and X is a certain kind of mean diameter, which often has a value of approximately 20% less than $D_{V0.5}$.

Normal Distribution

The equation for volume-based normal distribution is

$$q_n(D) = \frac{1}{s\sqrt{2\pi}} e^{-\frac{(D-\bar{D})^2}{2s^2}} \tag{2}$$

where s is the standard deviation, D is the particle diameter, and $\bar{D}$ is the mean size. This is a symmetrical function around the mean size and is adopted only by a few researchers, but it forms the basis for square-root normal distribution and log-normal distribution.

Square-root Normal Distribution

The square-root normal distribution function was suggested by Tate and Marshall (1953). Its volume distribution function can be expressed as

$$q_{sqrt}(D) = \frac{1}{2s\sqrt{2\pi}} D^{-0.5} e^{-\frac{1}{2}\left(\frac{\sqrt{D}-\sqrt{D_{V0.5}}}{s}\right)^2} \tag{3}$$

where s is the standard deviation of $\sqrt{D}$.

Simmons (1977) reviewed a very large quantity of experimental data using jet engine nozzles. He concluded that the parameter s is related to the volume median diameter of the spray by the following equation for normalized standard deviation:

$$s^* = \frac{s}{\sqrt{D_{V0.5}}} = 0.24 \tag{4}$$

This means that the normalized shape and the normalized width of the square-root normal distribution are constant for all drop sizes. This observation was later adopted for black liquor spraying by groups who originated from the Institute of Paper Chemistry (IPC), which later became the Institute of Paper Science and Technology (IPST). Adams *et al.* (1990) and Empie *et al.* (1995) obtained similar results based on experiments with splashplate nozzles. Adams *et al.* (1990) found that the normalized standard deviation s^* grows to 0.32 with increasing velocity, and Empie *et al.* (1992) even measured a value of 0.38. In spite of this variation, the value of s^* was assumed to be constant at 0.24. Recently, Loebker and Empie (2001) measured slightly higher values of 0.25-0.29 for s^*.

Log-normal Distribution

There are many definitions for the log-normal distribution. Allen (1990) and Paloposki (1994) used the equation

$$q_{\ln}(D) = \frac{1}{(\ln s)\sqrt{2\pi}} e^{-\frac{1}{2}\left[\frac{(\ln(D/D_{V0.5})}{\ln s}\right]^2} \tag{5}$$

which is skewed in the direction of small fractions.

Relative Span Factor

The shape of distribution functions varies. Although the volume median size of all the above-mentioned distribution functions may be the same, the width can still vary. The width of a distribution can be studied, for example, by the relative span factor, which is defined by the equation

$$\Delta = \frac{D_{V0.9} - D_{V0.1}}{D_{V0.5}} \tag{6}$$

where the diameters $D_{V0.1}$, $D_{V0.5}$ and $D_{V0.9}$ are cumulative for 10%, 50%, and 90% volume fractions.

Data Handling

The particles were detected by an image-analysis system. Particles that were out of focus or in contact with the edge of the image were rejected. The volume of each accepted particle was calculated. Non-spherical particles were assumed to form spheres of equal volume. The particles were categorized into size categories, whose width was 1 mm. The least-square method was adapted to compare the measured and calculated volume fractions in the size categories.

RESULTS AND DISCUSSION

The Effect of Temperature on Spray Velocity and Spray Formation

The velocity at the spray centerline varied across a range of 9.7 to 14.5 m/s for Nozzle A and 10.2 to 15.3 m/s for Nozzle B. For both nozzles, increasing excess temperature increased the velocity of the spray, but the effect of mass flow rate was not so unambiguous. Increasing mass flow rate diminished the effect of excess temperature; see Figure 4. The spray velocity is highly dependent on the spraying temperature and pressure; at a higher temperature, flashing produces water vapor, which has a large specific volume and, as a result, accelerates the flow. At lower pressures, i.e. at a lower mass flow rate, flashing takes place more easily. The dimensionless velocity (Eqn. 7) can be used to describe this phenomenon.

$$u^* = \frac{u_s}{\frac{\dot{m}}{A\rho_{BL}}} = \frac{u_s}{u_p} \quad (7)$$

where u_s is the measured velocity at the centerline of the black liquor sheet and u_p is the velocity of the non-flashing case at the smallest cross-sectional area, A, of the nozzle with the same mass flow rate, $\dot{m}$ as presented by Miikkulainen *et al.* (2000).

