Paper IV

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THE EFFECT OF EXCESS TEMPERATURE AND FLASHING ON BLACK LIQUOR SPRAY PROPERTIES

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A series of spraying experiments was carried out at a modern Finnish recovery boiler within its normal operational range. The liquor dry solids content was between 75 – 80% and the spraying temperature was well above the boiling point of the liquor that resulted in heavy flashing in some cases. Spray properties such as velocity, the shape and the length of the black liquor sheet were measured both in the test chamber and in furnace environment with a furnace endoscope. In addition the droplet size and size distribution were measured simultaneously in a full scale test chamber which was built next to the operating recovery boiler furnace.

It was observed that the range of spraying temperature in which the modern recovery boilers operate is very narrow due the dramatic changes in the spray properties, caused by the changing flashing phenomenon.

INTRODUCTION

Black liquor is commonly sprayed into a kraft recovery boiler furnace by a set of splashplate nozzles. These nozzles produce a thin liquid sheet, which then breaks up, resulting in the formation of large drops with wide size distribution. The drop size, and the size distribution, are both of great importance for control of the combustion process in the furnace. They define combustion time and essentially the location where the reactions take place. The velocity and the mass flow distribution of the spray are also linked to the rate and the location of the combustion process. The properties of the spray determine in which part of the furnace drying, devolatilization and char burning take place. Liquor dry solids content, temperature, feed rate and the nozzle geometry are the main operating parameters that determine spray properties /1/.

Spray properties, such as velocity, opening angle and disintegration mechanisms of the liquid sheet result from the operating parameters listed above. They have a direct influence on the resulting droplet size and size distribution /2/. Nowadays, mills want higher black liquor solids content (>75%). Therefore, they need to increase the liquor temperature 10-20 °C above the atmospheric boiling point of the liquor, so as to avoid increases in the liquor viscosity. The spray velocity is highly dependent on the excess temperature (temperature above the atmospheric boiling point): at a higher excess temperature, flashing produces water vapor that has a large specific volume and as a result accelerates the flow.

The droplet formation mechanism is different from spraying at lower liquor temperatures where droplets are formed mainly by liquid sheet disintegration /3,4/. The liquid sheet disintegration mechanisms can be categorized into two main categories: perforated-sheet disintegration and wave disintegration /5/. In wave disintegration aerodynamic, inertial, viscous, and surface tension forces break up the sheet at half wavelength intervals and form bands of fluid. The fragments contract by surface tension in unstable ligaments which rapidly break down into drops /6/. In perforated-sheet disintegration surface tension forces rapidly expand a hole in a fluid sheet, and the fluid is drawn up into a thick rim about the hole. When the rim reaches the edge of the sheet or another perforation rim the expansion is halted. This results in the formation of a web of interconnected strands of fluid that will break up under surface tension and aerodynamic forces to form drops /7, 8/. If a black liquor sheet is formed those wave disintegration or perforated-sheet disintegration or combination of them can be observed. In the case of heavy flashing, a perforated sheet or no sheet at all is formed and the droplet formation mechanism is different. Atomization is accomplished by the rapid escape of gas exiting the nozzle. The classification of break-up mechanisms is often subjective and not just one mechanism takes place /9,10/.

In this study a set of experiments was carried out at a modern Finnish recovery boiler within its normal operational range to determine how spraying temperature, in this case the excess temperature, affects spray properties and the formation of drops. The spraying temperature was well above the boiling point of the liquor that resulted in heavy flashing in some cases. Spray characteristics were measured both in the test chamber and in the furnace environment with a furnace endoscope. By comparing the spray properties measured in the furnace to the ones measured in the test chamber it was possible to see how the furnace environment affected liquor sheet and its break-up mechanisms. It is not possible to measure drop size and size distribution directly in the furnace and therefore they were measured in the test chamber simultaneously. Spray formation was observed to be similar in the spraying chamber and furnace and therefore the results from spraying chamber are applicable to the furnace conditions /11/.

The objective of the study presented here is to determine the effect of excess temperature on the properties of the forming black liquor spray, especially on sheet break-up mechanisms, velocity and drop formation.

