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Characterizing Smelt Shattering Performance in a Recovery Boiler

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Abstract

Kraft recovery boiler smelt is shattered into droplets by a high pressure steam jet, to improve smelt dissolution, and to minimize the violence of smelt-water interaction in the dissolving tank. A scaled-down experimental apparatus is being used to examine smelt shattering, with water-glycerine solutions and air used in place of smelt and steam. A high-speed camera and an automated image processing methodology are being used to quantify liquid shattering (in terms of droplet size and number distributions). This paper presents preliminary results of shattering effectiveness as a function of air and water flow rates, and different air nozzle geometries and positions.

I. INTRODUCTION

The kraft pulping process involves the use of a chemical solution called “white liquor” to dissolve wood chips into fiber for making paper. The spent chemicals plus waste organic matter and water, referred to as “black liquor”, then enter a chemical recovery cycle that includes combustion in a recovery boiler. In the boiler, the organic matter burns to produce energy for steam and power generation, and converts the spent chemicals into a molten salt mixture referred to as “smelt”. **Figure 1** shows that smelt forms on the char bed at the bottom of the boiler, flows out of the boiler down multiple spouts, and falls into a dissolving tank where it mixes with an aqueous solution to form “green liquor”, which is later cauticized with lime to make fresh white liquor.

The smelt flows out of the boiler at about 800^{o}C, and when it falls into the dissolving tank leads to the rapid vaporization of water. To reduce the intensity and violence of the smelt-water interaction, boiler operators use high pressure steam jets to shatter the molten smelt stream into a spray of droplets to process large amount of molten smelt safely and effectively, as well as to produce consistent green liquor. The dissolving tank operation nevertheless is loud and violent. When smelt shattering is ineffective: when the steam flow rate is reduced, or the smelt flow rate increases, or the viscosity of the smelt increases, dissolving tank operation becomes more violent. In severe cases, a so-called “dissolving tank explosion” can occur, causing substantial equipment damage, production loss associated with an unscheduled boiler shutdown, and even personnel injury.

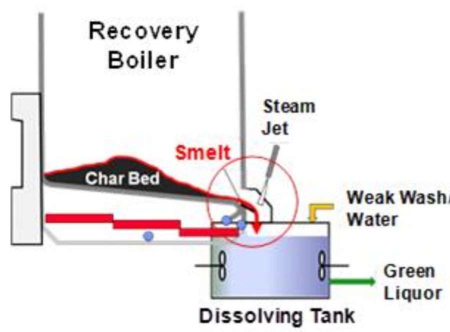

Figure 1. A smelt stream from the bottom of the recovery boiler is shattered by a steam jet before falling into the dissolving tank.

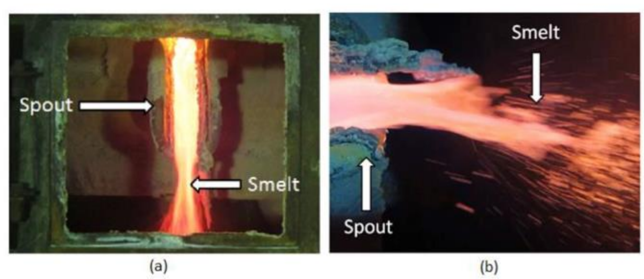

Figure 2. A smelt spout viewed (a) from the front, (b) from above. Note that these pictures do not illustrate shattering, as the shatter jets are located somewhat below the spout lip.

Over the past 30 years, about one explosion incident has been reported in North America each year [1], although other less catastrophic incidents likely go unreported. Despite the importance of safety, the pulp industry has not focused much attention on smelt shattering, which is not well understood. This study of smelt shattering will help define best practices for this industry.

The nature of the gas/liquid interaction in the smelt shattering process is known as cross-flow atomization [2].

Taranenko [3] constructed a lab-scale apparatus to study cross-flow atomization using air/water-glycerin mixtures and a simple round nozzle for the air jet. Taranenko showed that increasing air velocity and nozzle proximity decreases average droplet size, and increasing water flow rate increases average droplet size. Viscosity does not have a significant effect on the droplet size, unless a weak jet is used to shatter a highly viscous fluid.

Although smelt shattering has not been widely studied, similar processes known as melt shattering are used in the metal powder industry, and have been studied in detail [4-9]. Yule [4] suggests various droplet data collection techniques, and summarizes the advantages of cross-flow atomization. Liquid-gas multiphase interaction has also been widely studied in the form of open/closed air-blast atomization where a slow liquid is atomized using a high velocity gas stream, often co-axially [10-11].

