

A laboratory study of recovery boiler smelt shattering

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ABSTRACT: A scaled-down experimental apparatus was built to examine smelt shattering during typical recovery boiler operations. Water-glycerine solutions and air were used in place of smelt and steam. A high-speed camera and image processing software were used to record and quantify liquid shattering in terms of droplet number and size distributions, as a function of air velocity, air nozzle position, liquid flow rate, and liquid viscosity. The results showed that increasing shatter jet velocity reduced average droplet size, increasing the liquid flow rate increased droplet size, and placing the shatter jet nozzle closer to the liquid stream decreased droplet size. These results were all as expected. The effect of liquid viscosity (1-50 cP) depended on the shatter jet velocity. At high air velocities, even the viscous liquid was well shattered, but at lower velocities, the effect of viscosity on shattering was significant.

Application: Understanding how a molten smelt stream is shattered by a steam jet will help operators and process engineers to optimize their recovery boiler smelt shattering efficiency and to improve dissolving tank safety.

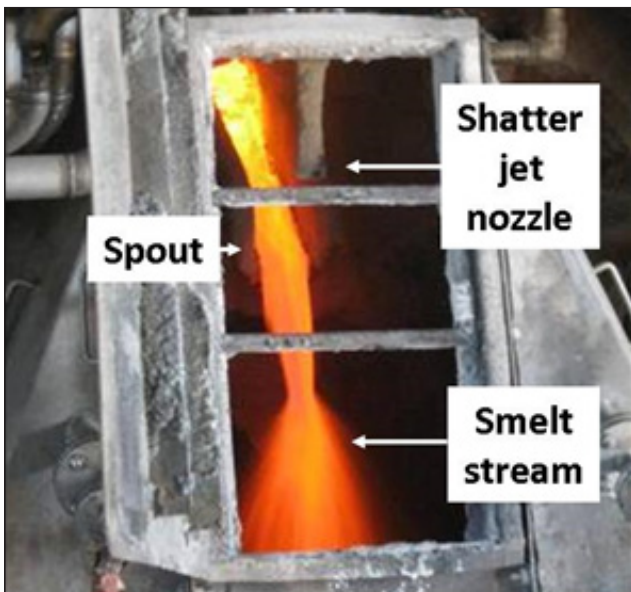
In kraft recovery boiler operations, molten smelt (mainly consisting of sodium carbonate and sodium sulfide, and small amounts of sodium sulfate, sodium chloride, and potassium salts) flows out of the boiler at 800°C-850°C down a number of spouts, at a flow rate on the order of 1 L/s per spout, before falling into the dissolving tank below (Fig. 1). In the tank, the hot smelt mixes with weak wash to produce green liquor that is subsequently causticized with lime to produce white liquor for reuse in the pulping process. The interaction between the molten smelt and water in the confined space of the dissolving tank is violent; the noise and

vibration of the tank often can be heard and felt far from the tank itself. To control the intensity of the smelt-water interaction, mills use steam “shatter jets” to break up the smelt stream into a spray of droplets just below the ends of the spouts.

Intense smelt-water interaction may be necessary to effectively dissolve smelt in the dissolving tank. Smelt shattering is important to distribute smelt evenly throughout the tank, rather than have large amounts of smelt simply pour into the tank from the spout. Inadequate smelt shattering increases the violence of dissolving tank smelt-water interaction. Experienced boiler operators claim to be able to assess dissolving tank operation by listening to the tank. At the extreme, inadequate smelt shattering can lead to a dissolving tank explosion that can cause equipment damage, an unscheduled shutdown, and even personnel injury [1,2]. Despite these concerns, smelt shattering practices vary widely from mill to mill, and the shattering behavior has not been studied before. The safety implications and lack of standards for smelt shattering motivated the study presented here.

