Paper II

BLACK LIQUOR SPRAY PROPERTIES IN OPERATING RECOVERY BOILER FURNACES

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ABSTRACT

Black liquor spraying and drop formation have been studied previously in cold test chambers. In this paper, spray properties in an operating furnace were studied with the unique furnace endoscope developed at the HUT. The velocity, the shape and the length of the black liquor sheet were measured with this furnace endoscope in five operating recovery boiler furnaces by using a multiple exposure CCD-camera and an image-analysis-system. Mass flux varied between 4 and 14 g/mm^2s. When firing at more than 7 °C above the atmospheric boiling point it was observed that the lower the mass flux the higher the rate of flashing. When flashing occurs, the sheet velocity may be accelerated by a factor of 3.4. No droplets were observed, only ligaments and large fragments of the sheet within the limits of the operation range (2 m) of the endoscope. When the liquor sheet was formed, two main sheet break-up mechanisms were observed, i.e. perforated-sheet disintegration and wave disintegration. In the case of flashing, the sheet break-up mechanism was different. The comparison between results from the test chamber and furnace showed that the spray properties in both environments depend on same main parameters, i.e. on the difference between the firing temperature and atmospheric boiling point as well as on the mass flux.

KEYWORDS
Black liquor, spraying, drop formation, recovery boiler

INTRODUCTION

Black liquor is a by-product of the pulping process, containing water, organic matter separated during cooking and inorganic cooking chemicals. Black liquor is burned in recovery boilers and is usually sprayed by splash plate nozzles. These nozzles produce a thin liquid sheet, which then breaks up with the result that a wide size distribution of large droplets is formed. The objective is to recover the expensive cooking chemicals and to recover the energy content of the organic matter.

Because the drop size and the size distribution are both of great importance for the control of the combustion process in the furnace, it is important to understand the affecting processes in liquor spraying. Drops, which are too small, are entrained in the combustion gases and, in the worst case, result in plugging of heat exchangers in the upper part of a recovery boiler. If the droplets are too large they do not have time enough to dry up before falling to the char bed and therefore cost temperature decrease. Drops of about 3 mm in diameter are usually considered the proper size for good recovery boiler operation. (Adams, Frederick, Grace, et al. 1997)

The most important parameters affecting black liquor spraying and drop formation are the operating temperature, pressure, liquor viscosity and density. The operating temperature is usually a few degrees centigrade above the atmospheric boiling point. If the difference is more than 8 °C, flashing may take place inside the nozzle and accelerate the liquor flow and increase the rate of sheet break-up. (Empie, Lien and Yang 1992)

Black liquor spraying and drop formation have been studied previously in test chambers with small and full scale nozzles (Kankkunen and Helpiö 1994, Helpiö and Kankkunen 1995, Kankkunen and Nieminen 1997). At the moment, it is also 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 in furnace conditions. The idea is that if the droplet formation processes in a test chamber and a furnace are similar enough, test chamber measurement results can be applied to a furnace. Therefore, it is of importance to study the sheet properties in furnace conditions where the temperature and flow direction of surrounding gas differs from test chamber conditions. As stated previously by Lefebvre (1989), this could have a significant effect on the atomization process.

In this study, the velocity, the shape and the length of the black liquor sheet were measured in five operating recovery boiler furnaces with the furnace endoscope. A multiple exposure CCD-camera and an image-analysis-system were used. Break-up mechanisms of black liquor sheet were also studied within the limits of the operation range. The shape and the length of liquor sheet will be reported in near future in another paper.

The maximum penetration of the endoscope into the furnace was approximately 2 m from the furnace wall. At that distance, ligaments and large fragments of the sheet were observed, but no droplets. When a liquor sheet was formed, two main sheet break-up mechanisms were observed, i.e. perforated-sheet disintegration and wave disintegration.

At higher firing temperatures, no sheet was formed because the liquor already flashed intensively inside the nozzle tube.

