SPRAYING CHARACTERISTICS OF MIXED BLACK LIQUOR – TWO DIFFERENT SPRAYING CASES

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ABSTRACT

Black liquor spray droplets - especially their initial stages - were studied inside a recovery boiler burning high-solids liquor using a new optical probe developed at Aalto University. Arrangement allowed measurements at different locations as far as 2.3 meters from the nozzle. Two different cases was studied, one similar to the boilers normal spraying practice and another case, where black liquor temperature was decreased before spraying.

In both cases droplet formation process was found to be in furnace environment different compared to earlier expectations. One essential finding was the droplet explosion caused by flashing Hollow particles, which have very thin surface, could be detected at the distance of 2.3 meters from the nozzle. These particles may break very soon to smaller particles. The timescale of the formation of hollow particles is less than 0.2 seconds after they have left the nozzle.

The spray velocity of test cases was measured to be 15.4 and 17.5 m/s. Results are presented on flashing map to be able to compare spraying practice of test cases to earlier measurements at other boilers. The droplet size was approximated for both test cases.

The spray formation in both test cases was studied by a nozzle model, which took into account flash formation inside the nozzle. Predicted spray velocities were comparable to measured values.
Keywords: Recovery boiler, black liquor, spraying, combustion

1. INTRODUCTION

The combustion process of black liquor droplets in the furnace is understood only partially. A lot of important information has been achieved by single particle studies [1,2] and detailed single particle combustion simulation [3]. Some of the most essential information can be obtained only by studying spray and droplet behaviour in the furnace. This study aims to increase understanding of spray and droplet properties in a real furnace.

Experimental information on droplet shape, size and size distribution in varying locations of the spray inform us about essential processes in the furnace. How droplets are formed after they leave the nozzle. How fast droplets swell and decelerate. What is the direction and velocity of droplets in varying locations of the spray. What is the speed at which particles dry, ignite or start combustion.

Single droplet studies are necessary to achieve good understanding of black liquor combustion phenomena. In a laboratory it is possible to change parameters affecting combustion one by one. Unfortunately most laboratory measurements cannot be carried out in an operating furnace.

Single particle studies in well controlled conditions have been carried out in laboratory furnaces. Frederick et al. [1] measured swelling factors of black liquor droplets hanging on a hook. It was found that the combustion process could be divided into the following four stages: (1) drying, (2) pyrolysis and combustion of the pyrolysis gases, (3) char burning, and (4) reactions of the inorganic residue. The time of each stage was determined. Swelling was found to be multifold and dependant on the liquor type. Drying time in air was measured to be between 1 and 2 seconds/mg H₂O, when the furnace temperature was 800 ºC. Single particle laboratory measurements have been carried out by Forssen et. al. in Åbo Akademi University [2] and by Ip et al. in Brigham Young University [4]. This kind of measurement are of extreme importance to be able to understand furnace operation and droplet behaviour in the furnace. The laboratory data is necessary for CFD calculations, which are used for boiler design and problem solving.

Black liquor sprays have previously been studied in spray test chambers and valuable information on spray properties for high solids content has been obtained by Kankkunen et al. [5]. Depending on the black liquor properties, spraying practice and nozzle geometry mass median diameter varied between 4.5 and 14 mm.

During last years a special furnace endoscope have enabled spray studies even in the furnace [6,7,8]. Black liquor sheet break-up mechanism and sheet length as well as spray velocity have been studied. Based partly on this data modelling of nozzles have been carried out by Järvinen et al. [9,10].

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The present study concentrates to the spray properties measured in the furnace both near the nozzle and at the distance of 2.3 meters from the nozzle. Special interest is on the fast explosion of droplets caused by evaporating steam.

2. Experimental

2.1 Research boiler and operating conditions

The measurements were carried out in a recovery boiler with a design capacity of 4450 tds/d, fired with high dry solids black liquor. The black liquor properties can be seen in Table 1. The temperature of the furnace was approximately 1000 ºC.