In what follows we describe an experimental apparatus and methodology applied to the study of smelt shattering, and present some preliminary results.

II. APPARATUS AND METHODOLOGY

A. Overview

Figure 2 shows the lab-scale apparatus originally constructed by Taranenko [3] to study smelt shattering using water and air in place of smelt and steam. Experimental parameters include nozzle design, air nozzle orientation and impingement distance (the distance between the gas nozzle exit and the point of impingement on the water stream), and air flow rate, listed in **Table 1**. A high speed camera is used to image the spray, and image analysis software is used to capture, process and measure droplet size information.

Figure 4 shows four nozzle designs that are representative of shatter jet nozzles used by industry. The experimental parameters have been scaled from actual dimensions.

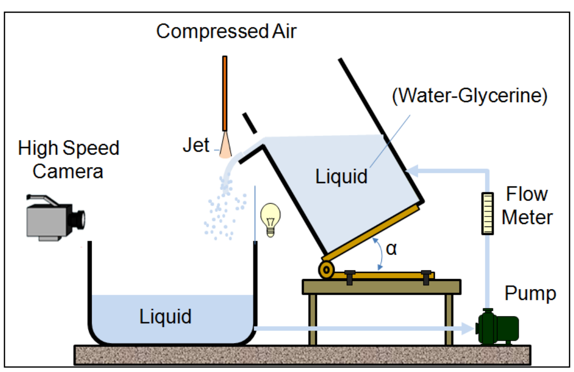

Figure 3. Lab scale experimental shattering apparatus.

Table 1: Experimental Parameters

Nozzle Profiles	Angle of Nozzle (from horizontal)	Proximity	Air flow rate (SCFM)*
Hollow Cone	90°	7 in	10
Full Cone	75°	9 in	15
Flat	60°	5 in	
Wide-Airflow			

Figure 4. Various nozzle geometries. Top left: hollow cone, top right: full cone, bottom left: flat, bottom right: wide-airflow.

B. Methodology

As per **Figure 3**, water is pumped from a base tank to an inclined tank using a 3600 RPM BurCam™ rotary pump, and then flows down a 1.5 in diameter acrylic spout back into the base tank. A liquid flow meter is used to set the flow rate. An air nozzle is positioned at the end of the spout to shatter the exiting water stream. The air nozzle is connected to a constant 80 psig air supply line controlled by two ball valves. A pressure gauge and a gas flow meter are used to set the air flow rate. An adjustable ball fitting is used to control the angle of the nozzle.

A Mega-Speed greyscale high speed camera captures 512 x 512 pixel images of droplets over a 12 x 14 inch matrix two feet below the spout. The matrix is composed of 42 (6x7) evenly spaced locations. The camera is set to 50 frames per second with 50 μs exposure time, 200 mm focal length and an F-stop of 3.5. A light source with a diffuser is placed behind the spray to provide sufficient lighting for these low exposure times. The water flow rate is 0.2 L/s for all the experiments. A grid placed above the apparatus is used to identify the coordinates for the 42 imaging locations.

C. Image Analysis Technique

An image analysis macro was developed using ImageJ™ software to convert greyscale images to binary images and filter out-of-focus droplets that cannot be accurately measured (**Figure 4**). Droplets cut off at the image border are also removed. Images are dimensionally calibrated before measuring each droplet projected area, which best represents the true cross-sectional area of a droplet [12].

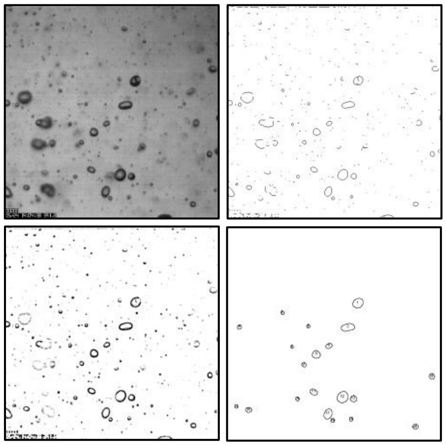

Figure 5: Image processing and analysis using ImageJ™.

Due to the low resolution of the high speed camera, it is difficult to determine if extremely small droplets are in focus since they only cover a few pixels in area. These droplets are discounted to prevent skewing of data, and only droplets larger than 0.16 mm in diameter are counted and analyzed. The average droplet size and count is calculated from 500 images at each of the 42 locations. Tecplot™ is used to plot the average droplet size and droplet count distribution for each test configuration.