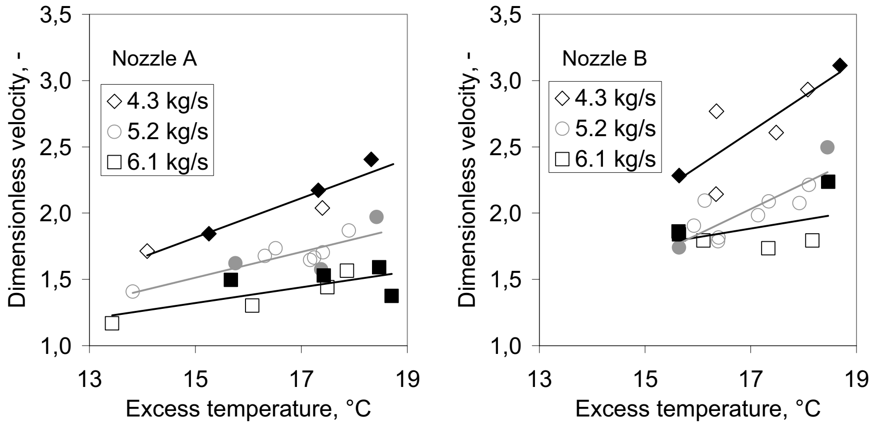


Figure 4. The effect of temperature on spray velocity

In Figure 4, measurements in the test chamber and under furnace conditions are presented by open and black symbols respectively. The flashing phenomenon has a great effect on spray formation and the sheet disintegration process and therefore affects the formation of drop size and shape. It was observed that in the case of decreased spraying temperature a half-meter-long uniform liquid sheet was formed, which then broke up into a spray with a high fraction of large non-spherical droplets. At higher temperatures the sheet was either shorter or non-existent.

<u>*The Effect of Mass Flow Rate and Temperature on Mean Diameters*</u>

The median drop size was affected most by excess temperature above the boiling point. An increase of 4°C decreased the median drop size by approximately 50%. An increased mass flow rate increased the median drop size slightly for Nozzle A. The median drop size for Nozzle B was not as clearly affected by mass flow rate; see Figure 5. The fraction of non-spherical particles was high, from 60 vol-% to 90 vol-%. In this study, these fractions are assumed to form spherical particles. High-magnification tests, marked by black triangles, produced very similar results compared to normal tests. Therefore, the optics used in normal tests seems to be relevant.