SPRAYING EXPERIMENTS

The spraying experiments took place at a modern Finnish pulp mill where softwood liquor was sprayed during the test period at a temperature of 129 to 135°C, which was 13 to 19°C above the atmospheric boiling point (excess temperature, dTb). The liquor dry solids content was high; it varied between 75 and 79%. Three different mass flow rates of 4.3 kg/s, 5.2 kg/s and 6.1 kg/s were used to observe the effect of the load. 5.2 kg/s at 16°C above the atmospheric boiling point was approximately the normal operating condition. Two different types of commercial splashplate nozzles were used in the tests, see Fig.1: Nozzle A, where the nozzle exit area is partly reduced by the splashplate and nozzle B, where the splashplate is attached to a nozzle tube with a jacket whose inner diameter is larger than the nozzle tube exit. The nozzles were equipped with air cooled pressure measurement assemblies. Black liquor spray properties and their effect on drop formation were studied both in the horizontal spraying chamber that was built in the boiler room next to the operating recovery boiler and under furnace conditions to ensure the applicability of the results.

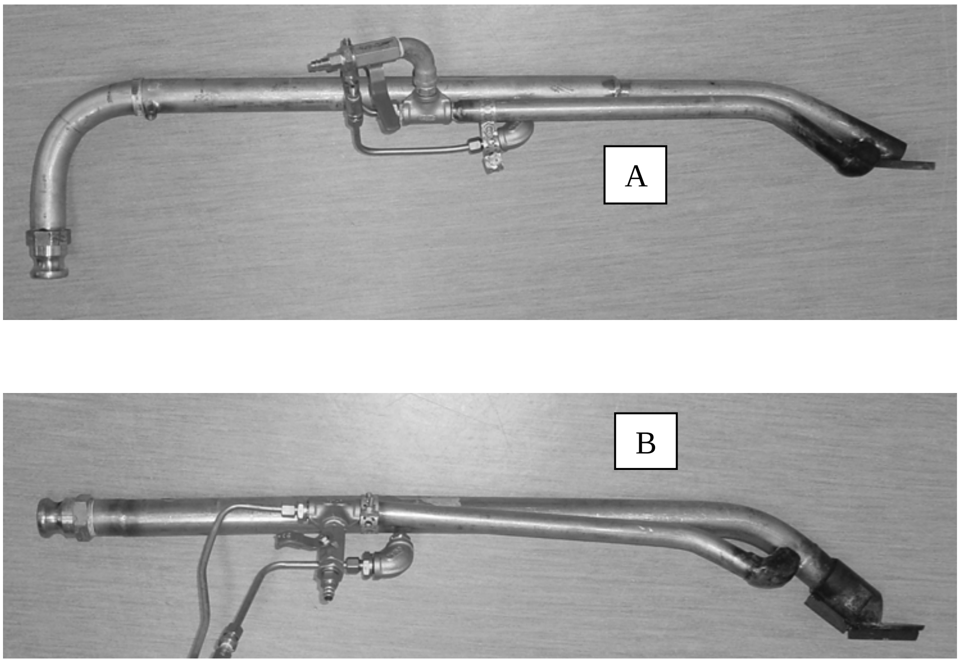


Figure 1. *Splashplate nozzles of types A and B /12/*

Main dimensions of nozzles:

A:	Diameter of the nozzle pipe	27 mm
	Splashplate angle	23°
B:	Diameter of the nozzle pipe	28 mm
	Splashplate angle	36°

A schematic experimental configuration is shown in Fig. 2. A 13-m black liquor hose came from the ring header of the boiler. The hose was well insulated. The spraying chamber enabled horizontal spraying of black liquor. The endoscope was located at 0.3 to 0.5 m above the splashplate nozzle. The liquor spray was illuminated with eight studio lamps operating beneath a plexiglass window. In the furnace, the required backlight came from the char bed. 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 spraying chamber. The main dimensions of the spraying 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. Process data such as liquor volume flow rate, temperature, pressure and dry solids content were stored in the boiler control system database. A liquor sample was taken daily and analyzed at the Finnish KCL –laboratory. Temperature and pressure were also measured from the nozzle pipe. /11/ The atmospheric boiling point of black liquor was approximately 120°C, depending mainly on the solids content.

