Paper III

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THE EFFECT OF A FURNACE ENVIRONMENT ON BLACK LIQUOR SPRAY PROPERTIES

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ABSTRACT

Black liquor spray properties such as the velocity, opening angle and disintegration mechanisms were determined in an operating recovery boiler and in a horizontal spraying chamber by using a furnace endoscope. Spraying chamber measurements can be correlated to a furnace environment if the spray properties are sufficiently similar in both environments. The sheet break-up mechanism, and other spray properties, were found to be similar in both environments in the tests, which were carried out within the normal operating range of a modern kraft recovery furnace.

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, both are 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. 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. 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 spraying temperature: at a higher 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 [2,3]. The liquid sheet disintegration mechanisms can be categorized into two main categories: perforated-sheet disintegration and wave disintegration [4]. If a black liquor sheet is formed those two main sheet break-up mechanisms can be observed. In heavy flashing a perforated sheet or no sheet at all is formed and the droplet formation mechanism is different. Classification of break-up mechanisms is often subjective and not just one mechanism takes place. [5]

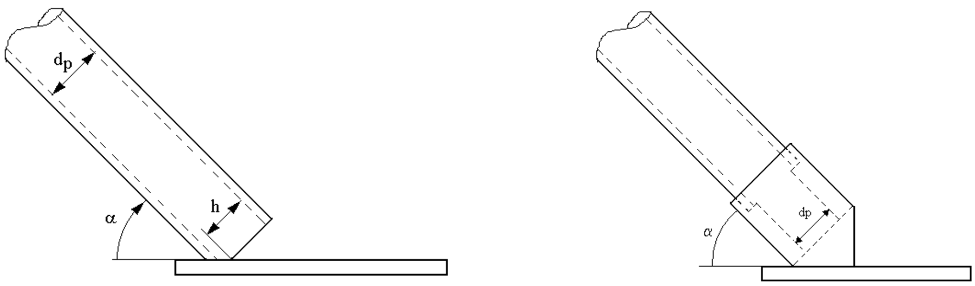
Black liquor spraying and drop formation has been studied previously in test chambers with small and full scale nozzles [2,3,6,7,8]. The spraying environment in the test chambers differs greatly from the furnace environment. Therefore, it was of great interest to study the sheet properties in furnace conditions where the temperature and flow direction of surrounding gases differ from test chamber conditions. As stated previously [7], this could have a significant effect on the atomization process. At the moment, it is possible to study spray properties in an operating furnace with the unique furnace endoscope developed at Helsinki University of Technology (HUT). However, droplet size cannot be measured under furnace conditions. [5]

In this study, the velocity, the shape of the spray and the spray break-up mechanisms were determined in an operating recovery boiler and in a spraying chamber. A horizontal spraying chamber was built in the boiler room at the nozzle level of the recovery boiler. The same liquor, nozzles and operational parameters were used in both environments to make the comparison relevant. The rationale behind this is if the droplet formation processes described above in the test chamber and the furnace are sufficiently similar, test chamber measurement results could be applied to a furnace.

EXPERIMENTAL

Black liquor spray properties and their effect on drop formation were studied both under furnace conditions and in the horizontal spraying chamber that was built in the boiler room next to the operating recovery boiler. This study focuses on the comparison of the results in the two environments.

The measurements took place at a modern Finnish pulp mill where softwood liquor was sprayed at a temperature of 129 to 135 °C, which was 13 to 19 °C above the atmospheric boiling point. The dry solids content varied between 75 and 79%. Two different types of widely used mill scale splashplate nozzles were used in the tests, Fig. 1: 1) Nozzle A, where the nozzle exit area is partly reduced by the splashplate and 2) Nozzle B, where the splashplate is not attached to a nozzle tube. 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.