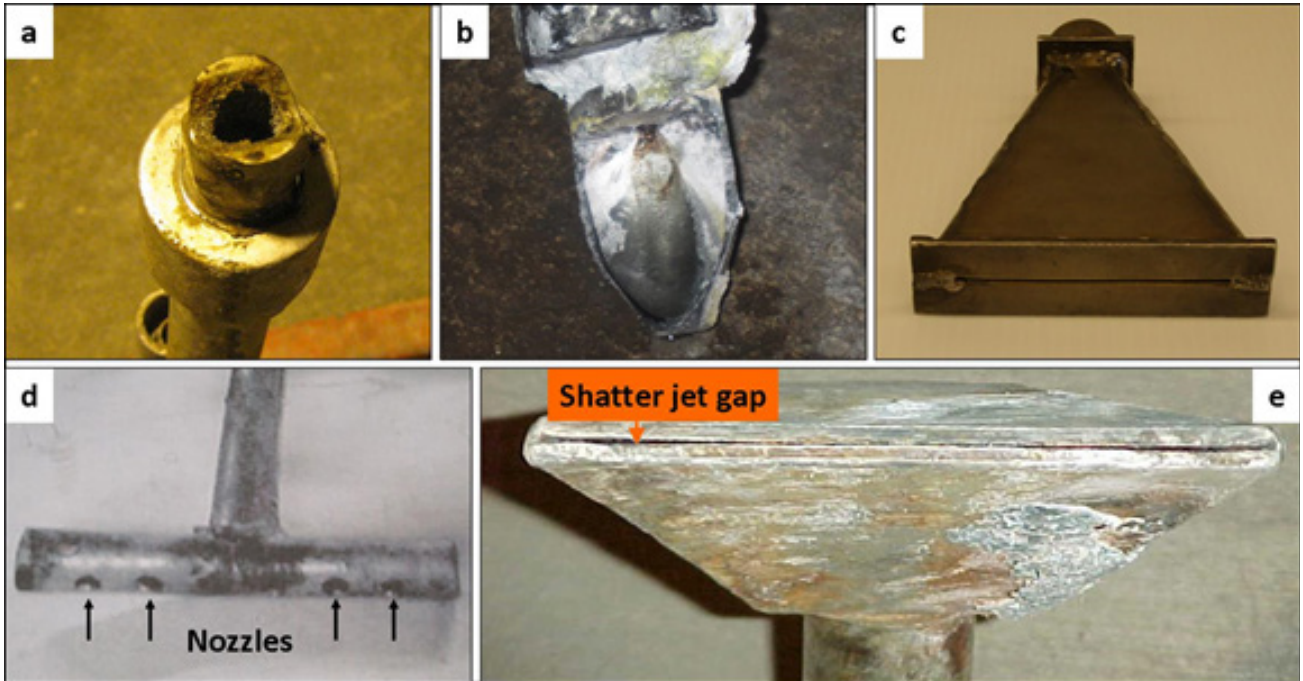
CURRENT PRACTICE

An informal survey of a number of mills led us to conclude that smelt shattering practices vary widely. Shatter jet nozzles come in a variety of designs. Figure 2 shows examples of a few designs that we encountered during mill visits. Some mills simply modify the end of a steam tube to create a single nozzle (Fig. 2a), or attach a T to create multiple nozzles (Fig. 2d). Shatter jet nozzles can be round (Figs 2a, 2b, and 2d) or slit-shaped (Figs. 2c and 2e). Frozen smelt can build up on shatter jet nozzles, which has led some mills to install the nozzle within a guard (Fig. 2b) or to use hot water or weak wash to clean the shatter jet nozzle (Fig. 2a).



1. Typical smelt shattering practice.

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2. Examples of shatter jet nozzle designs.

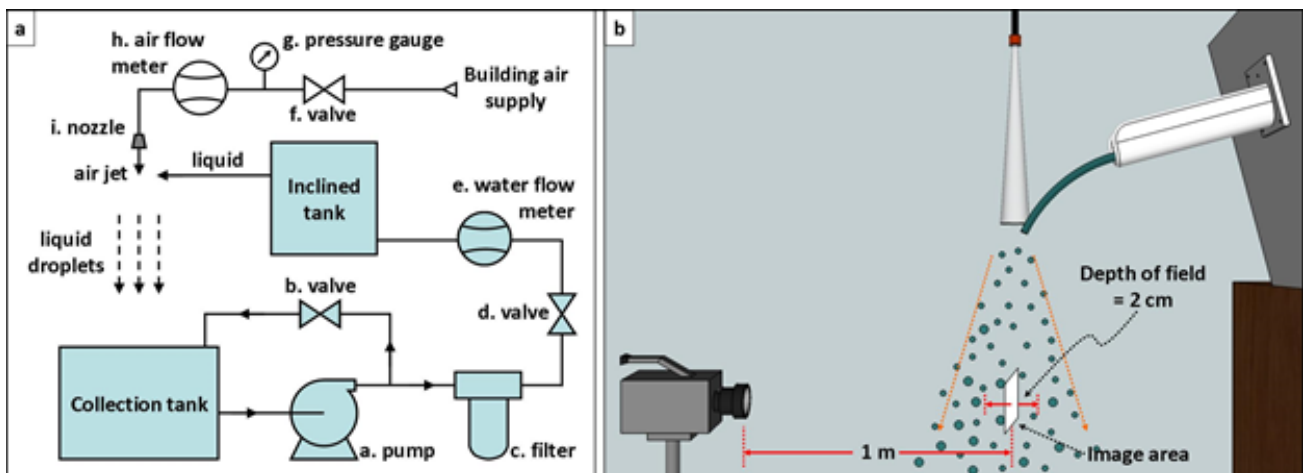
Steam used for smelt shattering varies from mill to mill, but typically measure 3-15 bar (45-220 psi) and 150°C-250°C. Steam consumption also varies widely, from 180 kg/h to 2250 kg/hour per nozzle, or an order of magnitude range.