The furnace endoscope was used for comparison of the spray properties, such as the velocity at the spray centerline and the opening angle from two different spraying environments. This air-cooled endoscope tube is approximately 3 m long; there is a high shutter-speed CCD –camera at one end of the tube and a prism for a right angle view at the other /11/. The resolution of the camera was 1280 x 1024 pixels when used in the test chamber. In the furnace, the lack of light led to a reduction in resolution to 640 x 512 pixels. The furnace endoscope was put into the furnace using the liquor gun hole (above the liquor gun) so that the shooting distance from the endoscope lens to the liquor sheet was 30 cm. The experiments in the test chamber were similar, apart from the shooting distance being approximately 50 cm in the test chamber, see Fig. 2. The velocity was measured by using the triple-exposure mode of the camera and an image-analysis system. The distance that the black liquor sheet had moved during the delay between the exposures was then measured from the images. To calculate the sheet velocity, the trajectory of the sheet had to determined. In addition, the shape and the length of the black liquor sheet were measured and the sheet break-up mechanism was determined.

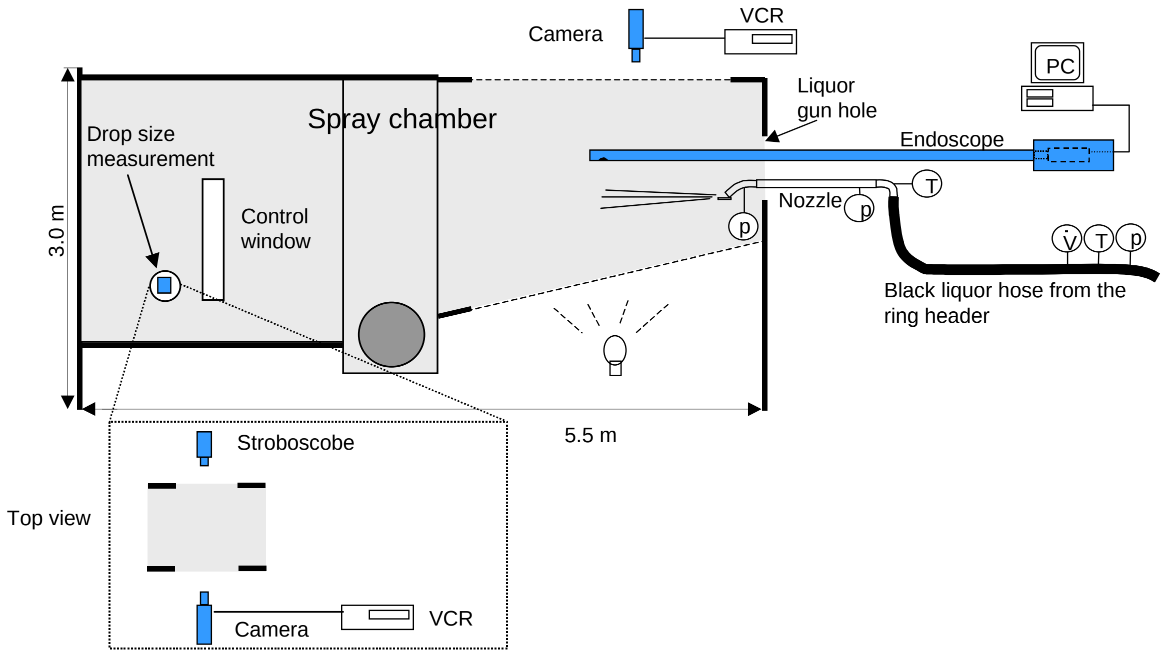


Figure 2. *Experimental configuration in the test chamber*

The drop size and shape was determined by a system using a video camera and image analysis. A video camera was used to record the spray at a distance of 4 meters from the nozzle. The drop size and shape were assumed to be final at that distance. Spray separation baffles restricted the spray width. The spray was lit by a stroboscope from the opposite side of the chamber, so the droplets could be detected without motion blur by a standard video camera, see Fig. 2. Each test section took 11 minutes and produced 15000 frames of video pictures for analysis. In the study presented here only 1500 frames were studied for each case /12, 14/. Most of the drops observed were not spherical /15/. In this study the volume of all the objects were determined and the diameter of corresponding spherical drop was then calculated. Drop size measurements are described in more detailed in /13/.

RESULTS AND DISCUSSION

It was observed that spraying temperature is one of the most important parameters that affects the spray characteristics. Typically, in a modern recovery boiler liquor is sprayed at 16 °C above the atmospheric boiling point. At this temperature, no actual liquid sheet is formed as flashing takes place inside the nozzle tube and breaks up the continuous liquid phase.