A-type splashplate nozzle, d_p = 27 mm, h = 21 mm, α = 23°

B-type splashplate nozzle, d_p = 28 mm, α = 36°

Figure 1. Splashplate nozzles of types A and B

Spray properties, such as velocity at the spray centerline and opening angle, were studied with the furnace endoscope developed at HUT. 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. 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 inflexible structure of the optical system makes the endoscope very sensitive to bending. Thus, it is possible to use the endoscope for only 15 minutes at a temperature of 1000 to 1200 °C without a cooling pause. 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, Fig. 2.

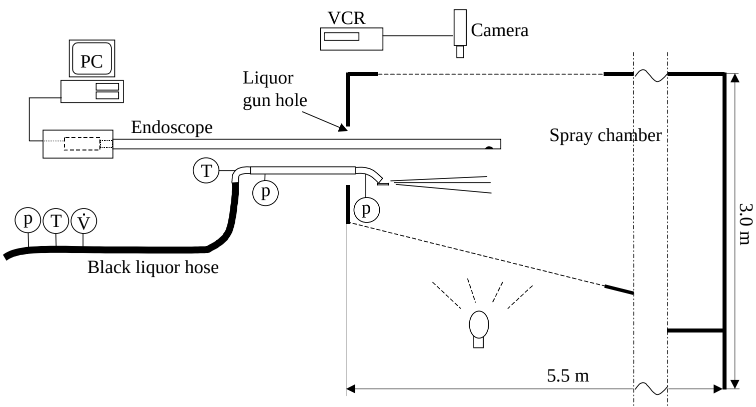


Figure 2. Experimental configuration

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. 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 analysed at the Finnish KCL laboratory. Temperature and pressure were also measured from the nozzle pipe. 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 an over-all picture of the spray, another camera was located in the roof structure of the spraying chamber. These pictures were compared to pictures taken with the endoscope so as to verify the results. 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.

The black liquor sheet centerline was filmed every 10 cm up to 120 cm from the splashplate. The velocity was measured by using a triple-exposure mode of the camera and an image-analysis system. Three exposures in the same frame and delay of 1 ms between every exposure were used. The distance that the black liquor sheet had moved during the delay time was then measured from the images. To calculate the sheet velocity, one had to determine the trajectory of the sheet. In addition, the shape and the length of the black liquor sheet were measured and the sheet break-up mechanism was determined.

RESULTS AND DISCUSSION

The objective of this work was to study the effect of the furnace environment on black liquor spray properties. Velocities at the spray center line, the spray opening angle and liquor sheet length and break-up mechanisms for the test chamber and furnace were compared. The distribution of the mass flow in the spray was also measured in order to obtain nozzle specific characteristics for both nozzle types.

Sheet break-up

Research into the black liquor sheet break-up mechanism was carried out by comparing images from the furnace and test chamber taken with the endoscope. The sheet break-up mechanism varied with the nozzle type, temperature and mass flow rate. The spraying situations chosen for this comparison are within the normal operating range for the mill.