The velocity measured was related to the velocity calculated by the mass flow rate of liquid. This relative velocity describes well the phenomenon of flashing inside the nozzle tube. Relative velocity for the non-flashing situation is usually below 1.5 (Helpiö and Kankkunen 1995). Mass flux (mass flow rate per cross-sectional area) was used instead of mass flow rate to make measurements with different nozzle size in tests to be commensurable. Because the measurements took place in normal operational limits of the mills, the testing conditions were not so flexible. Some similar (nozzle type, mass flux and firing temperature difference to boiling point) measurement situations from furnace and test chamber could be found and compared with each other to study the differences in the sheet break up mechanism.

EXPERIMENTS

Experiments were carried out in operating furnace conditions and in the test chamber, which was built into the boiler room of a recovery boiler. This study is focused on the recovery boiler experiments and the test chamber results are used here only for comparison.

Experiments at five recovery boilers

Furnace measurements took place in five chemical recovery boilers of Finnish pulp mills, which are here named from A to E. They all differed from each other by nozzles, properties of black liquor (liquor type, dry solids content, viscosity etc.), firing temperature and pressure. Spray properties were studied with a unique furnace endoscope (1 in Figure 1) developed at HUT. This air-cooled endoscope tube was approximately 3 m long; there was a fast CCD –camera at one end of the tube and a prism for right angle view at the other. Inflexible structure of the optical system made the endoscope very sensitive to bending. It was possible to use the endoscope for 15 minutes at a temperature of 1000 °C without a cooling break. A furnace endoscope was put into the furnace by using the liquor gun hole so that the shooting distance from the endoscope lens to the liquor sheet was 30 – 50 cm, see Figure 1. The black liquor sheet centerline was filmed at every 10 cm up to 150 cm from the splash plate. In order to calculate the sheet velocity, the trajectory of the sheet had to be determined. In addition, the shape and the length of black liquor sheet were measured and the sheet break-up mechanism was determined.

Velocity measurements were done by using a multiple exposure CCD camera and an image-analysis system. Three exposures in the same frame and delay of 1ms between every exposure were used. The distance which the black liquor sheet had moved during the delay time was measured by doing twice a FFT (Fast Fourier Transformation) for the picture captured. Velocity was then calculated as: moved distance / time used.
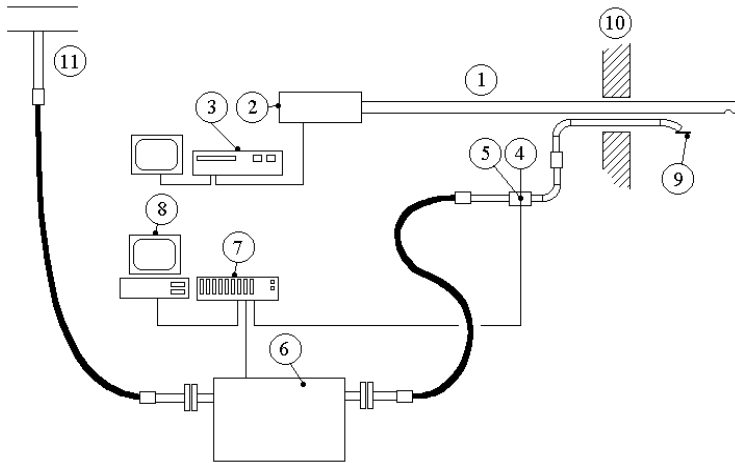
1   Furnace endoscope
2   CCD – Video camera, PCO - Flash Cam
3   SVHS – Video recorder
4   Pressure sensor, Keller PAA-25-5
5   Thermo element, K-type
6   Mass flow meter, Schlumberger 2" + Datamate 2000 –Control unit
7   HP 3852A Data Aquisition / Control Unit
8   Computer
9   Splash plate nozzle
10   Furnace wall
11   Black liquor tube

Figure 1. *Experimental configuration at a operating recovery boiler*

The sketch of the measuring equipment is shown in Figure 1. In addition to these, the process data such as dry solids content, density, temperature, viscosity was stored into the boiler control system data base.