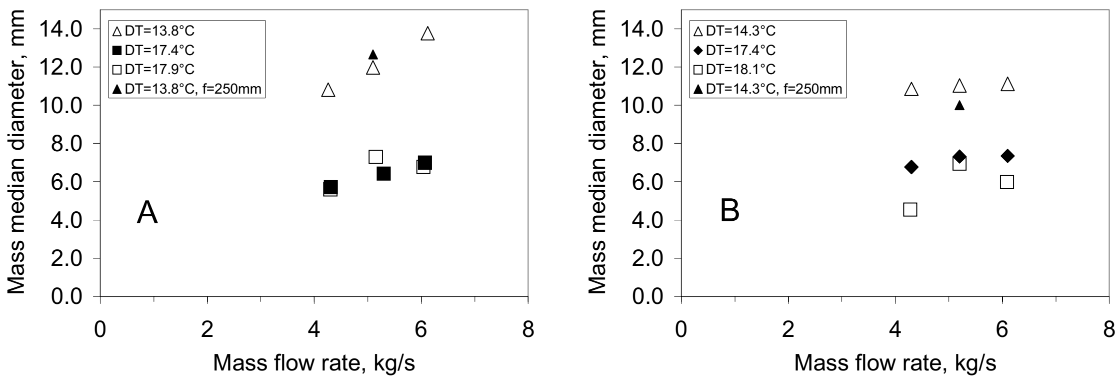
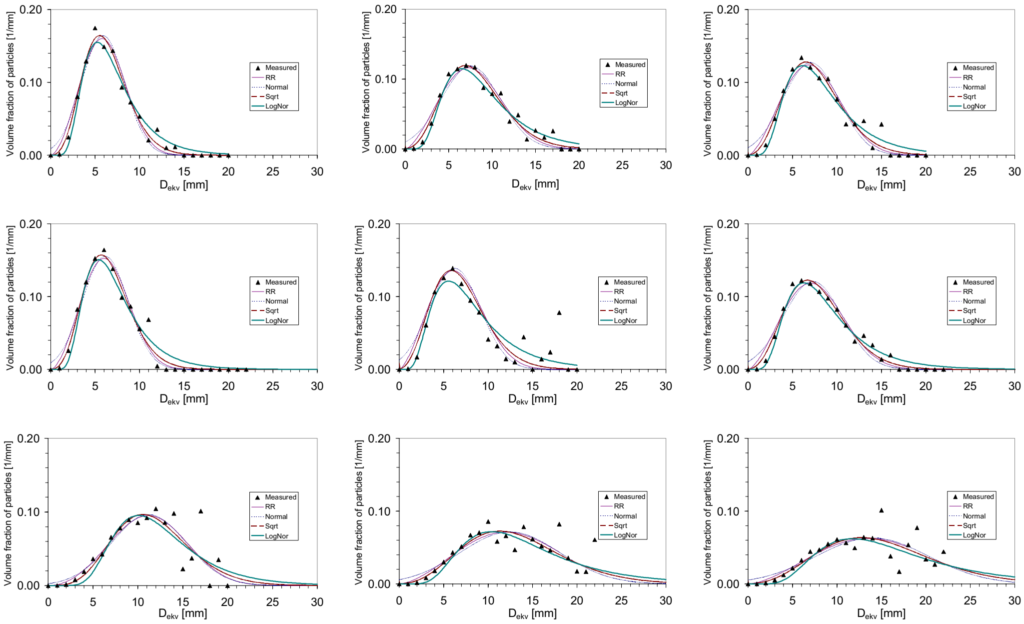


Figure 5. The effect of mass flow rate on combined median drop size, Nozzles A and B

Best Distribution Function

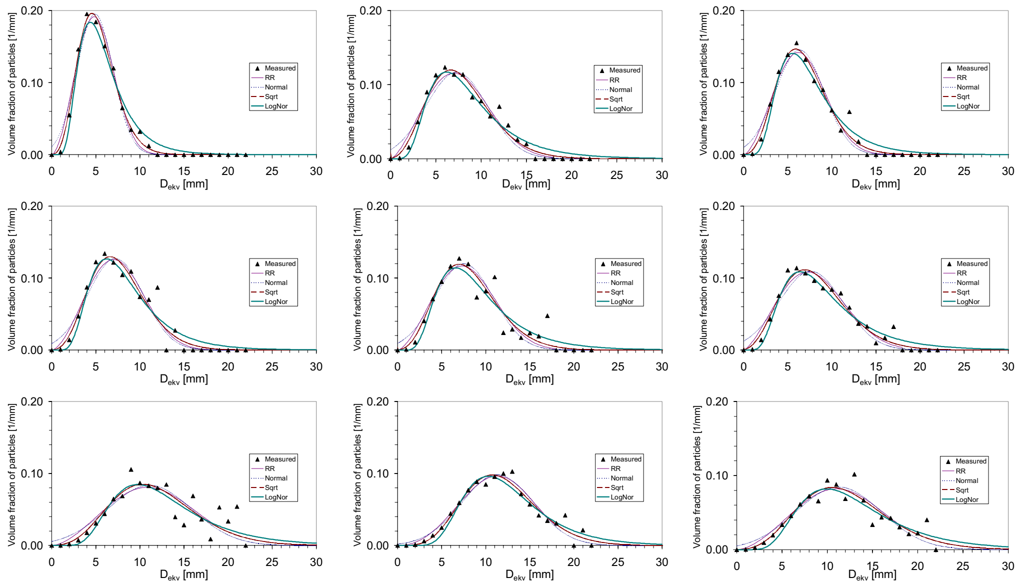
In Figures 6 and 7, all particles are assumed to form spherical particles and the corresponding cumulative size distribution is then formed. The temperature increases upwards and mass flow rate increases from left to right in Figures 6 and 7. An increased mass flow rate and decreased temperature seem to increase the width of the drop size distribution. The median diameter of the experimental measurements varied from 4.5 to 13.8 mm and increased as a result of either a decrease in temperature or an increase in mass flow rate.