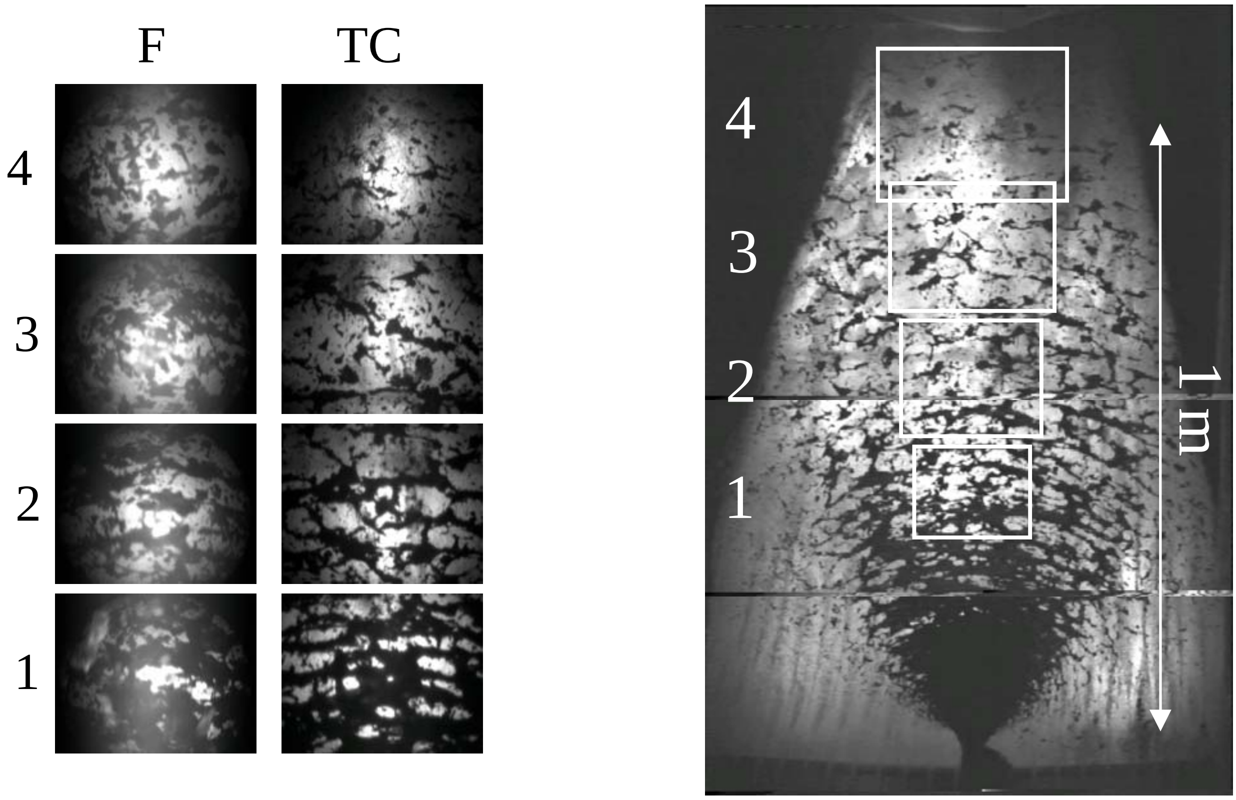


Figure 3. Black liquor sheet break-up in the furnace (F) and in the test chamber (TC) at distances of 0.4 m (1), 0.6 m (2), 0.8 m (3) and 1.0 m (4) from the exit of the nozzle and the over-all view of the black liquor spray in the test chamber, nozzle A.

In Fig. 3, the eight pictures on the left are at the spray centerline at distances of 0.4, 0.6, 0.8 and 1.0 m from the exit of the nozzle from the furnace (F) and from the test chamber (TC) numbered from 1 to 4, respectively. The scales have been adjusted to be identical. The scales at distances of 0.8 m and 1.0 m are not necessarily accurate: they are estimated on the basis of the calculated sheet trajectory. In Figure 3, there is also an overall view of the spraying situation. The numbered white rectangles present the location of the frames that are analogous to the frames on the left.

Figure 3 illustrates the spray pattern for nozzle A when the excess temperature, ΔT_e (spraying temperature - atmospheric boiling point of black liquor) was 18 °C and mass flow rate was 5.2 kg/s. The velocity of the spray center line was 13.7 m/s. The sprays seem identical in both environments. The nozzle produces a thin and flat liquor sheet with a length of 0.3 m. The dominating sheet break-up mechanism could be classified as wave disintegration based on pictures F1, F2, TC1 and TC2 in Fig. 3. Perforated sheet disintegration probably takes place at the same time as the wave disintegration. Small holes can be observed at a distance of 0.3 m from the nozzle exit: small vapor bubbles that break through the sheet surface may form these. The shape of the holes is not spherical but elongated. After this, the sheet breaks up very fast into smaller ligaments, but spherical droplets cannot be observed.