Nozzles normally used in each of the boilers were also used in the experiments. They differed by size and type, and were divided into two categories, B and F, Figure 2.
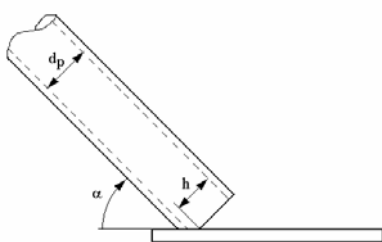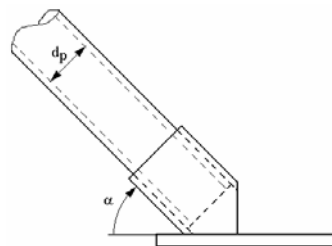
B-type splash plate nozzle   F-type splash plate nozzle

Figure 2. *Splash plate nozzles of types B and F.*

The experiments were done with nozzle type B at all mills except at mill B, where type F was used, Table 1. A part of the round exit area is cut off in the case of type B.

Experiments in test chamber

The test chamber was built in the boiler room of a recovery boiler. The height of the chamber was 6 m and the nozzle was located near the top of the chamber so that the flat spray produced on the splash plate was vertical. Air removal was arranged near the bottom of the chamber to keep the observation windows clean and the replacing air was taken behind the nozzle. The type of the nozzle was B and the diameter of the nozzle tube was 22 mm. The black liquor sheet break-up mechanism was studied through the window in the upper part of the chamber by CCD –video camera. The velocity was measured at a distance of 0.5 m by a double exposure method of the video camera and analysis was carried out later from video tapes by an image-analysis system. (Kankkunen et al., 1997)

Table 1. *Spraying parameters and nozzle types and dimensions in different mills and in the test chamber (TC)*

Mill		A	B	C	D	E	TC
Dry solids content	%	72-76	76	73-76	75-80	73-77	68
Viscosity	Pa s	0.04-0.10	0.12	0.07-0.12	0.11-0.17	0.07-0.08	0.05-0.08
Mass flux	g/mm^{2}s	8-12	4-9	9-13	6-9	5-8	7-19
Firing temperature	°C	120-124	124-126	123-124	128-132	118-122	112-127
Atmospheric boiling point	°C	115-118	117	117-119	117-119	116-119	113
Type of the nozzle		B	F	B	B	B	B
Diameter of the nozzle tube, d_p	mm	27	26/30	27.3	34.5/40	27.3	22
Angle of the splash plate, α	°	25	35	25	25	20	25/35
Free height at the outlet, h	mm	22	26/30	22	29/31	24	15/18

RESULTS AND DISCUSSION

Usually, in recovery boilers the firing temperature of black liquor is a few degrees centigrade above the atmospheric boiling point. It was found that mass flux, temperature and dry solids content are the most important parameters affecting the velocity and velocity distribution of the spray.

Velocity of black liquor spray

The velocity of the black liquor at the sheet centerline (u_s) was measured by the image-analysis system. The error of the velocity measurements was estimated by the total differential. Maximum error varied between 3-10 %. The velocity in the smallest area of the orifice output was calculated from the measured mass flow and from the geometrical dimensions. The most important parameters that affect the velocity of black liquor spray are 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 relative velocity $u^* = u_s/u_p$. Here, 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 of the nozzle with the same mass

flow rate. Dimensionless relative velocity allows for size of orifice and mass flow, but the effect of nozzle type and size cannot be totally eliminated due to geometrical reasons.