Shatter jet nozzle placement and orientation and spout inclination can also affect shattering. Shatter jets are usually aimed at the smelt flow just below the end of the spout, and the nozzles are usually installed above the spout and point downwards, or further from the boiler wall and point back towards the smelt flow. The choice affects how well smelt can be shattered when the flow rate is unusually high or low, which along with spout inclination, affects the trajectory of the smelt. When the smelt flow rate is low, and especially if the spout inclination is shallow, smelt will simply drip off the tip of the spout. When the smelt flow rate is high, and espe-

cially if the spout inclination is steep, smelt will shoot off the spout. In either case, shatter jet placement will affect shattering effectiveness. To accommodate such situations, some mills install two jets per spout and turn on both during periods of high smelt flow. Some mills also install adjustable shatter jets that an operator can point toward abnormal smelt flows.

EXPERIMENTAL SETUP AND METHODOLOGY

A laboratory-scale experimental setup (Fig. 3a) was constructed to study smelt shattering. A water-glycerine solution (liquid) was used in place of molten smelt, and compressed air in place of steam. Liquid shattering was characterized as a function of air velocity, nozzle position, liquid flow rate, and liquid viscosity by imaging the spray with a high speed camera (Fig. 3b), and then processing those images to extract



3. Shattering apparatus: a) schematic and b) illustration.

droplet number and size distributions. Although the apparatus was built at a reduced scale, the various parameters were chosen to reflect typical values of these parameters in recovery boilers.

As shown in Fig. 3a, the apparatus was operated as follows. A large collection tank stored the water-glycerine solution. The solution was pumped through a flow meter to an inclined tank, with a spout mounted near the top (Fig. 3b). After that tank filled, the liquid began to flow down the spout (the inclination was maintained at 15° for all of the experiments described here) at a known flow rate, and fell back into the collection tank.

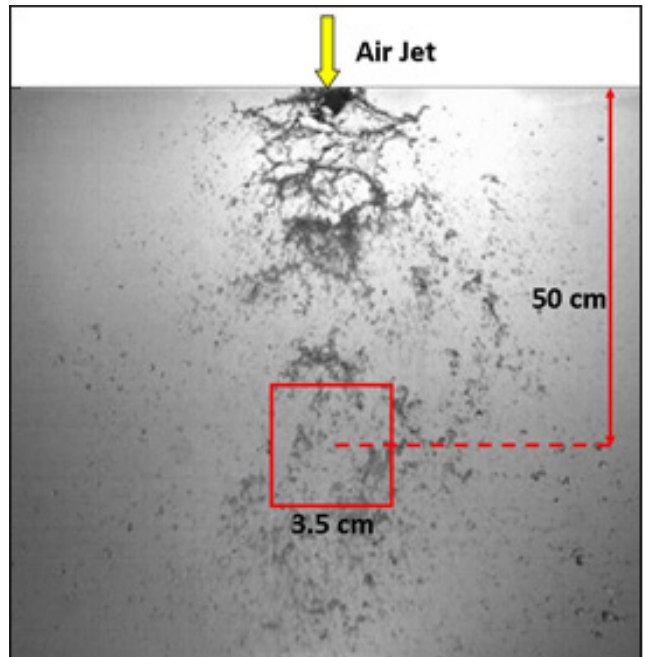
The liquid stream was shattered into droplets by an impinging air jet (Fig. 3b). The air was drawn from the building supply. The air flow rate was controlled by a ball valve and measured by a flow meter. The air line was capped with a Laval-type nozzle (11.9 mm outlet diameter, 7.9 mm throat diameter). The nozzle was positioned either 7.5 cm or 15 cm above the liquid stream and pointed straight down. This nozzle proximity to the liquid stream, if scaled up, translates into 30-60 cm, a typical distance between a shatter jet nozzle and the smelt stream.

Shattering experiments were conducted at liquid flow rates of 0.1 L/s and 0.2 L/s to yield liquid velocities at the end of the spout similar to those in practice. The lower flow rate (0.1 L/s) is representative of the smelt flow encountered under normal recovery boiler conditions; 0.2 L/s is more representative of heavy smelt flow. Different water-glycerine solutions were used to obtain liquid viscosities of 1, 2.5, 10, and 50 cP, where 3-5 cP is typical of recovery boiler smelt at 800°C-850°C [3]. (Liquid viscosity was limited to 50 cP because more viscous liquids could not be pumped at the requisite 0.2 L/s.) The air velocity at the shatter jet nozzle exit was set to 100, 150, 200, 250, or 300 m/s, corresponding to inline air pressures of 10, 12.5, 15.5, 18.5, and 21.5 psig.