Spray break-up

Figures 3 and 4 present examples of spray disintegration mechanisms at three excess temperatures as a function of mass flow rate. At a constant excess temperature the increase in mass flow rate results in a longer uniform liquid sheet before sheet disintegration by perforation or flashing. In Figure 3 (Nozzle A) the sheet break-up mechanism is similar in all the cases. Only the length of uniform sheet varies.

Examples of remarkably changing disintegration mechanisms can be shown for both nozzle types. In Figure 3, at 4.3 kg/ the change of excess temperature by 4°C has a similar effect, as the case at 5.2 kg/s and the change of excess temperature from 14°C to 16°C, in Figure 4. Only a minor change in spraying temperature, especially in the latter case, can cause a dramatic change in sheet break up mechanism. At a 2°C higher excess temperature flashing breaks up the liquid sheet rapidly after the splashplate and no uniform liquid sheet is formed.

For nozzle B, a uniform and long liquor sheet was unexpected. The splashplate is attached to a nozzle tube with a jacket whose inner diameter is larger than the nozzle tube exit, see Fig.1. One could assume that at an excess temperature as high as 14 °C, flashing would take place in the liquor flow immediately after the nozzle tube exit, before the flow hits the splashplate and no sheet would form. It is also noteworthy, that the mill operates normally at a 16°C excess temperature.

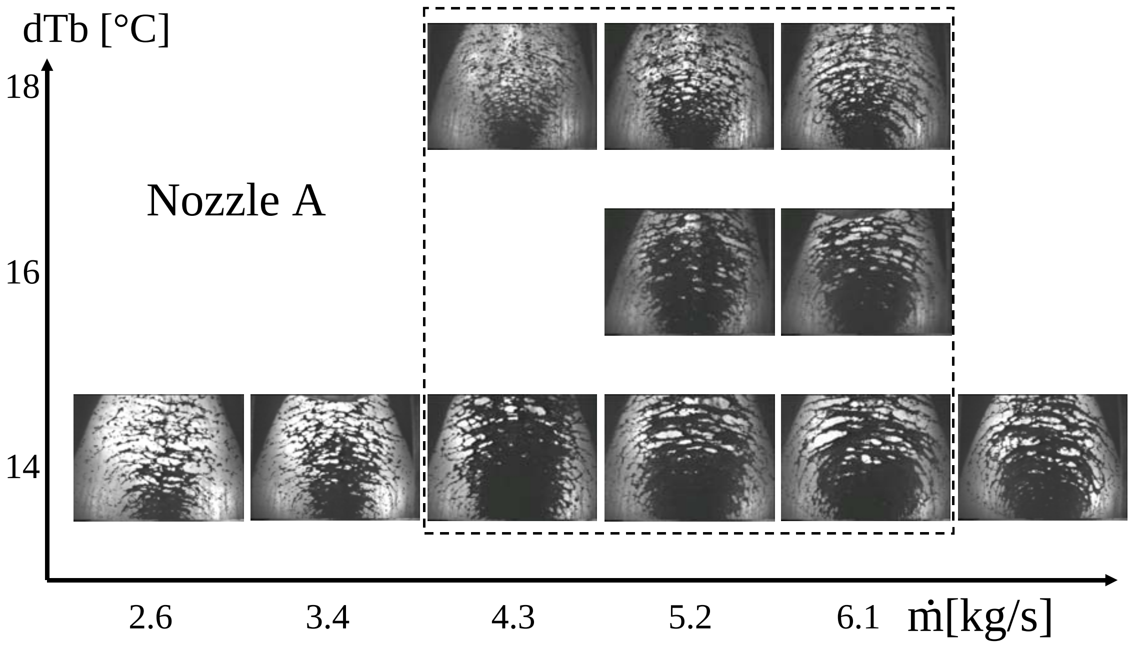


Figure 3. *The effect of excess temperature and mass flow rate on sheet disintegration, Nozzle A, (height of a single picture is approximately 0.7 m).*