III. Results and Discussion

Droplet size distributions are shown in **Figure 6** as top view 2D contour plots of the 12 x 14 in matrix that was imaged. The values shown are average droplet diameter (mm) based on the projected area. The black circle represents the air nozzle location. The top of the contour graph is facing the spout direction. These experiments were conducted with the air nozzle at a 90^o (vertical) orientation, and with a spout angle α (**Figure 3**) of 15°. This set of experiments examines the effects of varying the nozzle profile, impingement distance and flow rate on the shattering characteristics, as per **Table 1**.

The results clearly show that different nozzles produce different droplet size and count distributions. At 10 SCFM, the wide-airflow and flat nozzles produce generally larger droplets across a larger area than the hollow cone and full cone nozzles. When the air jet impinges the water stream, the droplet trajectory is determined by the transfer of kinetic energy from air to water.

The air jet atomizes the water by continually shearing layers of the water stream. The top layer of the stream is atomized most effectively, resulting in smaller droplets with high kinetic energy scattered across a wide area. The bottom layer receives the least kinetic energy from the air jet, resulting in larger droplet formation. As result, the larger droplets retain more of the initial water stream momentum. The wide-airflow and flat nozzle are less effective at shattering, and so the center of the "red zone" (largest droplets) are further from the nozzle. This is presumably due to the wider air distribution these nozzles produce, which reduces the kinetic energy of air that actually impacts the water stream. The hollow cone and full cone nozzles produce smaller droplets in general and the center of the red zone is closer to the nozzle.

Increasing the impingement distance significantly increases the droplet size, particularly below the nozzle. Increasing the air flow rate by 50% to 15 SCFM results in a significant droplet size reduction. For both the wide-angle and flat nozzles, the center of the red zone shifts towards the nozzle, indicating higher kinetic energy transfer from air to water. (We were unable to push 15 SCFM through the full cone nozzle.) Finally, the hollow cone and full cone nozzles produce very similar droplet size distributions, as do the wide-airflow and flat nozzles.

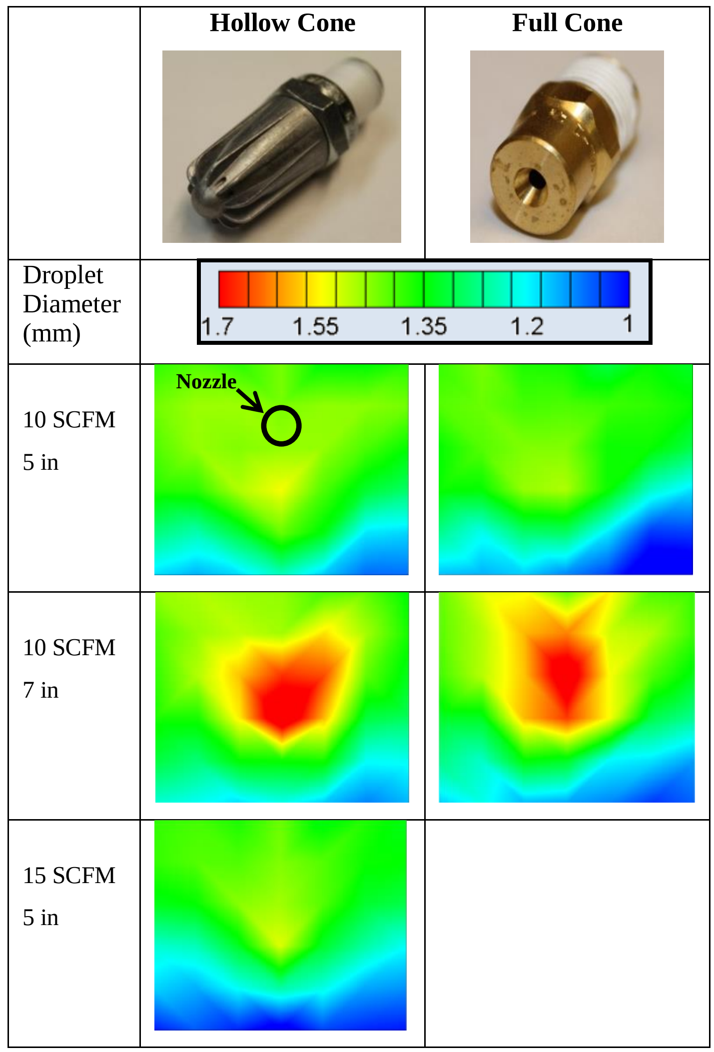

Figure 6(a). Droplet size distributions under various operating conditions. The left column indicates air flow rate and impingement distance. 15 SCFM was not achievable for the full cone nozzle due to excessive pressure.