Figure 3. presents the relative velocity as a function of the mass flux (i.e. mass flow rate per cross-sectional flow area at the nozzle outlet) and the temperature difference from atmospheric boiling point. A dashed line shows the theoretical maximum of the relative velocity, which corresponds to the choking condition of the flow (Järvinen 1998).
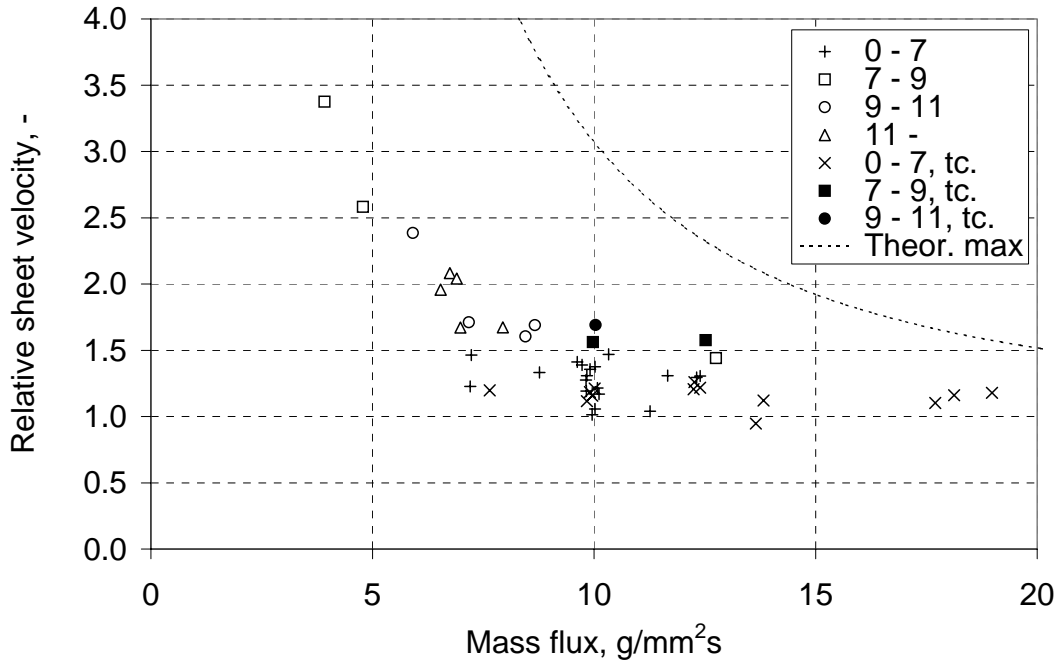

Figure 3. *Relative velocity as a function of mass flux, parameter is the temperature difference to boiling point (°C), tc = test chamber*

On the basis of Figure 3., two different cases can be observed. 1) A case wherein the boiling does not accelerate the flow noticeably can be seen when the temperature difference is below 7 °C. At this range, the relative velocity is fairly constant in both test chamber and in furnace, however, there is some scattering observed. 2) When the difference to boiling point is larger than 7 °C, the flashing phenomena seems to take place and accelerate the flow. The smaller the mass flux is, the greater the relative velocity. A high value of the relative velocity will result in a completely different sheet break-up mechanism.

All the measured values are located far below the theoretical maximum, although they form a similarly shaped curve. In the case of similar mass flux and difference to boiling point, the relative velocity was higher in the test chamber. One possible explanation for this could be that in the test chamber experiments the dry solids content and viscosity of black liquor were lower, increasing the rate of bubble growth. In the furnace conditions, 20-40 cm of the nozzle tube is exposed to the combustion radiation heat transfer. The difference between the furnace and test chamber conditions shows that the effect of radiation heat flux does not have a significant effect on the sheet velocity.