Although it is better to use the original measured size distribution for each spraying condition, there is a need for a general form of particle size distribution. This kind of distribution function can then be adapted for the interpolation and extrapolation of measured size distributions. When adapting distribution functions, one must be aware of the possibility of a change in the sheet break-up mechanism or in the drop formation mechanism. These changes are caused, for example, by a change in the solids contents, in the temperature or in the mass flow rate of black liquor, or by a change in the nozzle geometry. A general form of particle size distribution can help a volume fraction of the spray in the preferred size classes for CFD modeling to be obtained.



4.3 kg/s **5.2 kg/s** **6.1 kg/s**

Figure 6: Particle size distribution of Nozzle A with fitted size distribution curves for nine spraying experiments, at excess temperatures of 14°C, 17°C, and 18°C in an upwards direction.



4.3 kg/s **5.2 kg/s** **6.1 kg/s**

Figure 7: Particle size distribution of Nozzle B with fitted size distribution curves for nine spraying experiments, at excess temperatures of 14°C, 17°C, and 18°C in an upwards direction.

The Rosin-Rammler, normal distribution, square-root normal distribution, and log-normal distribution were fitted to experimental data for the particle size distributions. The graphic results and measured data values are presented in Figures 6 and 7. The best estimated mean and width parameters and consequent least-square differences are presented in Tables 2 and 3. All the studied distribution functions fit the experimental data quite well, especially in the mean part of the distribution. The smallest least-square difference was achieved most often by the square-root distribution function. The log-normal distribution function produced the next best fit. The normal distribution and Rosin-Rammler distribution overestimated the fraction of small particles.

Table 2. Estimated parameters for size distribution functions and least-square differences for nine spraying experiments for Nozzle A

EXP	MEAN PARAMETER				WIDTH PARAMETER				LEAST-SQUARE DIFFERENCE			
$\Delta T_e / \dot{m}$	RR	Norm	Sqrt	LN	RR	Norm	Sqrt	LN	RR	Norm	Sqrt	LN
17.8/4.3	6.81	5.88	6.03	6.43	2.75	2.43	0.51	1.56	0.0025	0.0032	0.0012	0.0016
17.9/5.2	8.85	7.52	7.73	8.2	2.56	3.36	0.62	1.61	0.0024	0.0033	0.0016	0.0014
17.9/6.0	8.28	7.04	7.23	7.69	2.56	3.13	0.59	1.61	0.0030	0.0040	0.0021	0.0021
17.4/4.3	7.1	6.13	6.25	6.61	2.72	2.56	0.52	1.56	0.0027	0.0035	0.0020	0.0030
17.4/5.2	7.44	6.24	6.55	7.29	2.5	2.87	0.59	1.68	0.0110	0.0114	0.0095	0.0085
17.4/6.1	8.58	7.28	7.46	7.9	2.53	3.3	0.61	1.62	0.0018	0.0028	0.0010	0.0009
13.7/4.3	12.7	11.22	11.41	11.87	3.07	4.16	0.63	1.49	0.0078	0.0080	0.0079	0.0085
13.8/5.1	14.52	12.46	12.61	13.08	2.58	5.58	0.79	1.61	0.0054	0.0059	0.0055	0.0061
13.9/6.1	16.37	13.99	14.26	14.89	2.55	6.31	0.85	1.63	0.0081	0.0086	0.0082	0.0087

Table 3. Estimated parameters for size distribution functions and least-square differences for nine spraying experiments for Nozzle B