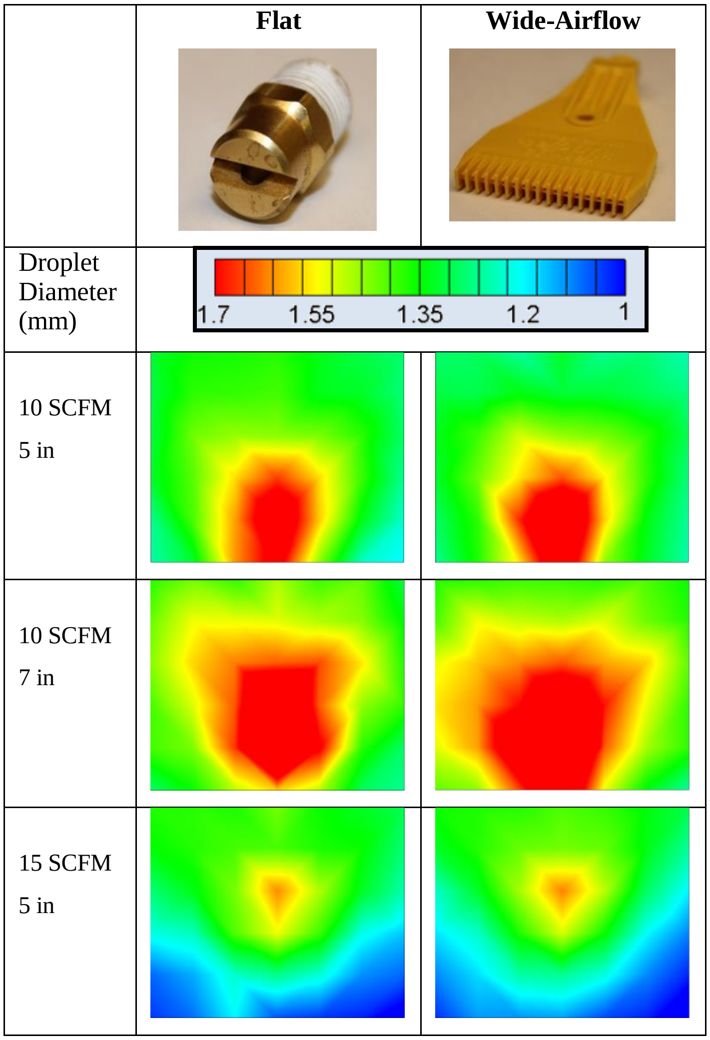

Figure 6(b). Droplet size distributions under various operating conditions. The left column indicates air flow rate and impingement distance.

Figure 7 shows the effect of impingement distance, and **Figure 8** shows the effect of gas flow rate on the droplet size along the centreline (axis of symmetry) of the spray. The shatter jet is located 4 in from the nozzle. It is apparent that increasing the gas flow rate, and decreasing the impingement distance, both contribute to an overall decrease in droplet size. However, the decrease in droplet size varies at different locations from the spout. In some cases, the droplet size increases due to the shift in net momentum, as seen for the wide-airflow nozzle at 5 in from the spout (**Figure 8)**.

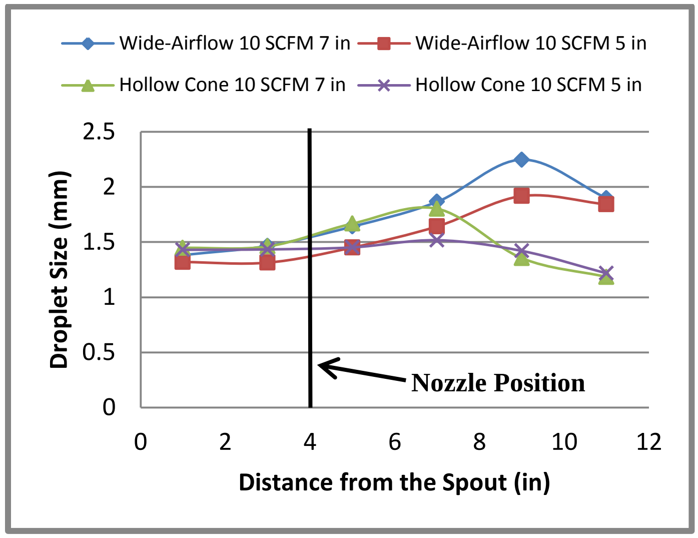

Figure 7. Effect of impingement distance on droplet size distribution. Graph shows centerline average droplet size with respect to the spout.

