A LABORATORY STUDY OF RECOVERY BOILER SMELT SHATTERING

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ABSTRACT

A scaled-down experimental apparatus was constructed to examine smelt shattering as it occurs during typical recovery boiler operation. Water-glycerine solutions and air were used in place of smelt and steam. A high-speed camera and image processing software was 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 demonstrated 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.

INTRODUCTION

In kraft recovery boiler operation, molten smelt (that consists mainly of Na_2CO_3 and Na_2S, and small amounts of Na_2SO_4, NaCl and potassium salts) flows out of the boiler at 800 to 850^{o}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 (Figure 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, as evidenced by the noise and vibration of the tank, that can often be heard and felt far from the tank itself. In order 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 end of the spout.

While intense smelt-water interaction may be necessary to effectively dissolve smelt in the dissolving tank, smelt shattering is important in order to distribute smelt evenly throughout the tank, rather than have large amounts of smelt simply pour into the tank from the spout. It is widely accepted that inadequate smelt shattering increases the violence of dissolving tank smelt-water interaction, and 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. Smelt shattering 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. Examples of a few that we encountered during mill visits are shown in Figure 2. Some mills simply modify the end of a steam tube to create a single nozzle (2a), or attach a T to create multiple nozzles (2d). Shatter jet nozzles can be round (2a, 2b, 2d) or slit-shaped (2c, 2e). Frozen smelt can build up on shatter jet nozzles, which has led some mills to install the nozzle within a guard (2b), or to use hot water/weak wash to clean the shatter jet nozzle (2a).

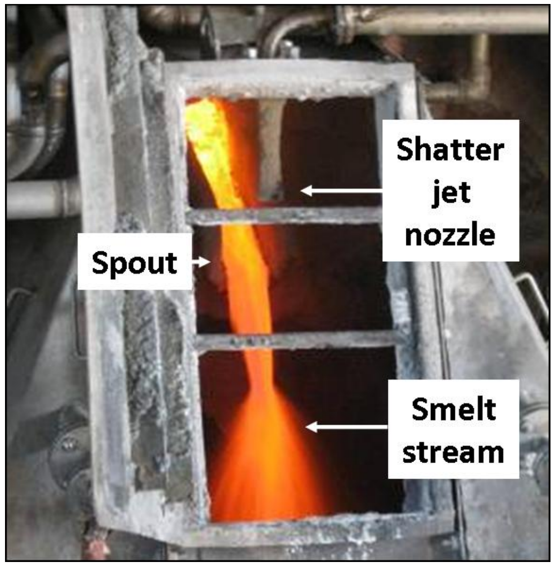


Figure 1. Typical smelt shattering practice.

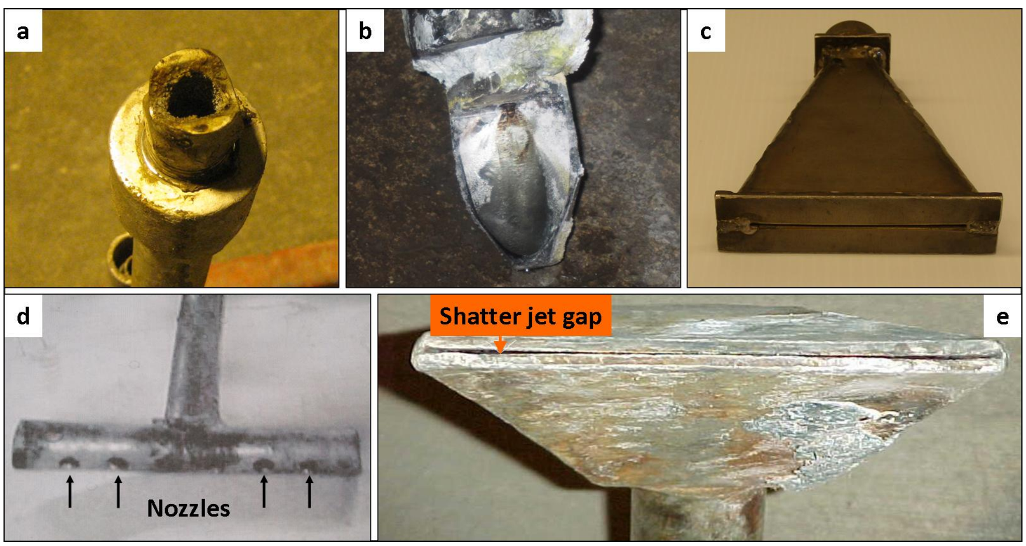


Figure 2. Examples of shatter jet nozzle designs.