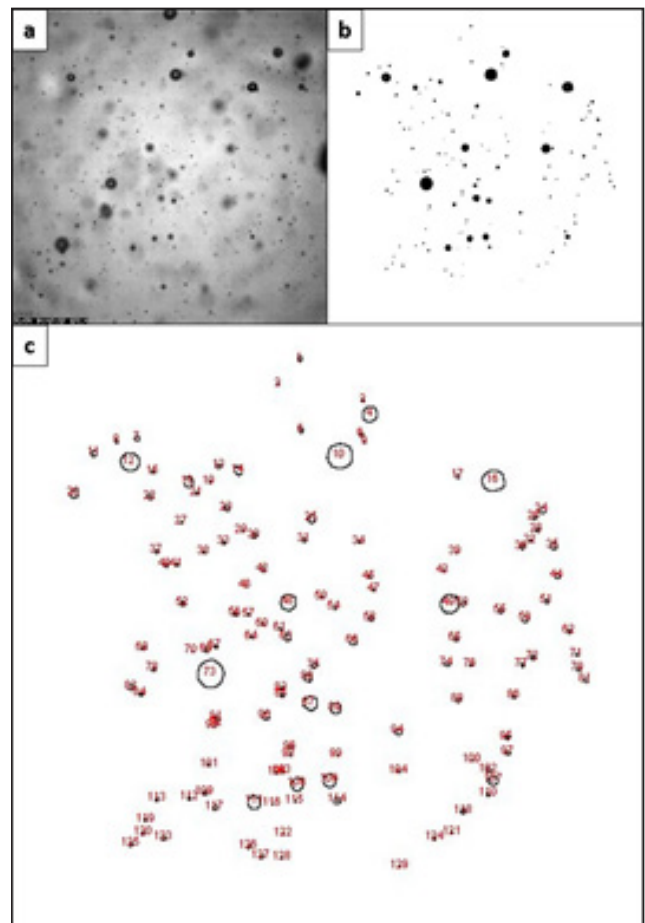
Image analysis

The liquid spray was backlit by a 300 watt light source and imaged by a Mega Speed MS70K S2 digital high speed camera (Canadian Photonics Lab, Inc.; Minnedosa, MB, Canada) fitted with a 28-300 mm f/3.5-6.3 DG macro lens (Sigma Corp.; Kanagawa, Japan). A translucent sheet behind the spray was used to diffuse the light, which then shone through the spray and into the camera. **Figure 4** shows a characteristic spray pattern from the end of the spout to 50 cm below, and the position of the 3.5 × 3.5 cm section of the spray that was imaged. The depth of field of the images was about 2 cm.

After a set of images of a particular spray configuration had been obtained, open source software (ImageJ) was used to process the images and extract droplet size data. **Figure 5** depicts the processing of a sample image. The original image (Fig. 5a) was first converted into a binary (black and white) format (Fig. 5b). ImageJ was then used to calculate individual droplet areas (in pixels) from the binary image, which were then converted into equivalent droplet diameters. Only circu-



4. A view of the overall spray, and of the section that was imaged (not to scale).



5. Image processing: a) original image, b) binary of the original image, and c) droplet outlines.

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lar droplets were analyzed; larger liquid fragments, and droplets that were out of focus, were discounted. Figure 5c shows the droplets that ImageJ identified from Fig. 5a.

Data from multiple images of any spray configuration was then consolidated into droplet number and size distributions, and the Sauter mean diameter (SMD or D_{32}) was calculated. The SMD is a common measure of the fineness of a spray; it reflects the average ratio of drop volume to surface area [4,5]:

$$D_{32} = SMD = \frac{\sum_{i=1}^N D_i^3}{\sum_{i=1}^N D_i^2} \quad (1)$$

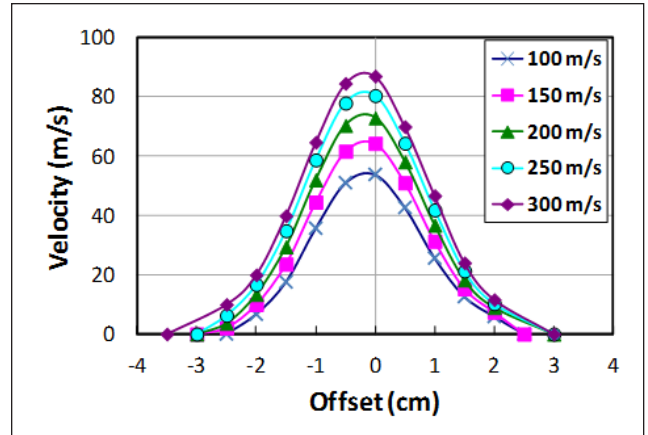
where D is the droplet diameter and N is the number of droplets.

RESULTS AND DISCUSSION

Results are presented of the effect of four parameters on liquid shattering: air velocity (u_{air}), liquid flow rate (Q_l), liquid viscosity (μ_l), and the distance between the nozzle and liquid (N_s). Images were processed for each of 80 experimental conditions, to allow for an analysis of the effect of each of the parameters while keeping the others constant.