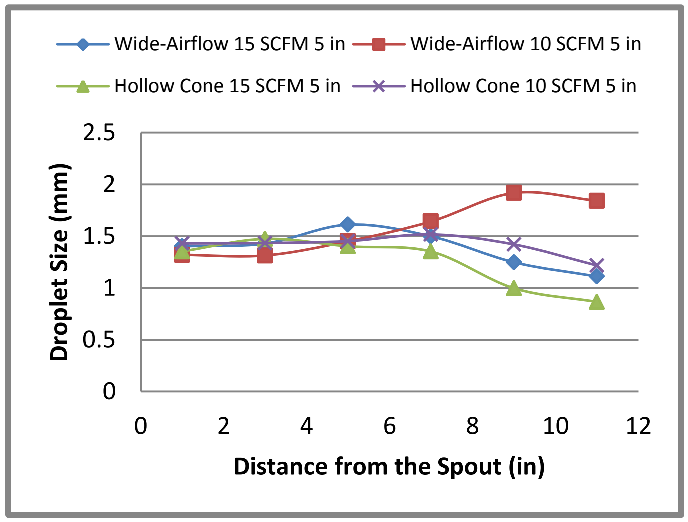

Figure 8. Effect of gas flow rate on droplet size distribution. Graph shows centerline average droplet size with respect to the spout.

IV. FUTURE WORK

Additional experiments will be conducted to look at droplet size distributions on other planes beneath the spout, to predict the spray growth pattern. We plan to correlate droplet size distributions to appropriate non-dimensional parameters, in order to extrapolate experimental results to predict droplet size distributions at mill scale. Questions for future research include: How does shatter jet nozzle placement relative to the spout affect shattering? And how well can we expect to shatter so-called “jelly roll smelt”, that is very viscous?

References

[1] Lien, S. and DeMartini, N. “Dissolving Tank Explosions: A Review of Incidents between 1973 and 2008”. Unpublished report to BLRBAC and AF&PA, sponsored by the American Forest & Paper Association, New York (2008).

[2] Mashayek, A. and Ashgriz, N. “Atomization of a Liquid Jet in a Crossflow” N. Ashgriz (ed.), Handbook of Atomization and Sprays. (Chapter 29). Springer Science+Business Media, LLC 2011.

[3] Taranenko, A. “Shattering Kraft Recovery Boiler Smelt by a Steam Jet” Masters Thesis. University of Toronto, 2013.

[4] Yule, A. J. et al. “Atomization of Melts for powder Production and Spray Deposition” Oxford University Press Inc., New York, 1994.

[5] Chen, Y. M. et al. “Modeling of Atomization Rate During Gas Atomization” Acta mater. Vol. 46, No 3, pp. 1011-1023, 1998.

[6] Mullis, A.M. et al. “Log-Normal Melt Pulsation in Close-Coupled Gas Atomization” Metallurgical and Materials Transactions B, Volume 44B, August 2013.

[7] Anderson, I. E. et al. “Progress toward Gas Atomization Processing with Increased Uniformity and Control” Materials Science and Engineering A326 101-109, 2002.

[8] Rieken, J.R. “Reactive Gas Atomization Processing for Fe-based ODS alloys” Hournal of Nuclear Materials 428, 65-75, 2012.

[9] Dunkley J.J. “Atomization” ASM Handbook, Volume 7: Powder Metal Technologies and Applcations, 35-52, 1998.

[10] Lasheras J. C. and Hopfinger E. J. “Liquid Jet Instability and Atomization in a Coaxial Gas Stream” Annu. Rev. Fluid Mech. 32: 275-308, 2000.

[11] Lefebvre, A. H. “Airblast Atomization” Prog. Energy Combust. Sci., Vol. 6, pp 233-261. Pergamon Press Ltf., 1980.

[12] Allen, T. “Particle Size Measurement” Chapman and Hall. (1990)