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

Shatter jet nozzle placement and orientation, and spout inclination may 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 especially 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 towards abnormal smelt flows.

EXPERIMENTAL SETUP AND METHODOLOGY

A lab-scale experimental setup (Figure 3(a)) 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 (Figure 3(b)), and then processing those images to extract droplet number and size distributions. While the apparatus was built at a reduced scale, the various parameters were chosen to reflect typical values of these parameters in recovery boilers.

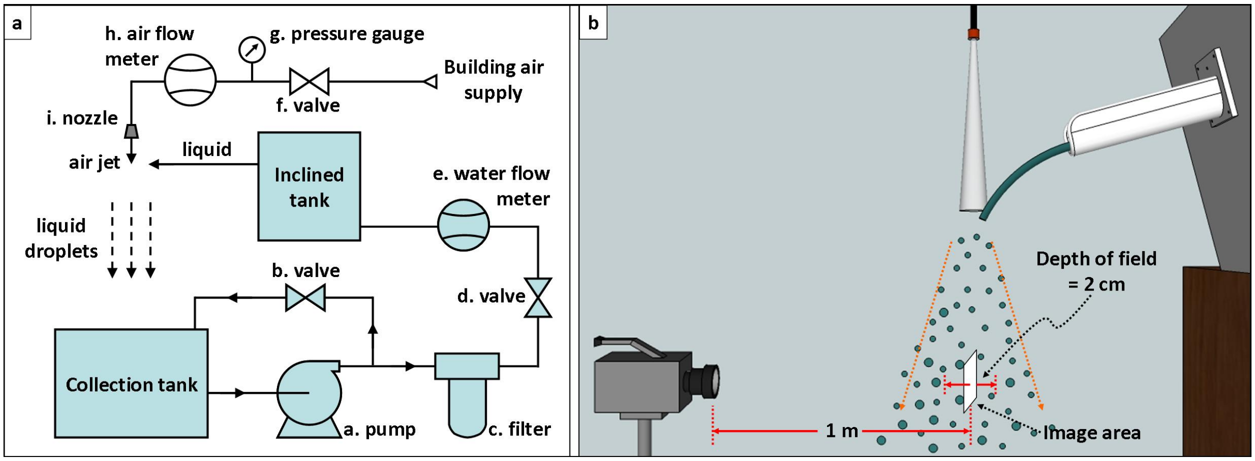


Figure 3. Shattering apparatus: a) schematic and b) illustration.

Referring to Figure 3(a), 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 (Figure 3(b)). Once 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 (Figure 3(b)). 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, 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 and 0.2 L/s, to yield liquid velocities at the end of the spout similar to those in practice. The lower flow rate 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 to 5 cP is typical of recovery boiler smelt at 800 to 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 digital high speed camera (Mega Speed ® MS70K S2) fitted with a Sigma 28-300 mm f/3.5-6.3 DG macro lens. A translucent sheet behind the spray was used to diffuse the light, which then shone through the spray and into the camera. Figure 4 illustrates a characteristic spray pattern from the end of the spout to 50 cm below, and the position of the 3.5 x 3.5 cm section of the spray that was imaged. The depth of field of the images was about 2 cm.

Once a set of images of a particular spray configuration had been obtained, the open-source software ImageJ was used to process the images and extract droplet size data. The processing of a sample image is illustrated in Figure 5.