Effect of air velocity

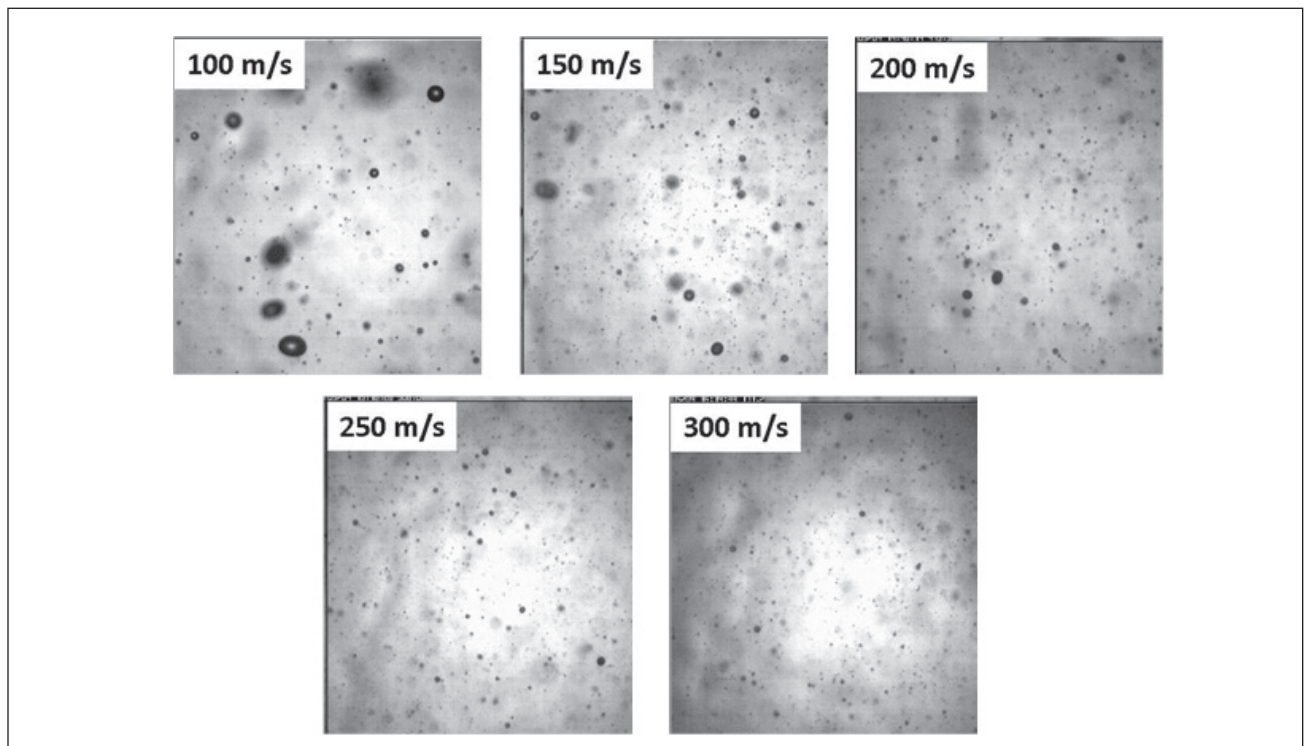
We considered five air flow rates, characterized by average nozzle exit velocities of 100, 150, 200, 250, and 300 m/s, as



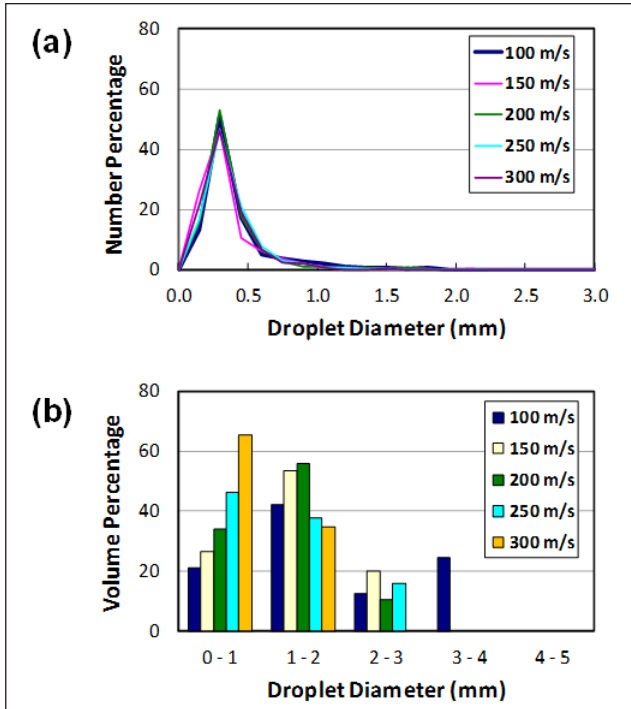
6. Shatter jet air velocity distribution; $N_s = 7.5$ cm.

measured by the air flow meter. Axial velocities downstream of the nozzle were then measured with a pitot tube to assess the rate at which the air jets decayed. Velocities were measured horizontally, vertically, and diagonally across the jets. The results confirmed that the jets were approximately axisymmetric. **Figure 6** presents a sample measurement of horizontal air velocity profiles measured 7.5 cm from the nozzle exit. The nozzle exit diameter was 11.9 mm. Figure 6 illustrates jet profiles six nozzle diameters downstream of the exit. The jet center line velocities are only a half to a third of the average nozzle exit velocity, and the jet is several times as wide as at the nozzle exit.