Table 1. Black liquor properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquor type</td>
<td>Mixed, softwood 50%/Hardwood 50%</td>
</tr>
<tr>
<td>Dry solids content, %</td>
<td>80.7-81.8</td>
</tr>
<tr>
<td>Density, kg/m3</td>
<td>1491-1493</td>
</tr>
<tr>
<td>Boiling point rise, ºC</td>
<td>17-21.5</td>
</tr>
<tr>
<td>Spraying temperature</td>
<td>138.4-142</td>
</tr>
<tr>
<td>Excess temp. (ΔTe), ºC</td>
<td>17.1-20.4</td>
</tr>
<tr>
<td>Volume flow rate, l/s</td>
<td>5.8</td>
</tr>
</tbody>
</table>

Nozzles used in the tests were similar to original nozzles used in the boiler. Nozzle bending at the distance of 30 cm from splashplate was changed slightly to enable measurements with endoscopes. The inside diameter of nozzles were 48.3 mm and the opening was restricted by splashplate as can be seen in Figure 1.

Figure 1. A test nozzle.

2.2 Measurement equipment

The properties of black liquor spray near the nozzle were measured by a furnace endoscope. It enables measurement of spray velocity in the spray center line e.g. at distances of 50 cm and 80 cm. An other endoscope was used to measure spray velocity at a second gun hole at the distance of 2.3 meters from the nozzle. In this case the normal
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nozzle of the boiler was replaced with a nozzle spraying along the wall of the furnace. This enabled studying spray properties at the distance of 2.3 meters from the nozzle.

2.3 Experimental procedure
The mass flow rate was defined by the normal spraying practice of the boiler. Two cases were tested, base case and cold case. The base case was similar to the normal spraying practice. The cold was similar to normal spraying practice, but the temperature was decreased by water spooling of the flexible metal hose. The temperature was decreased by 2-3 °C compared to normal. The conditions near the nozzle were as they are in a real furnace. No remarkable problems caused by other nozzles were expected because nearest nozzle gun ports were empty.

2.4 Nozzle model
The spray nozzle measurements carried out here were used to validate a computational spray nozzle model [12]. Inputs to model are fluid properties, nozzle geometry and nozzle size. The nozzle inside diameter was 48.3 mm. The geometry of the nozzle was a typical splashplate nozzle with splashplate restricted opening as presented in Figure 1.

3. RESULTS
The velocity was measured in three locations and is presented in Figure 2. The absolute values of velocity near the nozzle were 15.5 m/s for cold case and 17.4 m/s for base case. The velocity of the spray decreased fast. The velocity at the distance of 2.3 meters from the of small particles was only 5.1 m/s for cold case and 7.6 m/s for base case. The velocity of large particles decreased more moderately. The velocity at the distance of 2.3 meters from the nozzle was 11.4 m/s for the cold case and 15.8 m/s for the base case. With these velocities a droplet achieves the location of 2.3 meters at about 0.2 seconds.

![Figure 2. Spray velocity at the spray centre line.](image)

The new nozzle model predicted the velocity of the spray rather well after small adjusting. For the cold case model predicted velocity of 13.9 m/s, when the measured velocity was 15.5 m/s. For the base case the model predicted velocity of 17.0 m/s, when the measured velocity was 17.4 m/s.
Examples of spray at the distance of 2.3 meter from the nozzle are presented in Figures 4 to 6, which present images of different locations of the spray. The width of an image is about 77 mm. There exist four different types of particles; lumpy, thin hollow core, small consistent and burning particles. Many particles have properties of two or more of these types. Rough estimate of number of different particles types and their fractions are presented in Tables 2 and 3. Both cases are rather similar. The fraction of large seems to higher for the cold case. The density of small and large particles would be of special importance, but is not available.

Figure 4. Base case at the distance of 2.3 m, upper part of the spray.