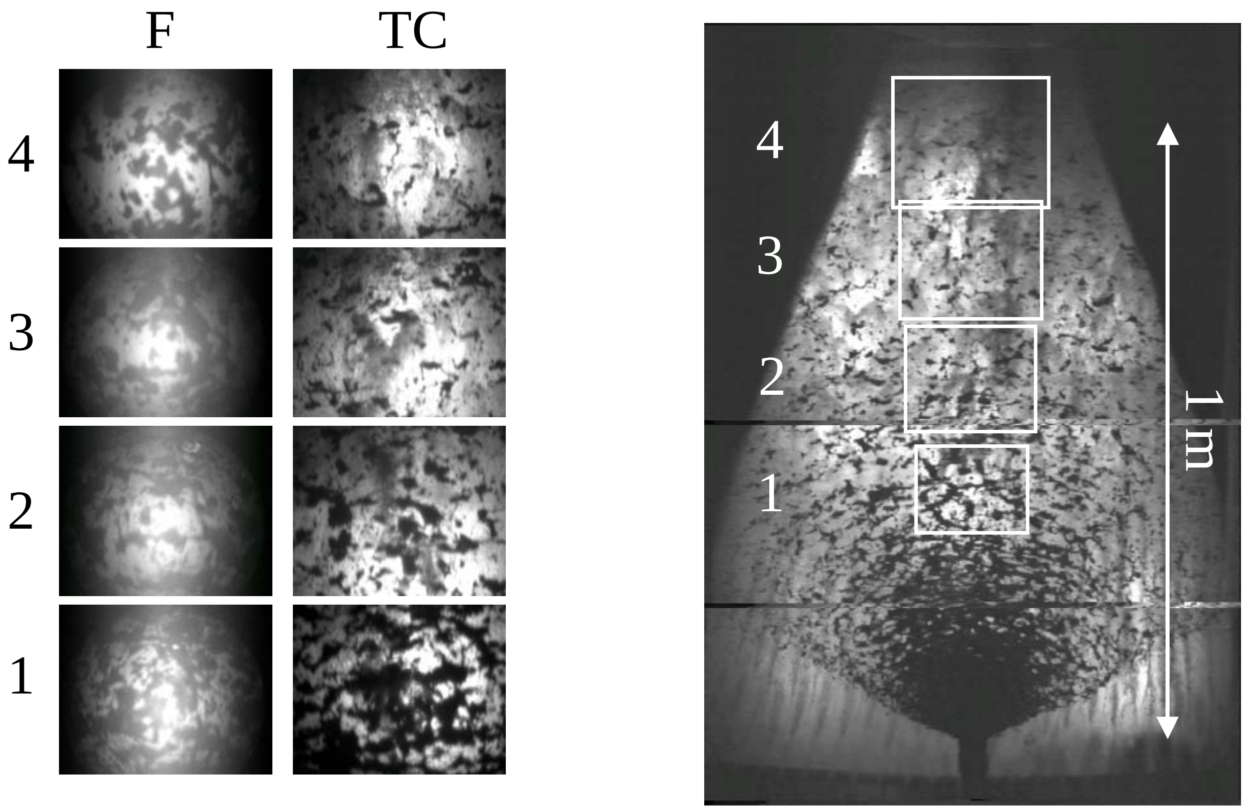


Figure 4. Black liquor sheet break-up in the furnace (F) and in the test chamber (TC) at distances of 0.4 m (1), 0.6 m (2), 0.8 m (3) and 1.0 m (4) from the exit of the nozzle and the over-all view of the black liquor spray in the test chamber, nozzle B

In the case of nozzle B, as Fig. 4 illustrates, the spraying situation was similar to the case of nozzle A in Figure 3. The excess temperature of the black liquor was 18°C. The mass flow rate was 5.2 kg/s and the velocity at the spray centerline was 13.8 m/s. In the case of nozzle B, the sheet break-up mechanisms in the furnace and in the test chamber were again quite similar. At the distance of 0.4 m from the nozzle exit, only short ligaments could be observed in both cases, pictures F1 and TC1 in Figure 4. No formation of waves was observed (see Fig. 4). Flashing causes spray disintegration by perforation and the spray seems to be very shattered.