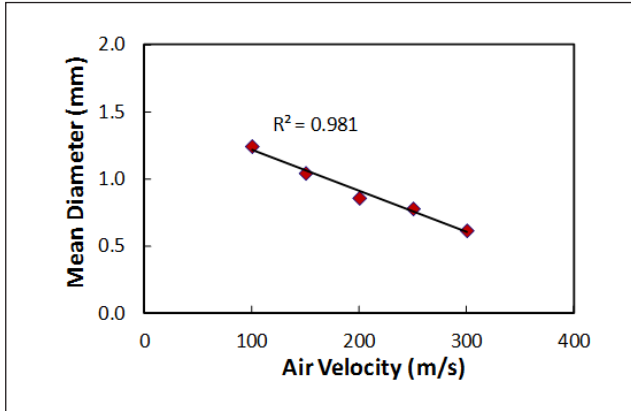
Figure 7 displays a set of representative images that il-



7. Spray images depicting the effect of air velocity on shattering; $Q_l = 0.1$ L/s, $\mu_l = 2.5$ cP, $N_s = 7.5$ cm.



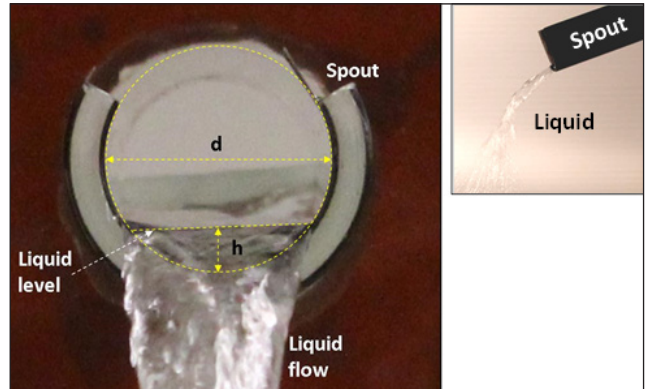
8. The effect of velocity on droplet size distribution: a) number density and b) volume density; $Q_l = 0.1$ L/s, $\mu L = 2.5$ cP, $N_{ls} = 7.5$ cm.



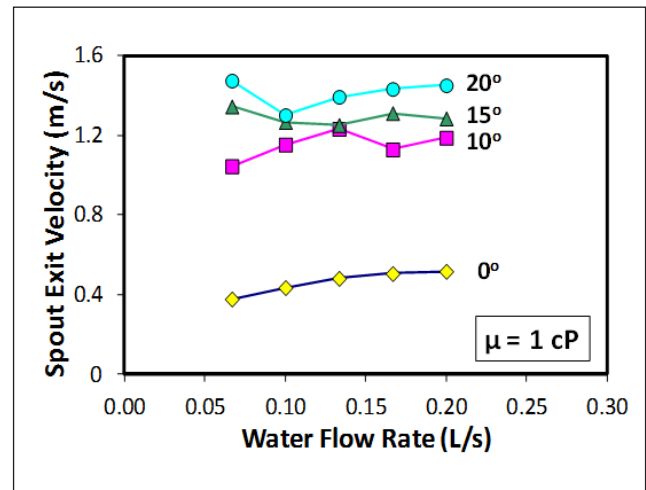
9. The effect of air velocity on Sauter mean diameter; $Q_l = 0.1$ L/s, $\mu L = 2.5$ cP, $N_{ls} = 7.5$ cm.

illustrate the effect of air velocity on liquid shattering. In this case, $Q_l = 0.1$ L/s, $\mu_l = 2.5$ cP, and $N_{ls} = 7.5$ cm. As expected, the stronger the jet, the smaller the droplets, as a result of an increase in the aerodynamic drag applied to the liquid stream. The 100 m/s jet is not strong enough to adequately shatter the liquid stream, as the image shows several large drops of liquid. Increasing the velocity of the shatter jet by 50 m/s largely eliminates those large drops, and further increments of air velocity lead to a progressively finer spray.

Figure 8 shows two droplet size distributions as a function of air velocity. The number distribution (Fig. 8a) can be misleading, as it appears to indicate that shattering is nearly independent of air velocity. The problem is that even inade-



10. Liquid flow down a spout (front view).



11. Effect of liquid flow rate on spout exit velocity at different inclination angles.

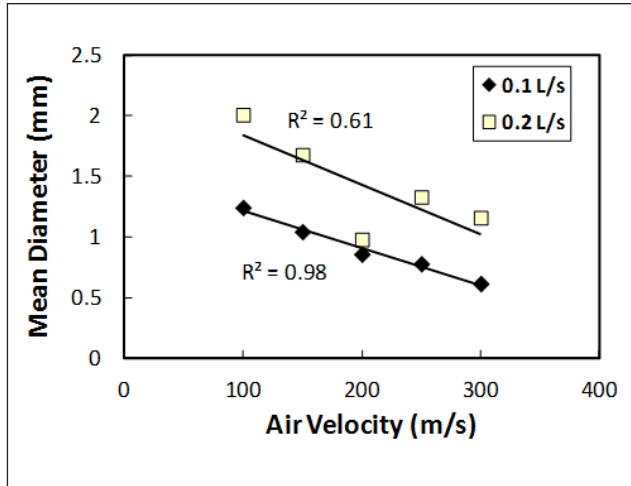
quate shattering yields many small droplets, but also a few large drops that contain a large fraction of the total liquid volume. The liquid volume distribution (Fig. 8b) conveys a better sense of the effect of air velocity. The plot shows that increasing air velocity shatters more of the liquid volume into small droplets, and that large drops only appear at low air velocities.