The original image (5a) was first converted into a binary (black and white) format (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 circular droplets were analyzed; larger liquid fragments, and droplets that were out of focus, were discounted. Figure 5(c) illustrates the droplets that ImageJ identified from Figure 5(a).

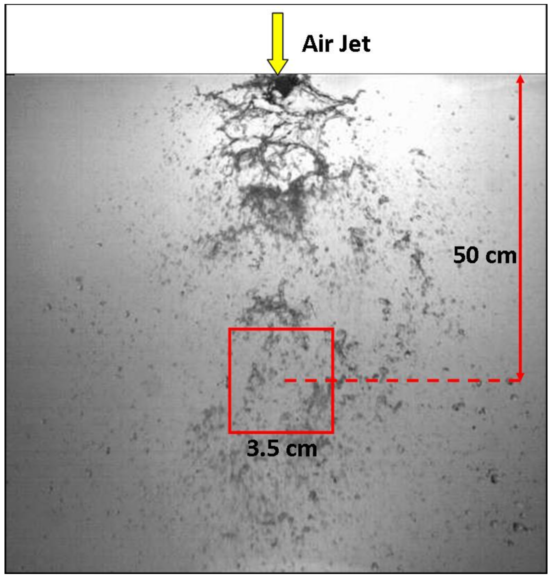


Figure 4. A view of the overall spray, and of the section that was imaged (not to scale).

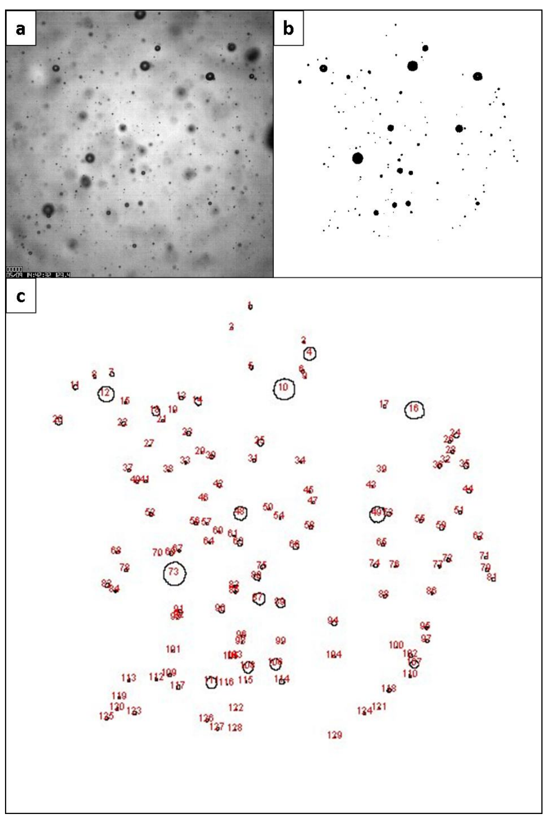


Figure 5. Image processing: a) original image, b) binary of the original image, and c) droplet outlines.

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 very common measure of the fineness of a spray; it reflects the average ratio of drop volume to surface area [4,5]:

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

where D is 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_{ls}). 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 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. Since the nozzle exit diameter was 11.9 mm, Figure 6 illustrates jet profiles six nozzle diameters downstream of the exit. The jet centerline 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 illustrate the effect of air velocity on liquid shattering, for the case of $Q_l = 0.1$ L/s, $\mu_l = 2.5$ cP, and $N_{ls} = 7.5$ cm. As expected, the stronger the jet, the smaller the droplets, due to 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 illustrates two droplet size distributions as a function of air velocity. The number distribution (Figure 8a) can be misleading, as it appears to indicate that shattering is nearly independent of air velocity. The problem is that even inadequate shattering yields many small droplets, but also a few large drops that contain a large fraction of the total liquid volume. As a result, the liquid volume distribution (Figure 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.