EXP	MEAN PARAMETER				WIDTH PARAMETER				LEAST-SQUARE DIFFERENCE			
$\Delta T_e / \dot{m}$	RR	Norm	Sqrt	LN	RR	Norm	Sqrt	LN	RR	Norm	Sqrt	LN
18.1/4.3	5.67	4.89	5	5.38	2.73	2.04	0.46	1.57	0.0020	0.0029	0.0007	0.0016
18.1/5.2	8.62	7.28	7.44	7.87	2.46	3.42	0.63	1.64	0.0021	0.0033	0.0015	0.0017
18.2/6.1	7.42	6.35	6.5	6.9	2.63	2.74	0.55	1.59	0.0026	0.0036	0.0017	0.0021
17.5/4.3	8.39	7.22	7.32	7.69	2.64	3.14	0.58	1.58	0.0039	0.0052	0.0043	0.0044
17.3/5.2	8.85	7.52	7.77	8.27	2.58	3.32	0.62	1.61	0.0057	0.0063	0.0048	0.0049
17.3/6.0	9.06	7.61	7.81	8.29	2.42	3.64	0.66	1.66	0.0022	0.0033	0.0016	0.0017
14.3/4.3	13.02	11.11	11.38	11.85	2.63	4.77	0.71	1.55	0.0070	0.0076	0.0061	0.0058
14.3/5.2	12.76	11.32	11.51	11.86	3.17	4.05	0.61	1.46	0.0017	0.0017	0.0015	0.0023
14.2/6.1	13.1	11.27	11.59	12.13	2.7	4.72	0.71	1.56	0.0042	0.0044	0.0037	0.0040

Span

The span of the experimental drop size distribution is presented in Figure 8. The span is normally about 0.95-1.4. In the high magnification case for Nozzle B, the span was exceptionally low, at 0.6. This exception was probably caused by the rejection of the largest particles because of image edge contact.

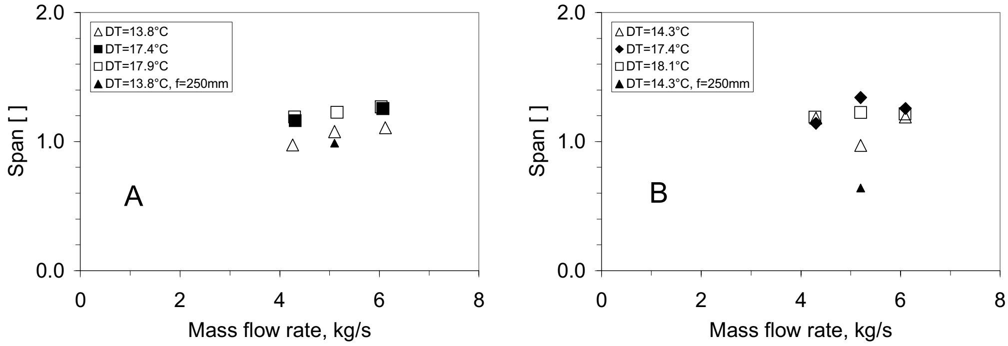


Figure 8: The effect of mass flow rate on the span of experimental drop size distribution for Nozzles A and B

ADAPTING THE DISTRIBUTION FUNCTION TO STUDY THE QUALITY OF SPRAYING

Now the most likely form of distribution function can be adapted to a real case. As we know, small particles cause the fouling of heat transfer surfaces and large particles may decrease the temperature of the char bed. The size of a harmful particle could be calculated by an accurate single-droplet combustion model (Järvinen, 2002), when the properties of the black liquor and flow and temperature field in the furnace are available. In addition, particle shape should be considered.

Adams and Frederick (1988) estimated that particles smaller than 2.8 mm may form carry-over, and the probability of particles being entrained increases with decreased particle size. Here we assume that carry-over is formed from particles smaller than 2 mm. On the other hand, particles larger than 6 mm will hit the char bed without adequate drying and therefore cool down and increase the size of the char bed. With these assumptions, we obtain the data in Tables 4 and 5, where the volume fraction of particles smaller than 2 mm and larger than 6 mm can be seen for varying spraying conditions.

The fraction of small particles below about 1 mm is inaccurate. The fraction of small particles below 2 mm varies from 0.02% to 3.7%. These particles form carry-over and they make up particle concentrations of roughly 0.01 to 2.6 g/Nm^3. The fraction of large particles larger than 6 mm varies from 2% to 77%. These particles hit the boiler wall and the char bed without adequate drying.