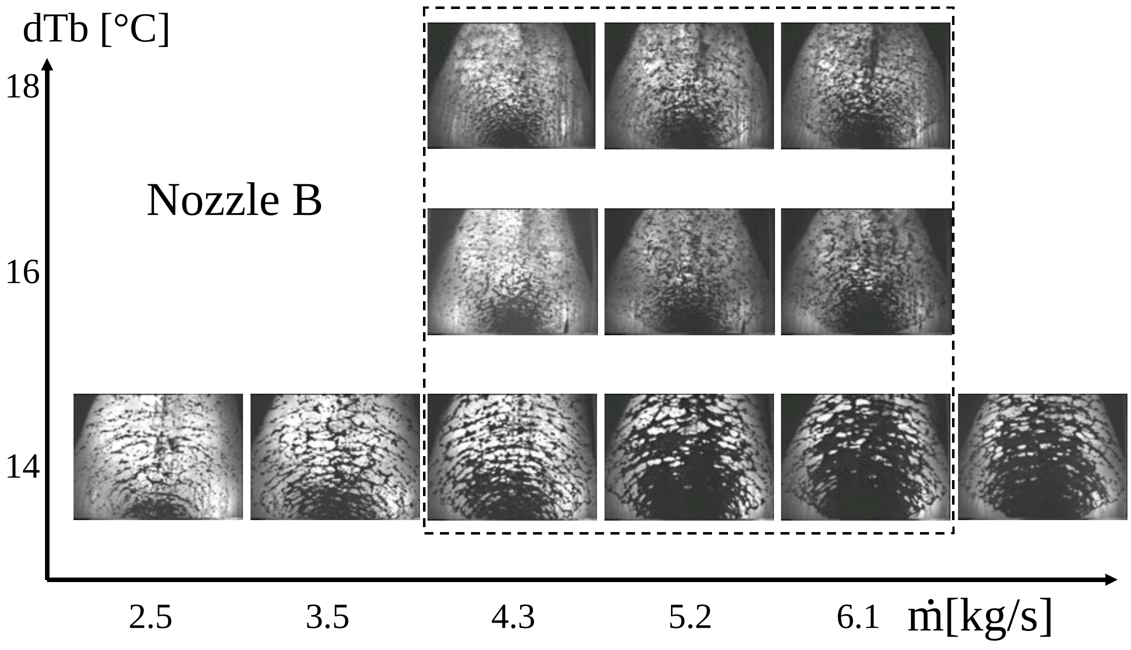


Figure 4. *The effect of excess temperature and mass flow rate on sheet disintegration, Nozzle B, (height of a single picture is approximately 0.7 m).*

Flashing accelerates the flow inside the nozzle

Figure 5 presents the effect of excess temperature on spray velocity at the spray centerline. The velocity at the spray centerline varied in the 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 increases the velocity of the spray, but the effect of mass flow rate is not so unambiguous. Increasing mass flow rate diminishes the effect of excess temperature.

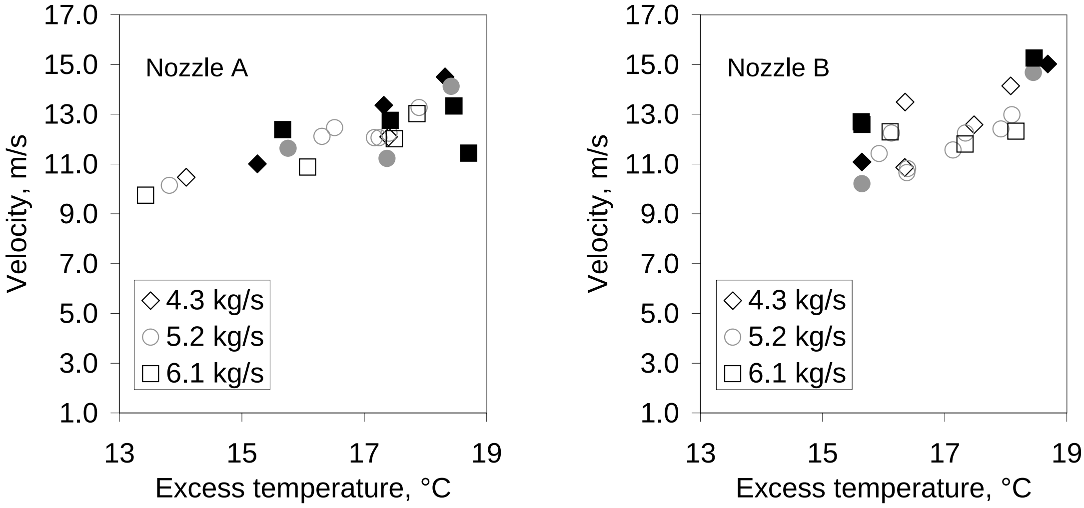


Figure 5. *The effect of excess temperature on spray velocity*

The spray velocity is highly dependent on the spraying temperature and pressure: at a higher temperature, flashing produces water vapor that has a large specific volume and as a result accelerates the flow. At lower pressure i.e. at lower mass flow rate flashing takes place more easily. The dimensionless velocity (Eq. 1) can be used to describe this phenomenon.

$$u^* = \frac{u_s}{\frac{\dot{m}}{A\rho_{BL}}} = \frac{u_s}{u_p} \qquad (1)$$

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, $\dot{m}$ /10/.