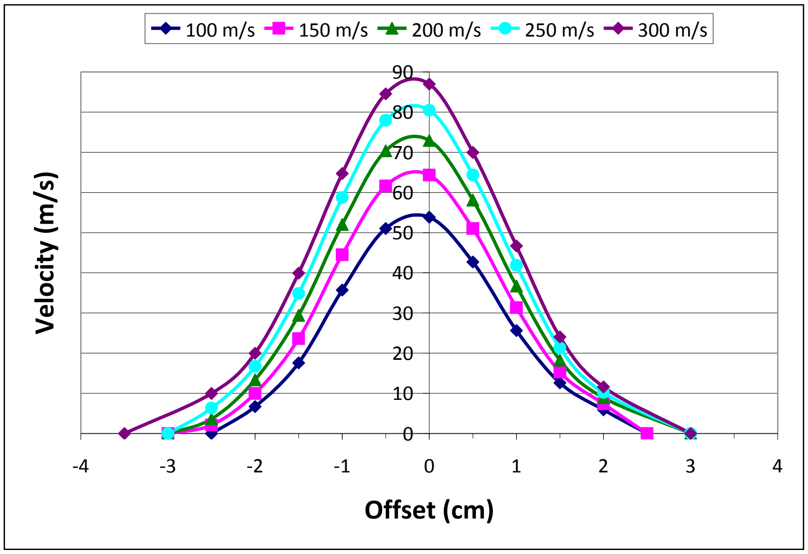


Figure 6. Shatter jet air velocity distribution. N_{ls} = 7.5 cm.

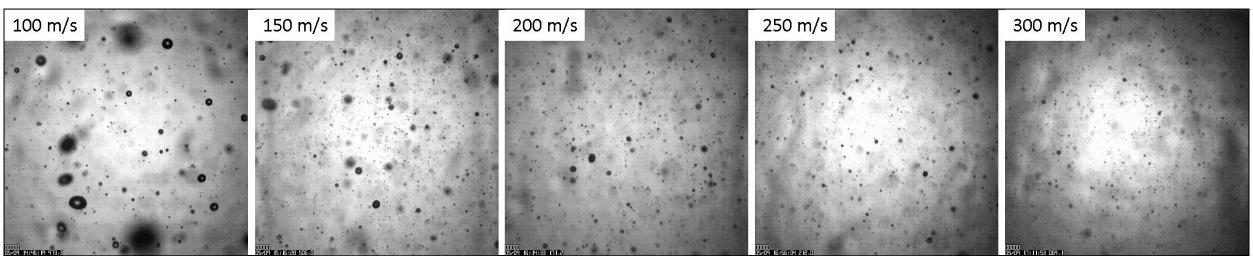
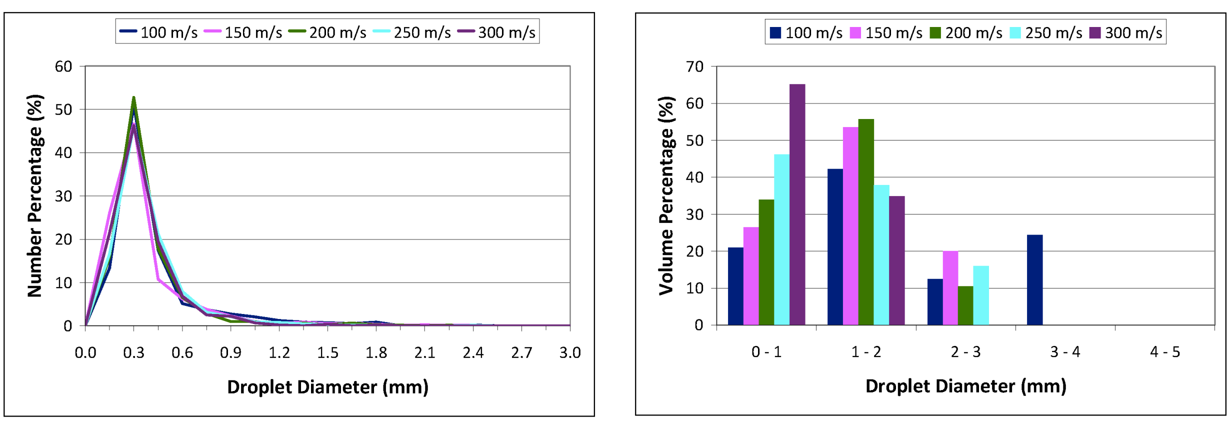


Figure 7. Spray images depicting the effect of air velocity on shattering. Q_l = 0.1 L/s, µl = 2.5 cP, N_{ls} = 7.5 cm.