The normalized standard deviation s^* of the square-root distribution defined in Equation (7) gave values of 0.18 to 0.24 for square-root distribution in standard cases, as presented in Tables 4 and 5. This is quite similar to the values obtained by Adams *et al.* (1989) and Empie *et al.* (1995) for splashplate nozzles. The results from two cases with magnifying optics (last cases in Tables 4 and 5) give slightly smaller values of normalized standard deviation.

Table 4: Parameters of square-root normal distribution function and consequent volume fractions for Nozzle A.

EXP	Square-root norm distr.		under 2 mm		over 6 mm
$\Delta T_e / \dot{m}$	MMD	s	s*	vol-%	vol-%
17.8/4.3	6.03	0.51	0.21	2.06	8.29
17.9/5.2	7.73	0.62	0.22	1.38	26.89
17.9/6.0	7.23	0.59	0.22	1.54	21.12
17.4/4.3	6.25	0.52	0.21	1.84	10.14
17.4/5.2	6.55	0.59	0.23	2.61	15.34
17.4/6.1	7.46	0.61	0.22	1.54	23.99
13.7/4.3	11.41	0.63	0.19	0.09	63.39
13.8/5.1	12.61	0.79	0.22	0.34	68.87
13.9/6.1	14.26	0.85	0.23	0.27	76.50
13.8/5.1	9.70	0.62	0.20	0.31	46.97

Table 5: Parameters of square-root normal distribution function and consequent volume fractions for Nozzle B.

EXP	Square-root norm distr.		under 2 mm		over 6 mm
$\Delta T_e / \dot{m}$	MMD	s	s*	vol-%	vol-%
18.1/4.3	5.00	0.46	0.21	3.70	2.20
18.1/5.2	7.44	0.63	0.23	1.85	24.51
18.2/6.1	6.50	0.55	0.22	1.95	13.26
17.5/4.3	7.32	0.58	0.21	1.30	21.55
17.3/5.2	7.77	0.62	0.22	1.34	27.28
17.3/6.0	7.81	0.66	0.24	1.82	28.88
14.3/4.3	11.38	0.71	0.21	0.29	61.69
14.3/5.2	11.51	0.61	0.18	0.06	64.72
14.2/6.1	11.59	0.71	0.21	0.25	63.35
14.3/5.2	9.99	0.50	0.16	0.02	49.87

CONCLUSIONS

High solids content black liquor spraying was studied in a test series with two splashplate nozzles. Three mass flow rates 4.3, 5.2, and 6.1 kg/s were examined. The excess temperature varied between 14-18°C. The spraying temperature varied from 130 to 135°C.

An important observation was the large median drop size. The large drop size occurred in connection with the high fraction of non-spherical particles that were found in high solids content black liquor sprays. Large, non-spherical particles occur when flashing inside the nozzle tube decreases (lower dimensionless velocity of a spray) and a long uniform black liquor sheet is formed at the splashplate.

The results were analyzed on the basis of the assumption that non-spherical particles form spherical particles. Four particle size distribution functions were fitted to the experimental data and the consequent parameters were presented. The square-root normal distribution was the best and the log-normal distribution was almost as good. The normal and Rosin-Rammler distributions did not give such good results.

The observation of Simmons (1977), that the normalized standard deviation of square-root normal size distribution is constant with a value of 0.24, seems generally to hold true here. However, it would be misleading to adapt this drop size distribution for combustion calculations or CFD modeling. It will be possible to take full advantage of the particle size distributions of black liquor spray when the particle shape is properly considered together with particle size. This improved information concerning the spray can then be utilized by a modified single-particle combustion model (e.g. Järvinen, 2002), when implemented in a CFD program.

It was found that less than 3.7% of black liquor could form carry-over particles smaller than 2 mm. This roughly corresponds to a maximum concentration of 2.6 g/Nm^3 inorganic dust in flue gases. On the other hand, 2-76% of particles are larger than 6 mm and hit the char bed or furnace wall without adequate drying. This information is important for optimizing furnace operation.