Increasing mass flow rate decreases the effect of flashing inside the nozzle tube. The smaller the mass flow rate and the higher the excess temperature, the higher the dimensionless velocity, see Figure 6. A similar trend can be observed for nozzle type B. Furnace environment has a negligible effect on the spray velocity in the cases studied here /11/.

The dimensionless velocity in different cases can be connected to corresponding sheet disintegration mechanisms. When dimensionless velocity is low (see Fig. 6, Nozzle B, 6.1 kg/s), flashing does not dominate the sheet disintegration mechanism and an unexpectedly long, uniform liquid sheet is formed, see Fig. 4.

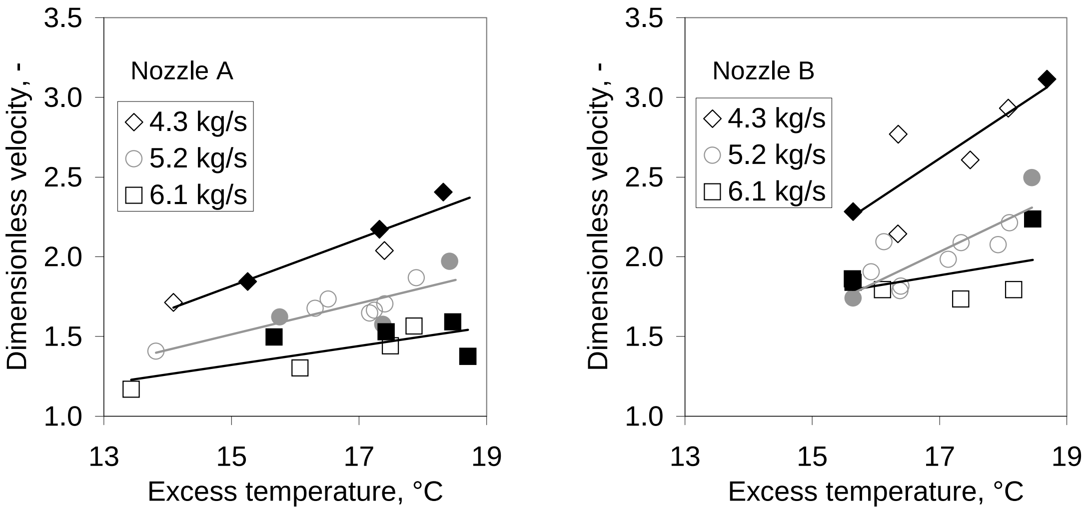
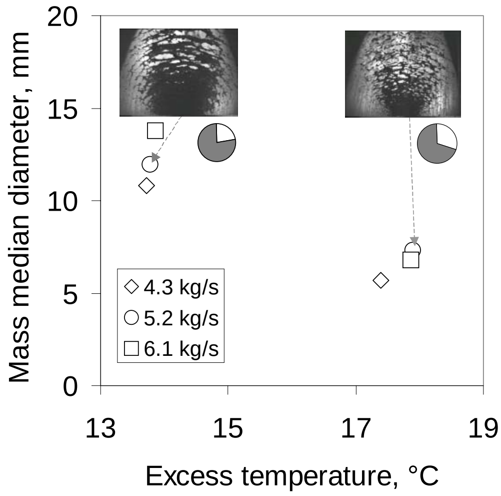


Figure 6. *Dimensionless velocity as a function of the excess temperature. The open and closed symbols represent the test chamber and furnace respectively.*