Figure 9 shows SMD versus air velocity and quantifies the extent to which mean droplet size decreases with air velocity. In this case, the mean droplet size decreases by half, as the air flow rate increases three-fold.

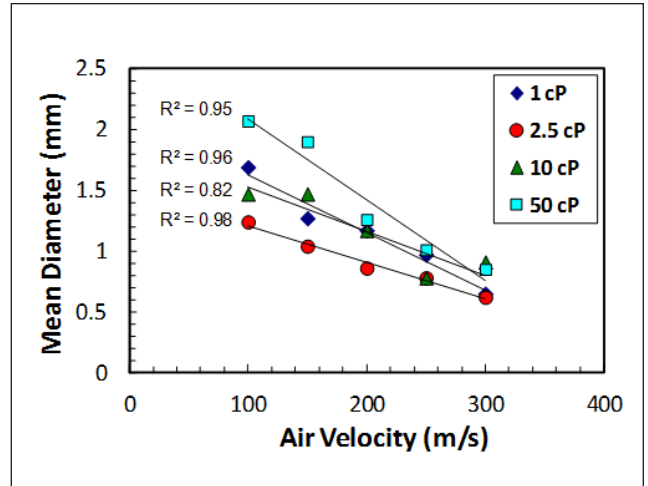
Effect of liquid flow rate

To examine the relationship between liquid flow rate and average liquid velocity, the liquid cross-sectional area was imaged at the end of the spout (Fig. 10) for various flow rates and spout inclinations (0°, 10°, 15°, and 20°) and used to calculate an average liquid velocity that is plotted in Fig. 11. One can draw two conclusions from this plot. At a given inclination, the velocity is almost independent of flow rate. This means that the water level in the spout rises with increasing flow rate. As long as the spout is inclined, the ve-

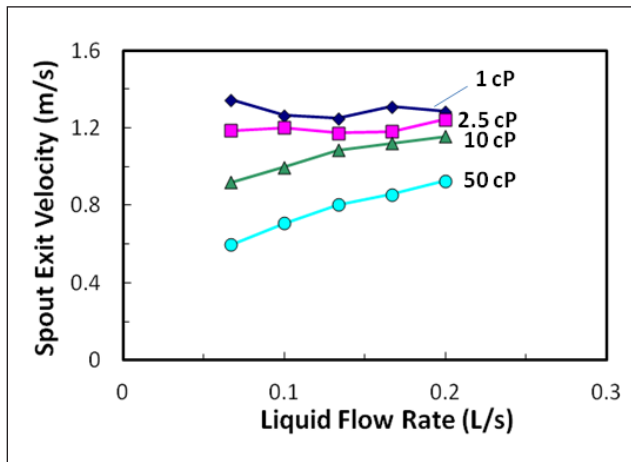
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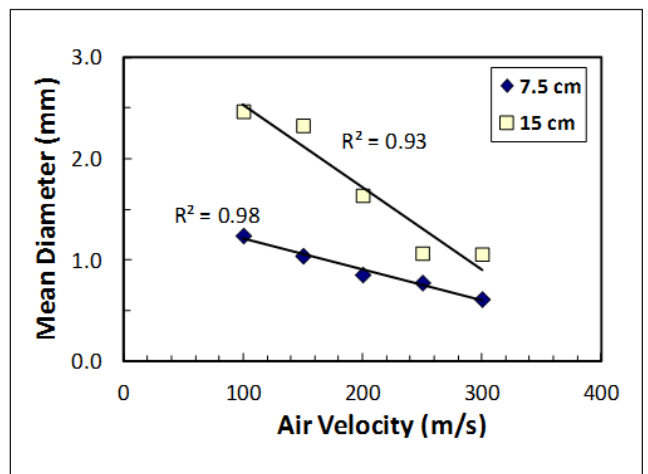
12. The effect of liquid flow rate on Sauter mean diameter; $\mu_l = 2.5 \text{ cP}$, $N_{ls} = 7.5 \text{ cm}$.



14. The effect of liquid viscosity on Sauter mean diameter; $Q_l = 0.1 \text{ L/s}$, $N_{ls} = 7.5 \text{ cm}$.



13. Liquid velocity at the spout exit versus viscosity; spout inclination = 15° .



15. The effect of nozzle proximity on Sauter mean diameter; $Q_l = 0.1 \text{ L/s}$, $\mu_l = 2.5 \text{ cP}$.

locity is not a strong function of the inclination. It is only in the horizontal spout that the liquid flows more slowly, and thus the water level is higher.

To examine the effect of liquid flow rate on shattering, two flow rates were considered: 0.1 L/s and 0.2 L/s. **Figure 12** shows the SMD as a function of air velocity for each of the two liquid flow rates. For these particular conditions, doubling the liquid flow rate roughly increased the mean droplet diameter by almost a factor of two.