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APPENDIX 1

VISCOSITY AND BOILING POINT RISE OF BLACK LIQUOR

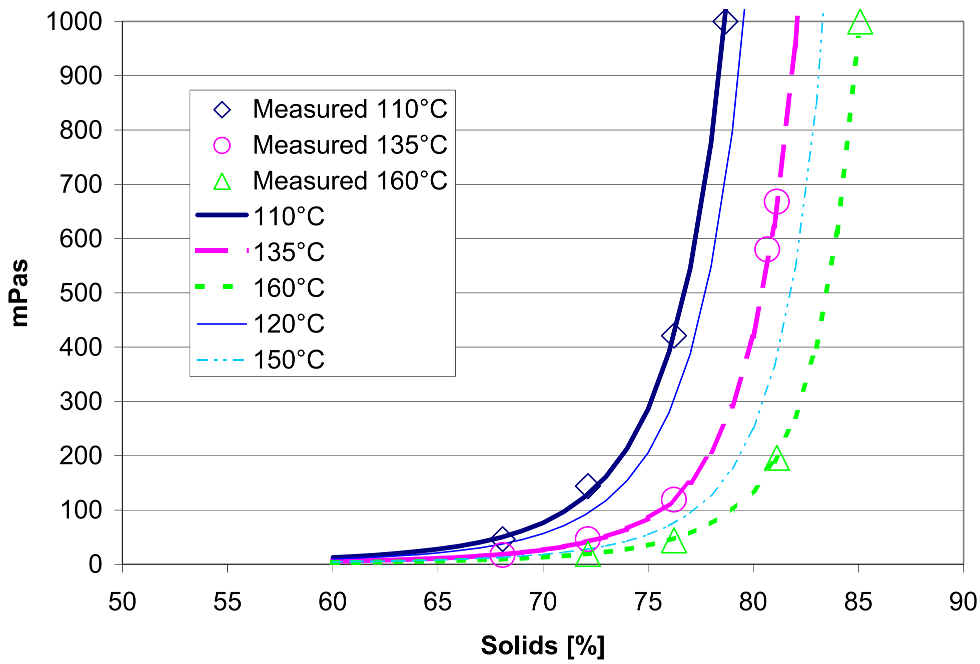

Figure A-1: Viscosity of high solids content black liquor at varying temperatures.

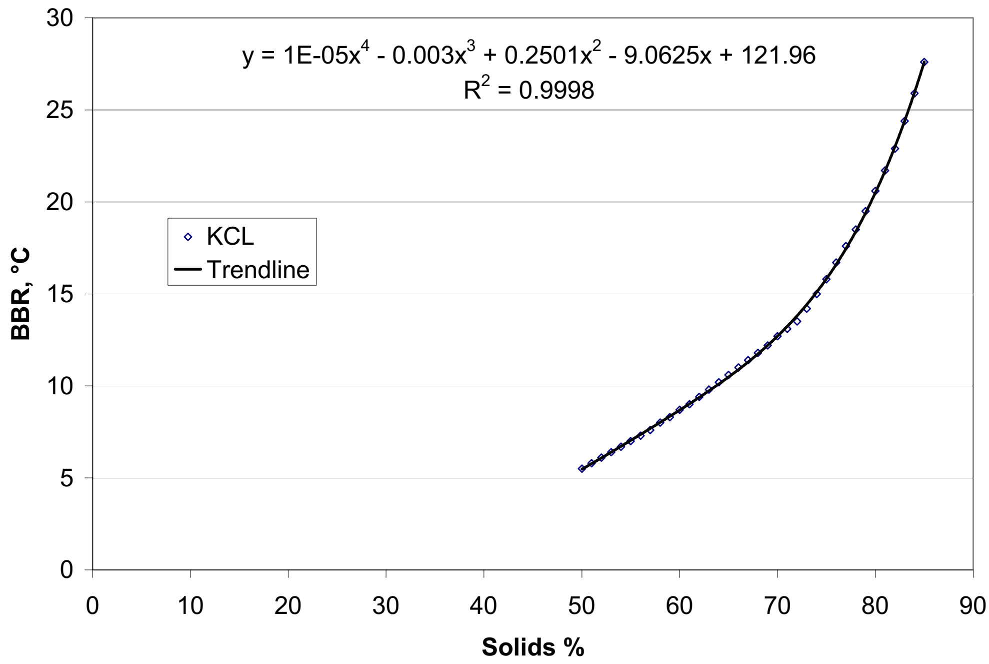

Figure A-2: The boiling point rise of high solids content in black liquor.