(a) (b)

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

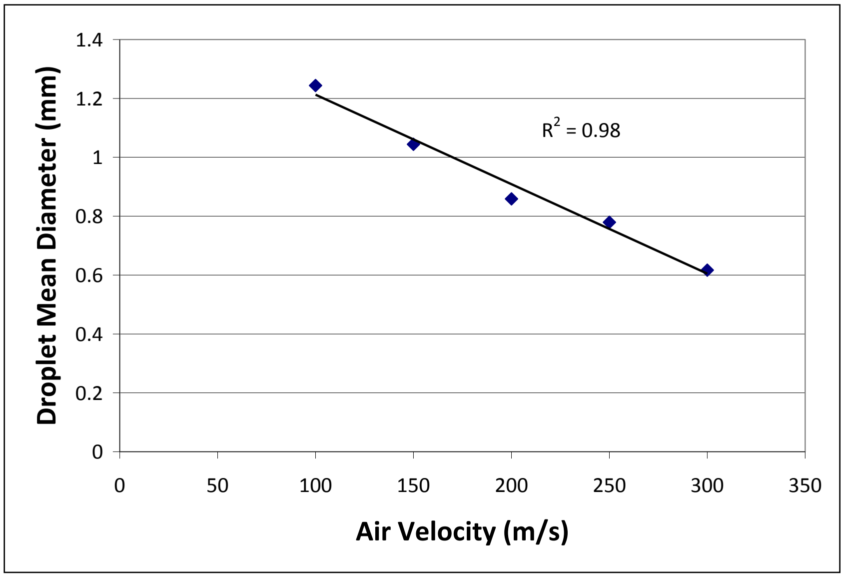


Figure 9. The effect of air velocity on SMD. Ql = 0.1 L/s, μl = 2.5 cP, N_{ls} = 7.5 cm.

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 (Figure 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 Figure 11. One can draw two conclusions from this plot. At a given inclination the velocity is almost independent of flow rate, which means that the water level in the spout rises with increasing flow rate. And as long as the spout is inclined, the velocity is not a strong function of the inclination. It is only in the horizontal spout that the liquid flows more slowly, at thus the water level is higher.

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

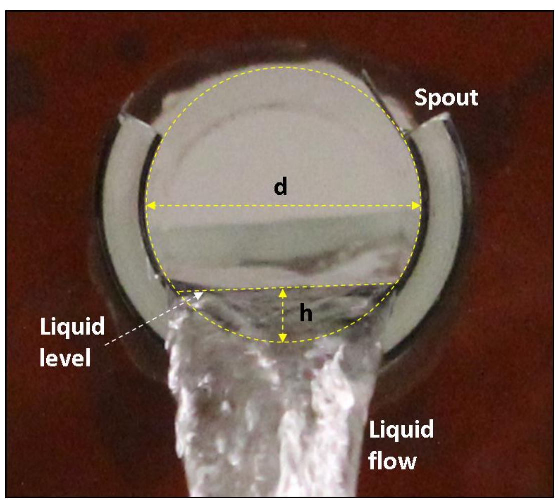


Figure 10. Liquid flow down a spout (front view).