Figure 5. Base case at the distance of 2.3 m, centre line of the spray.
Figure 6. Base case at the distance of 2.3 m, bottom part of the spray.

Table 2: Base case

<table>
<thead>
<tr>
<th></th>
<th>Black liquor fraction at image, %</th>
<th>Number of sparks/image</th>
<th>Length of large particles</th>
<th>Typical shapes</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 cm</td>
<td>75</td>
<td>0</td>
<td>90vol%&gt;50 mm</td>
<td>Breaking bulk</td>
</tr>
<tr>
<td>100 cm</td>
<td>30</td>
<td>0</td>
<td>10vol%&gt;50 mm</td>
<td>Rounding shapes</td>
</tr>
<tr>
<td>230 cm</td>
<td>15</td>
<td>1</td>
<td>1 vol%&gt;50 mm</td>
<td>Small round and large lumpy/hollow</td>
</tr>
</tbody>
</table>

Table 3: Cold case

<table>
<thead>
<tr>
<th></th>
<th>Black liquor fraction at image, %</th>
<th>Number of sparks/image</th>
<th>Length of large particles</th>
<th>Typical shapes</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 cm</td>
<td>80</td>
<td>0</td>
<td>90vol%&gt;50 mm</td>
<td>Breaking bulk</td>
</tr>
<tr>
<td>100 cm</td>
<td>40</td>
<td>0.5</td>
<td>10vol%&gt;50 mm</td>
<td>Rounding shapes</td>
</tr>
<tr>
<td>230 cm</td>
<td>15</td>
<td>4</td>
<td>5 vol%&gt;50 mm</td>
<td>Small round and large lumpy/hollow</td>
</tr>
</tbody>
</table>

Figure 7 shows spray break-up at different distances from the splashplate. At the distance of 50 cm from the nozzle not any sheet is observed. Ligaments are breaking and perhaps swelling. At the distance of 100 cm from the nozzle the swelling of ligaments and droplets is more obvious. The image width is about 46 to 48 mm. At the distance of 230 cm from the nozzle the swelling is obvious, but in addition there exists high number of small rather spherical particles. The image width is here 70 to 77 mm.
Figure 7. Spray at varying distances from the nozzle.

Flashing maps are used to estimate spray velocity if measurement data is not available. Maps can be used to compare of different nozzle sizes and mass fluxes and excess
temperatures to find its location in the flashing map. In the present cases the mass flux was rather small, 6 g/mm² s, compared to our earlier test cases. At the same time the excess temperature was rather high, 22.2°C and 18.8°C. Therefore the dimensionless velocity (measured spray velocity divided by black liquor velocity in the nozzle outlet assuming non-flashing flow) was higher than normally, 3.2 for cold case and 3.6 for base case. The flashing map with dimensionless velocity is presented in Figure 3. The flashing was also unevenly heavy compared to our earlier tests.

![Flashing map](image)

**Figure 3. Test points located to the flashing map.**

### 4. CONCLUSIONS

The velocity of black liquor is increased inside the nozzle by flashing. Black liquor droplets expand very fast after the nozzle. This is caused by the steam, which is flashing inside the nozzle and especially after the nozzle.

At the distance of 0.5 and 1 meter from the nozzle lumpy ligaments and particles can be detected. At the distance of 2.3 meter from the nozzle consists the spray of large lumpy or hollow particles and smaller rather spherical particles at the distance.

The velocity of the spray near the nozzle is very high in both cases. The velocity decreases very effectively during first 2.3 meters.

The new nozzle model predicts velocity rather well. It could be used to predict spray velocity of a CFD model, if measurement data is not available.

These results show the importance of studying the spray behaviour inside a real furnace. The fast swelling observed for droplets and the fast decrease of the velocity could not be predicted by other methods. Observed phenomena should be included to CFD models to be able to predict furnace operation reliably.

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5. REFERENCES


6. ACKNOWLEDGEMENTS

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