Effect of liquid viscosity

The effects of liquid viscosity on the flow down the spout and on shattering were studied. **Figure 13** shows the average liquid velocity at the spout exit versus flow rate for four different viscosities. As expected, as viscosity increased, the liquid velocity decreased (and the liquid level in the spout increased).

Figure 14 shows the effect of liquid viscosity on shattering. The 300 m/s air jet shattered all of the liquids well, as

demonstrated by the small variation in mean droplet diameter. But when the air velocity was only 100 m/s, the effect of viscosity was significant; the SMD varied from 1.2 mm for the 1 cP liquid to 2.1 mm for the 50 cP liquid. Liquid viscosity obviously matters when the shatter jet is not strong enough to simply overpower the liquid stream.

Effect of nozzle proximity

Figure 15 shows the effect of nozzle position on droplet size ($Q_l = 0.1 \text{ L/s}$ and $\mu_l = 2.5 \text{ cP}$). As expected, placing the nozzle closer to the liquid stream results in improved shattering. Droplet mean diameter decreased as the shatter jet nozzle was positioned closer to the liquid stream. Roughly speaking, the SMD decreased by half when the nozzle is moved from 15 cm to 7.5 cm from the liquid, for all air velocities.

PRACTICAL IMPLICATIONS

The results of this laboratory-scale study confirm what is

common sense: shattering improves with increased shatter jet flow rate, it improves as the shatter jet nozzle is moved closer to the liquid stream, and it is easier to shatter the liquid at lower flow rates than higher ones, as long as the nozzle is properly positioned. For the range of liquid viscosities that we studied (1-50 cP), the results show that adequate shattering requires a minimum shatter jet flow rate that must increase with liquid viscosity.

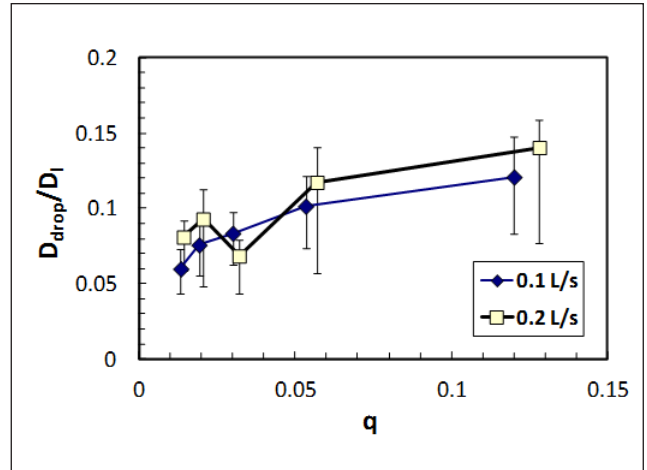
Although our results are preliminary, we can begin to develop correlations that can be applied to actual scale. A common parameter that is often used to characterize liquid atomization (shattering) is the liquid-to-gas momentum ratio q [6]:

$$q = \frac{\rho_l u_l^2}{\rho_g u_g^2} \quad (2)$$

where ρ_l and ρ_g are the liquid and gas densities, and u_l and u_g are the liquid and gas velocities. **Figure 16** shows median drop diameter normalized by the diameter of the liquid stream at the end of the spout, D_d , plotted against the momentum ratio q .

As expected, as the liquid-to-gas momentum ratio decreases, the mean drop size decreases as well. Despite considerable scatter in the data, the results are generally consistent for the two liquid flow rates that we considered. This is an example of a result that we plan to build on to generalize shattering behavior, and ultimately to reliably scale up the results.

Additional experiments are planned to examine the effectiveness of different nozzle geometries and positions, and to



16. Liquid-to-gas momentum ratio versus normalized droplet mean diameter.

examine an even larger range of flow rates and viscosities that might be encountered during boiler startup and upset conditions. **TJ**

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ABOUT THE AUTHORS

The way in which molten smelt is shattered by a steam jet is believed to greatly affect dissolving tank operation and safety. We chose this topic to study to provide better insight into the shattering behavior of molten smelt.

To our knowledge, no previous research has been done on this topic. The most difficult aspect of this research was the scarcity or non-existence of literature on smelt shattering. We addressed the problem by visiting a number of pulp mills, consulting with mill engineers and operators, and analyzing smelt shattering videos.

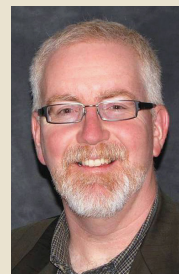
It was surprising to find that increasing the liquid flow rate in an open channel did not increase its velocity, and that increasing the liquid viscosity from 1 cP to 50 cP had little effect on the liquid droplet size.

Understanding how a molten smelt stream is shattered by a steam jet might help mills to optimize their smelt shattering efficiency and to improve their dissolving tank safety.

The next step is to continue to use the laboratory



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apparatus to examine the effects of different jet nozzle designs and positions on droplet size and distribution.

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tional Paper, Irving Pulp & Paper, Kiln Flame Systems, Klabin, MeadWestvaco, Metso Power, StoraEnso Research, Suzano, Tembec, and Tolko Industries.

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