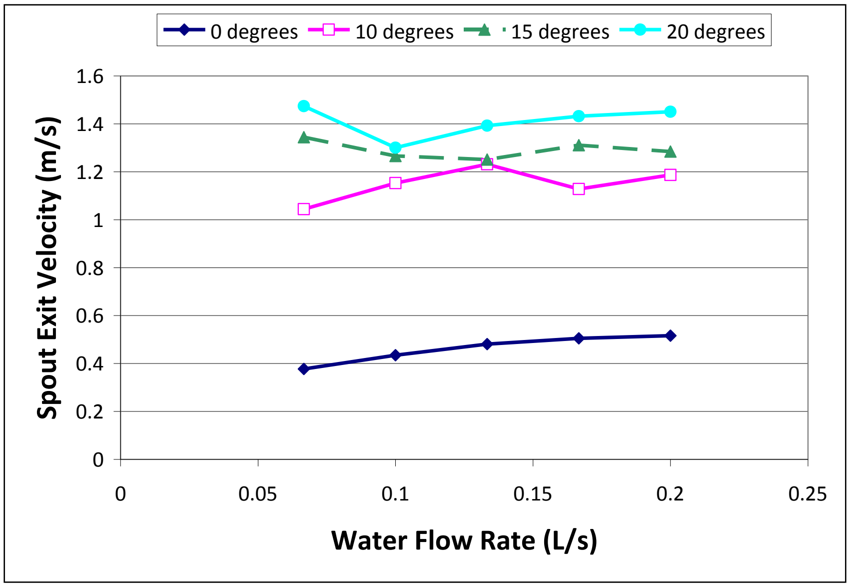


Figure 11. Water velocity at the spout exit versus flow rate.

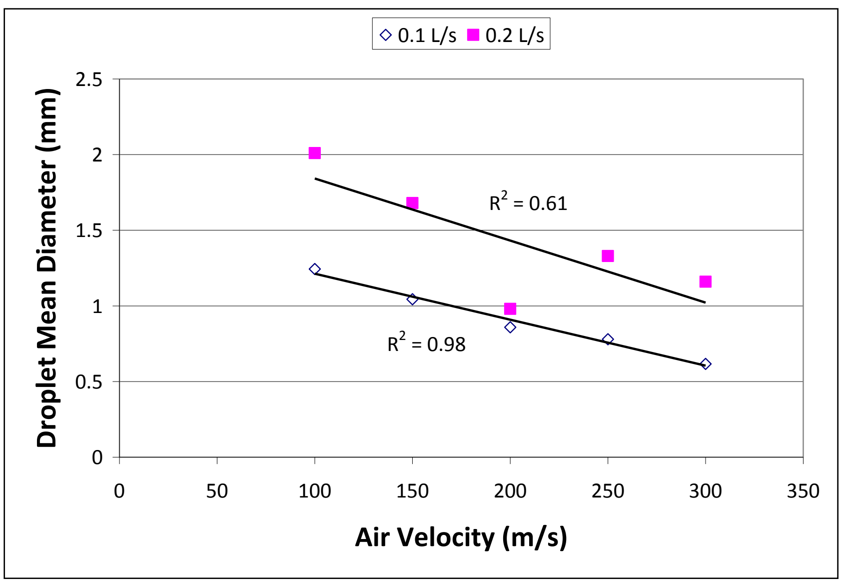


Figure 12. The effect of liquid flow rate on SMD. $\mu_l = 2.5$ cP, $N_{ls} = 7.5$ cm.

Effect of Liquid Viscosity

The effect of liquid viscosity on both the flow down the spout, and on shattering was studied. Figure 13 illustrates the average liquid velocity at the spout exit versus flow rate, for four different viscosities. As expected, as viscosity increases, the liquid velocity decreases (and the liquid level in the spout increases).

The effect of liquid viscosity on shattering is presented in Figure 14. The 300 m/s air jet shattered all of the liquids well, as the variation in mean droplet diameter was small. But when the air velocity was only 100 m/s, the effect of viscosity was significant, as the SMD varied from 1.2 mm for the 1 cP liquid to 2.1 mm for the 50 cP liquid. The liquid viscosity obviously matters when the shatter jet is not strong enough to simply overpower the liquid stream.