Figure 4. is similar to Figure 3. presenting the relative velocity as a function of the mass flux for different boilers (A, B, C, D and E) and test chamber (TC).
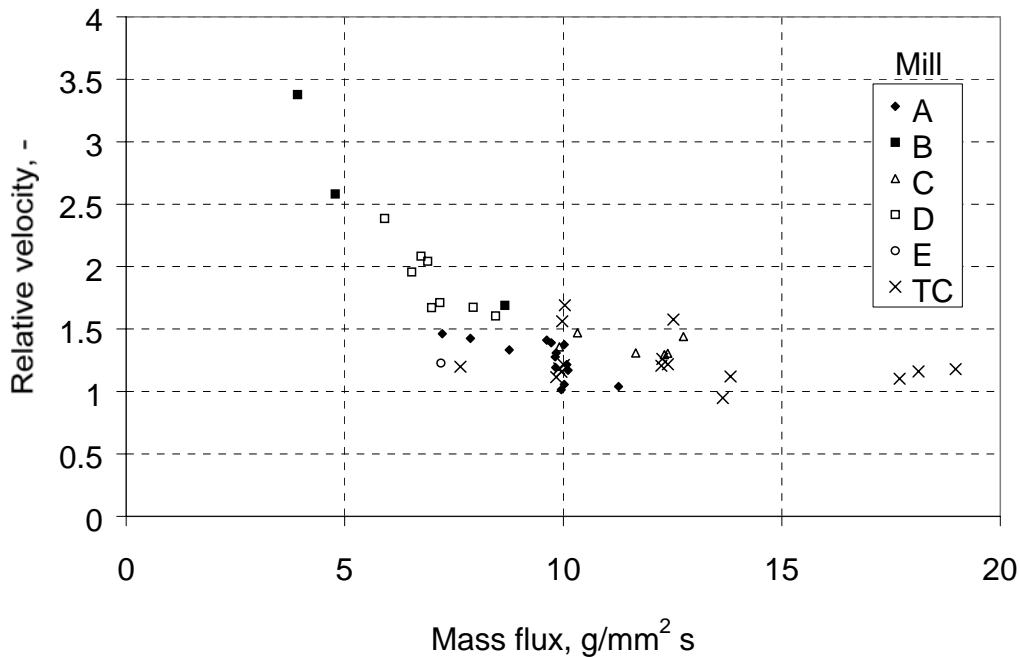

Figure 4. *Relative as a function of the mass flux for test chamber (TC) and for the mills A to E.*

From Figure 4 one can see that the highest relative velocity was measured on mill B where, unlike in all the other mills and test chamber, an F-type nozzle was used. It can be seen that different boilers prefer different firing philosophies. In some cases the normal firing conditions were disturbed by the measurement devices, such as mass flow meter.

Sheet break-up mechanism

In addition to the velocity measurements, the black liquor sheet break-up mechanisms were studied. When the black liquor sheet was formed on the splash plate, two main sheet break-up mechanisms were observed, i.e. perforated-sheet disintegration and wave disintegration. In the case of heavy flashing, no sheet is formed and drop formation mechanism is different. Classification of break-up mechanisms is subjective and often there is not only one mechanism present. In most cases it is still possible to find the dominating one.