Shape of the spray

The shape of the spray was determined and compared by measuring the horizontal opening angle of the liquor sheet with the image analysis program. In addition, an approximate analysis of the overall pictures from the test chamber was done. Nozzle A produced an almost constant opening angle regardless of the mass flow rate or the velocity of the spray. In the furnace environment the spray was approximately 15° narrower than in the test chamber. The opening angle of the spray in the spraying chamber was 135°. Nozzle B produced an evenly distributed spray. The opening angle produced by nozzle B varied between 125 and 135° regardless of the spraying environment or the velocity of the spray. The nozzle geometry, the opening before the splashplate, was the main reason for the almost constant opening angle (see Fig. 1).

The distribution of mass flow at a distance of 60 cm from the nozzle exit was measured for both nozzles in the test chamber at a mass flow rate of 5.2 kg/s. Figure 5 shows the mass flow rate in directions of 0 to 30° from the spray centerline. Nozzle A produces a mass flow distribution where most of the mass flow goes to the middle section. There are insignificant edges on both sides of the spray (see also Fig. 3). The heat in the furnace dries up the small liquor flow at the sheet edges and produces a solid layer, which confines the opening angle of the spray. This is probably the reason why the measured opening angle in the furnace was narrower than in the spraying chamber.

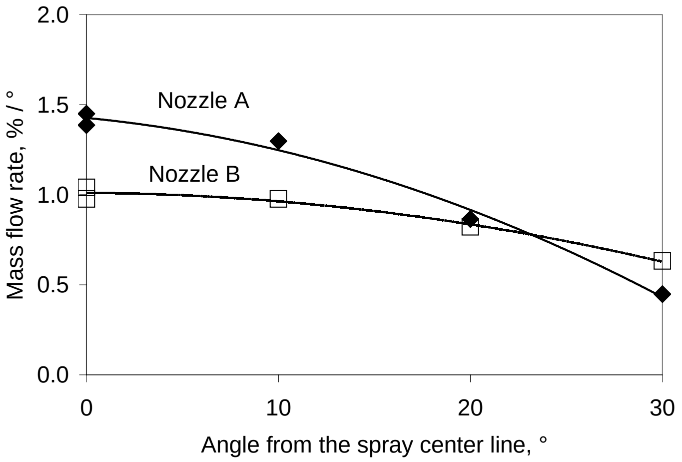


Figure 5. Distribution of the mass flow of nozzles A and B, 60 cm from the nozzle exit at a flow rate of 5.2 kg/s

Velocity of the spray

The velocity of the black liquor spray at the sheet centerline was measured by the image-analysis system. The absolute velocity at the spray center line varied in the range from 9.7 to 14.5 m/s for nozzle A, and from 10.2 to 15.3 m/s for nozzle B. The most important parameters that affect the velocity of the black liquor spray are the mass flow rate and flashing of the liquor inside the nozzle tube. Flashing produces water vapor that has a large specific volume and therefore it accelerates the flow. This phenomenon can be described by the dimensionless velocity:

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

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, $\dot{m}$ [5]. The density, $\rho_{BL,}$ of the black liquor was calculated based on the measured dry solid content and correlations for different temperatures [9].

Figure 6 shows the dimensionless velocity as a function of the excess temperature at three different mass flow rates for nozzle A. Increasing mass flow rate decreases the effect of flashing inside the nozzle tube. The smaller the mass flow rate and the higher the ΔT_e, the higher the dimensionless velocity. Some variation can be observed especially in the furnace measurements.

Increasing ΔT_e also accelerates the spray in the case of nozzle B. Figure 7 shows the dimensionless velocity as a function of ΔT_e for nozzle B. As in the case of nozzle A, an increasing mass flow rate decreases the effect of flashing.