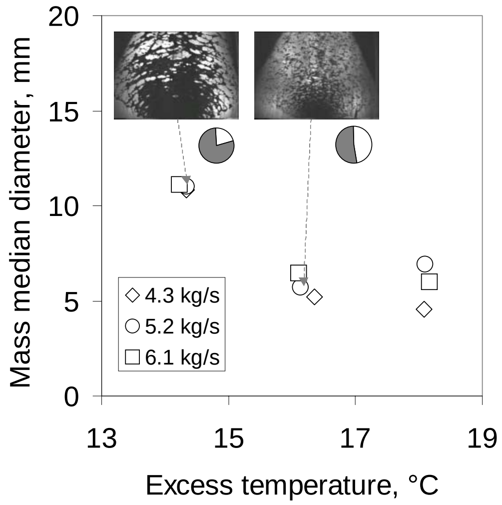


Figure 7. *Drop size as a function of excess temperature. The white area in the pie charts presents the fraction of spherical drops. Nozzle A.*

Figure 8. *Drop size as a function of excess temperature. The white area in the pie charts presents the fraction of spherical drops. Nozzle B.*

Resulting drop size

Figures 7 and 8 present the measured drop size of cases corresponding to Figures 3,4 and 6. Particles were counted and measured by the image-analysis system. The volume of each accepted particle was calculated. The results and methods used in drop size measurements are described in more detail by Kankkunen and Miikkulainen in /13/. Here the focus is on the connection between spray break up mechanism and resulting drop size.

In Figures 7 and 8 all particles, droplets and non-spherical particles, are assumed to form spherical particles. The resulting mass median diameter is larger than the mass median diameter of spherical droplets alone, or the equivalent smaller mean diameter of non-spherical particles at the corresponding case. This is a natural consequence of the transformation of the volume of non-spherical particles to equivalent spherical particles. Either decreasing the temperature or increasing the mass flow rate increased the mass median diameter./13/

The median drop size was affected mostly by excess temperature. An increase of excess temperature only by 2 °C (from 14 to 16°C) in the case of nozzle B decreased median drop size to approximately 50%, see Figure 8. Note also the huge change in the spray appearance. In Figures 7 and 8 there are pie charts under each of the spray pictures. The white area in the chart presents the fraction of spherical particles detected. The ratio of spherical and non-spherical particles and method to measure the sphericity are reported by Kankkunen *et al.* in /15/. In the case of nozzle B (Figure 8) the fraction of spherical particles increases noticeably when sheet disintegration changes to the flash break-up dominated mode.

Only a minor change in spraying temperature, especially in the case of 5.2 kg/s for nozzle B (Figure 8), can cause a dramatic change in mass median diameter but also in sheet disintegration. In the case of nozzle A the change in the sheet disintegration mechanism is not as sharp but the mass median diameter of drops decreases as excess temperature increases. It seems that at some point heavy flashing starts to dominate the sheet disintegration mechanism resulting in approximately 50% smaller drops for both the nozzles.

CONCLUSIONS

A series of large-scale spraying experiments were carried out both in an operating kraft recovery boiler and in a test chamber. The aim of this study was to observe the effect of excess temperature on black liquor spray properties such as velocity, sheet break up mechanism and resulting drop size. The focus was on research into the flashing phenomenon.

Increasing mass flow rate decreases the effect of flashing inside the nozzle tube. The smaller the mass flow rate and the higher the excess temperature, the higher the dimensionless velocity. Dimensionless velocity characterizes the acceleration of liquor flow inside the nozzle tube caused by flashing.

At their normal operation range modern kraft recovery boilers are controlled in such a way that flash-breakup is the dominating spray break up mechanism. The operational range is very narrow. When firing temperature was in the experiments lowered by 2°C outside the operational temperature range of a recovery boiler, an unexpectedly long, uniform liquor sheet appeared. More importantly, this doubled the mass median drop size and formed more non-spherical drops. The fraction of spherical drops is low even within the normal operation range. The shape of the black liquor particles must be taken into account when designing or modeling kraft recovery boilers.

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Nomenclature

A	The smallest cross-sectional area of the nozzle, m^2
$\dot{m}$	Mass flow rate, kg/s
p	Pressure, bar
T	Spraying temperature, °C
T_b	Atmospheric boiling temperature, °C
u_p	Velocity of the non-flashing pipe flow at the smallest cross-sectional area, m/s
u_s	Measured velocity at the centerline of the black liquor spray, m/s
$u*$	Dimensionless velocity, -
$\dot{V}$	Volume flow rate, m^3/s
dTb	$dTb = T - T_b$, excess temperature, °C
ρ_{BL}	Density of black liquor, kg/m^3

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