Figure 5. presents the non-boiling case of black liquor sheet. Dominating sheet break-up mechanism is the wave disintegration. The picture on the left is from test chamber experiments and white rectangles in it represent the locations of the pictures taken in the furnace. Relative velocity was in both cases as low as 1 when operating temperature was just few degrees centigrade above boiling point.
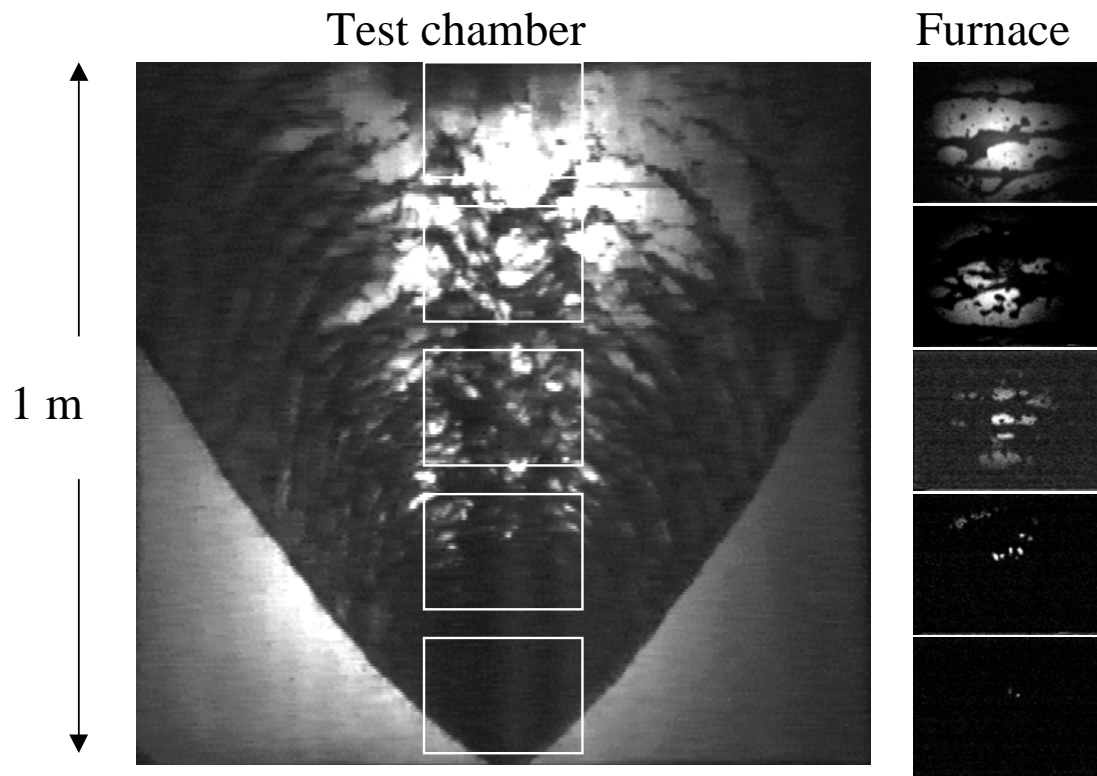
Figure 5. *Black liquor sheet break up mechanism in the test chamber and in a furnace. Mass flux 10 g/mm²s, relative velocity 1, difference to boiling point 0 – 4 °C. In the test chamber the viscosity was 0.076 Pa s and dry solids content 68 %. In the furnace they were 0.050 Pa s and 74%.*

There are similarities observed between furnace and test chamber. At a distance of 30 cm small round holes are formed. In both cases there are waves formed and as they move forwards they break into ligaments. The direction of the ligaments is perpendicular to flow direction. As can clearly be seen, no droplets are formed at a distance of 1 m from the nozzle.

Figure 6. presents the case when relative velocity was approximately 1.5 and the difference to boiling point 6 –7 °C. Empie et al. (1992) and Helpiö and Kankkunen (1995) found that, near this range, flashing could take place and change the break-up mechanism.
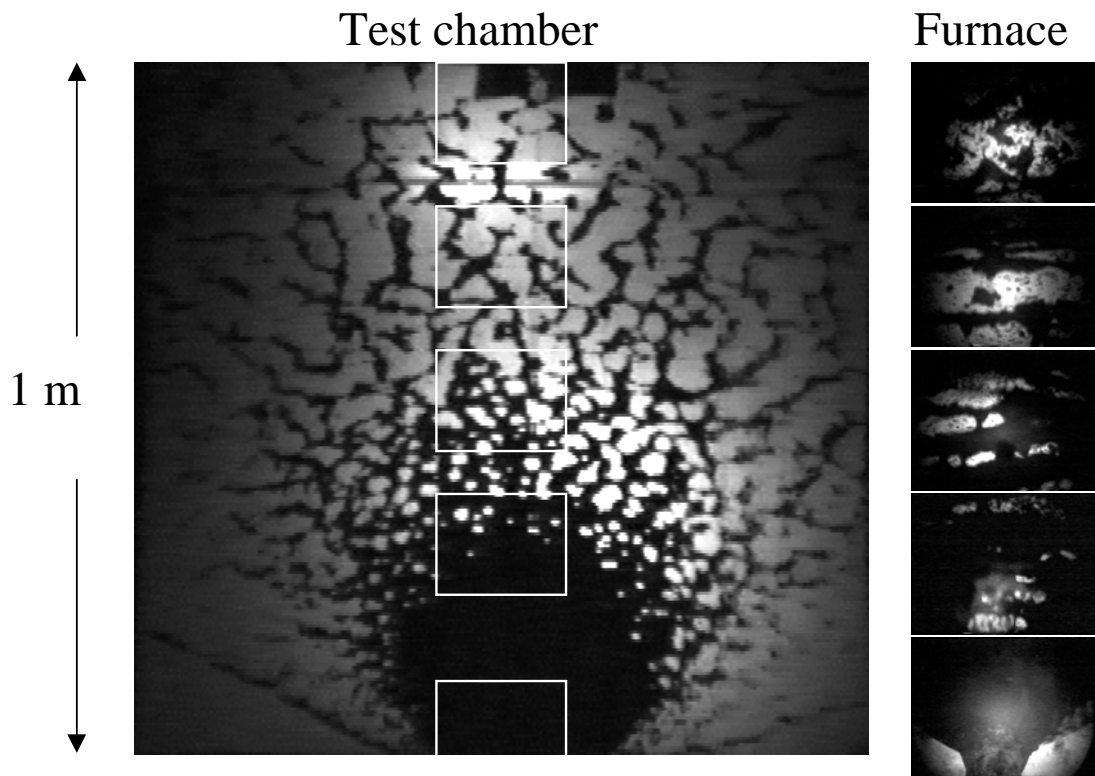
Figure 6. *Black liquor sheet break up mechanism in the test chamber and in a furnace. Mass flux 10 g/mm^{2}s, relative velocity 1.5, difference to boiling point 6 - 7 °C. In the test chamber the viscosity was 0.059 Pa s and dry solids content 68 %. In the furnace they were 0.070 Pa s and 74%.*