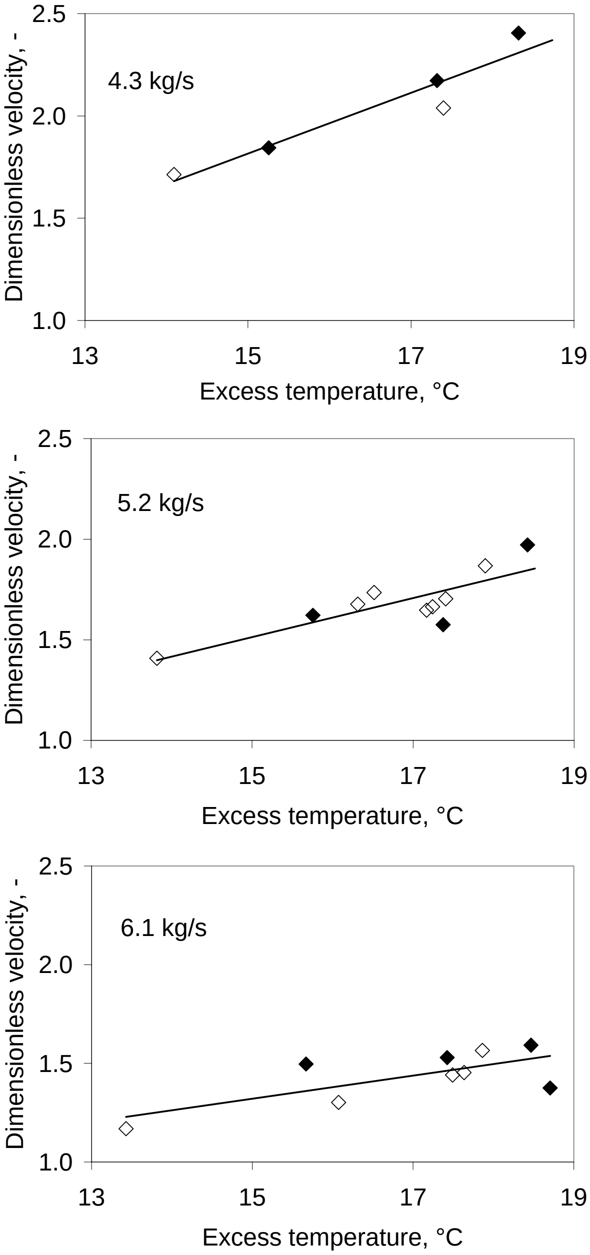


Figure 6. Dimensionless velocity as a function of the excess temperature for nozzle A. The black diamonds represent the furnace and the open diamonds the test chamber.