When comparing Figures 5 and 6, it can be seen that, in the case of the test chamber the raise of temperature has obviously an effect on the sheet break-up mechanism but in the furnace conditions the difference is not so clear. However, some differences between Figures 5 and 6 can be observed in the furnace conditions. The dominating sheet break-up mechanism (Figure 6) in furnace condition could be classified as wave disintegration but in the test chamber no wave formation was observed. In both cases, Figure 6, round holes are observed at the distance of 30 cm from the nozzle. Small vapor bubbles that break through the sheet surface may form these. The liquor sheet is much shorter and breaks up faster into smaller ligaments, Figure 6. Again, no droplets can be observed.

SUMMARY

It is possible to study black liquor spray properties in operating recovery boilers with furnace endoscope. Within the operation range of an endoscope which is 2 meters from the furnace wall, no droplets are formed. The comparison between results from the test chamber and furnace showed that the spray properties in both environments depend on same main parameters. The final conclusions cannot be done due to different dry solids content, viscosity and orifice sizes.

Different boilers prefer different firing philosophies. A case wherein the boiling does not accelerate the flow and the temperature difference is below 7 °C, the relative velocity is fairly constant in both test chamber and in furnace. When the difference to boiling point is larger than 7 °C, the flashing phenomena seems to take place and accelerates the flow. The relative velocity could be as high as 3.4 when mass flux was low enough (4 g/mm^{2}s) and the temperature difference to boiling point 8 °C. The smaller the mass flux is, the greater the relative velocity.

The dominating sheet break-up mechanism can be found in most cases if firing temperature is not more than 7 – 8 °C above the atmospheric boiling point. If the temperature difference is more than that, flashing inside the nozzle tube composes the dominating spraying parameter and no liquid sheet is formed.

In the near future more measurements will be done. The objective is to decrease the amount of various parameters by using the same liquor and nozzle both in test chamber and in furnace conditions. This will improve the reliability of essential data for the modeling of black liquor spraying and combustion.

ACKNOWLEDGEMENTS

NOMENCLATURE

u^* Relative velocity
u_s Measured velocity at the centerline of the black liquor sheet
u_p Velocity of the non-flashing case at the smallest cross-sectional area of the nozzle
h Free height of the nozzle outlet
d_p Nozzle tube diameter
α splash plate angle

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