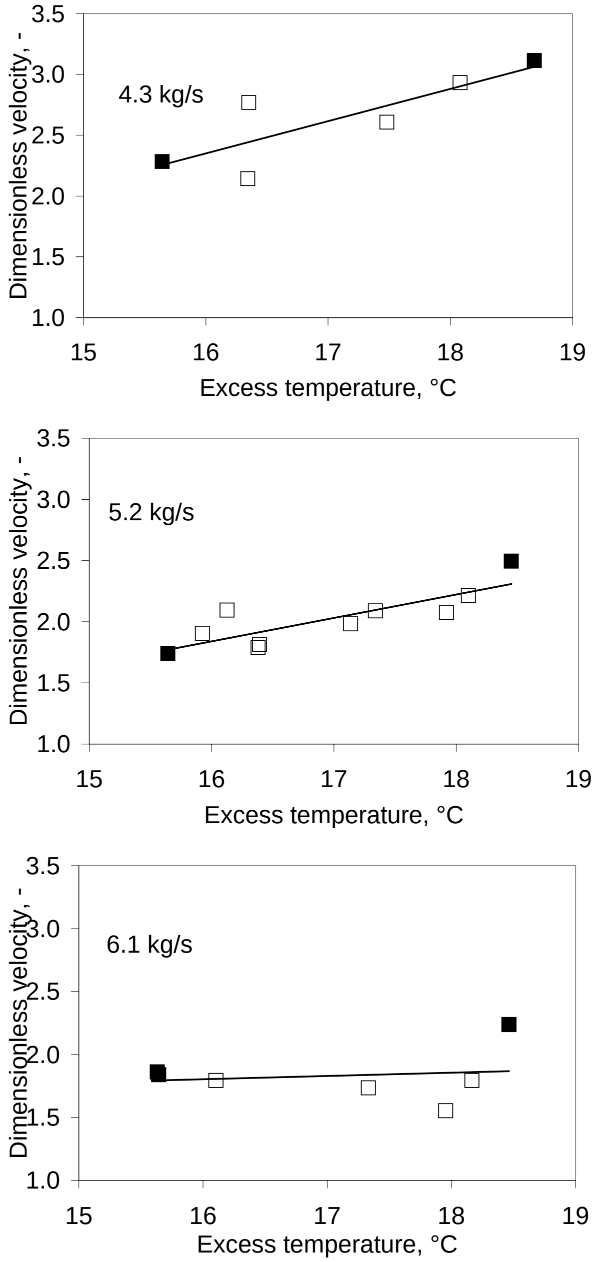


Figure 7. Dimensionless velocity as a function of the excess temperature for nozzle B. The black squares represent the furnace and the open squares the test chamber.

On the basis of Figs. 6 and 7, one can conclude, from the cases studies here, that the furnace environment has a negligible effect on the spray velocity. This suggests that the furnace radiation heat transfer to the liquor gun tube generates no additional water vapor and that flash evaporation dominates in both environments. Therefore, the spraying chamber results can be applied to a furnace. Different liquor flow conditions in the nozzle might give a different result. For example, a case without flashing inside the nozzle tube would probably produce a longer liquor sheet, thus increasing the effect of furnace heat radiation on the spray as explained in [7]. This would not be within the normal operational limits of a modern pulp mill where liquor with a high dry solids content is sprayed, but very close to it. This phenomenon will be studied in greater detail in our future work.

Error analysis

The accuracy of the measured and calculated results was estimated by error analysis. The relative error of the velocity measurements was approximated with total differential analysis [10] varying from 4 to 7%. Velocity measurements are most sensitive to the measured trajectory of a spray and to the resolution of the picture analyzed. The excess temperature of black liquor is sensitive to the calculated boiling point rise, which was determined from the liquor analysis as a function of dry solids content. The opening angle of a spray was determined from a sequence of pictures with the image analysis software, which can be considered to be a rather accurate (± 1°) method.

CONCLUSIONS

- The furnace endoscope is a very useful tool, which enables verification that spraying chamber measurements can be applied to a furnace environment.
- In modern kraft recovery boilers, black liquor is sprayed under conditions where flashing inside the nozzle tube is a common phenomenon. Under those conditions, spray formation is similar in the spraying chamber and furnace. This has been verified in the area of the nozzle exit. Further studies must be carried out to confirm whether this is the case when flashing is not the dominating reason for sheet disintegration, for example in applying the results for conventional boilers with lower dry solids content liquor.
- The shape of the spray remains the same in hot and cold environments. When the mass flow rate is small at the edges of a spray, black liquor may produce a salt layer on the splashplate in a hot environment. This makes the spray narrower but does not have an effect on the main liquor stream, particularly on the velocity at the spray centerline.
- Dimensionless velocity describes well the acceleration of the liquor flow when flashing takes place inside the nozzle tube. The smaller the mass flow rate and higher the ΔT_b, the higher is the dimensionless velocity.

ACKNOWLEDGEMENTS

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NOMENCLATURE

A	The smallest cross-sectional area of the nozzle, m^2
d_p	Nozzle tube diameter, m
h	Free height of the nozzle outlet, m
$\dot{m}$	Mass flow rate, kg/s
p	Pressure, bar
T	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
α	Splashplate angle, °
ΔT_e	$\Delta T_e = T - T_b$, excess temperature, °C
ρ_{BL}	Density of black liquor, kg/m^3

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