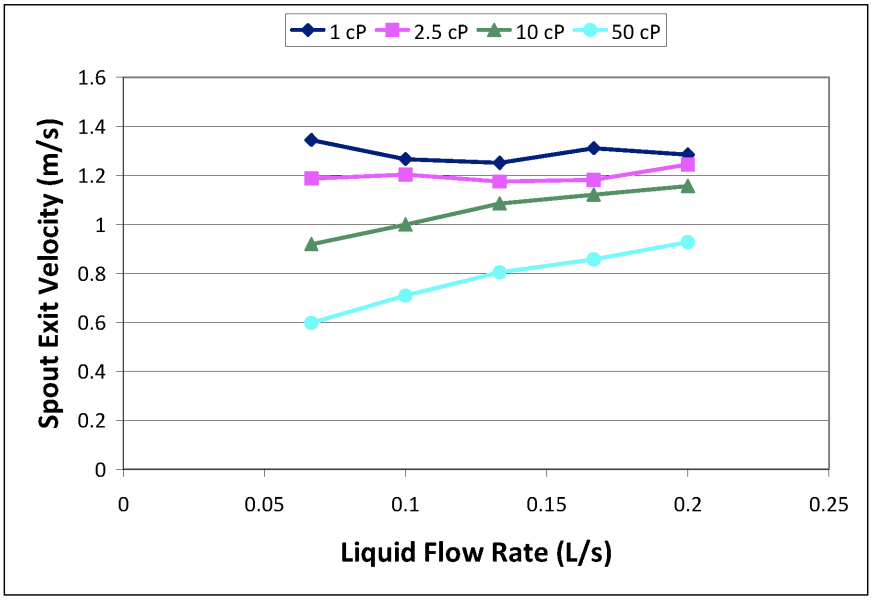


Figure 13. Liquid velocity at the spout exit versus viscosity. Spout inclination is 15°.

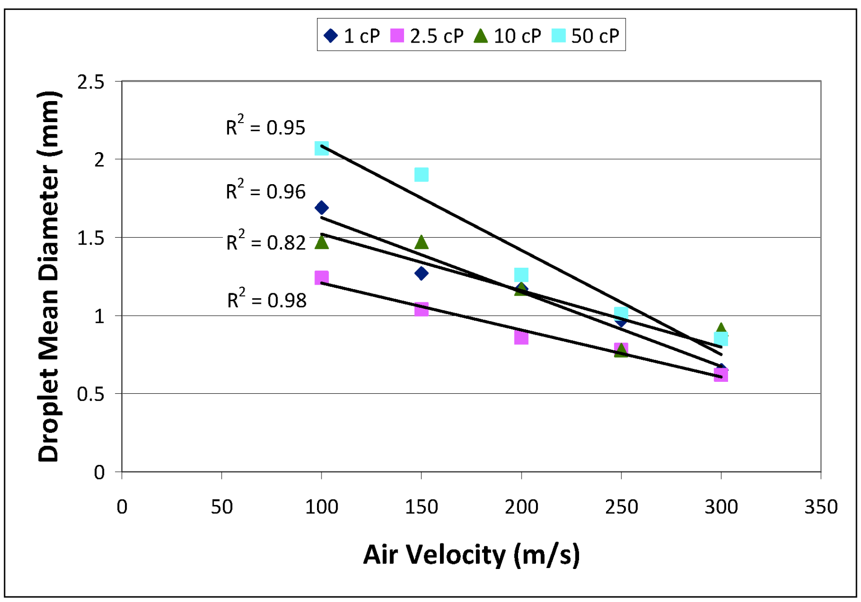


Figure 14. The effect of liquid viscosity on SMD. Q_l = 0.1 L/s, N_{ls} = 7.5 cm.

Effect of Nozzle Proximity

The effect of nozzle position on droplet size is shown in Figure 15, for Q_l = 0.1 L/s and μ_l = 2.5 cP. As expected, placing the nozzle closer to the liquid stream obviously results in improved shattering. Droplet mean diameter decreases as the shatter jet nozzle is positioned closer to the liquid stream. Roughly speaking, the SMD decreases by half when the nozzle is moved from 15 to 7.5 cm from the liquid, for all air velocities.

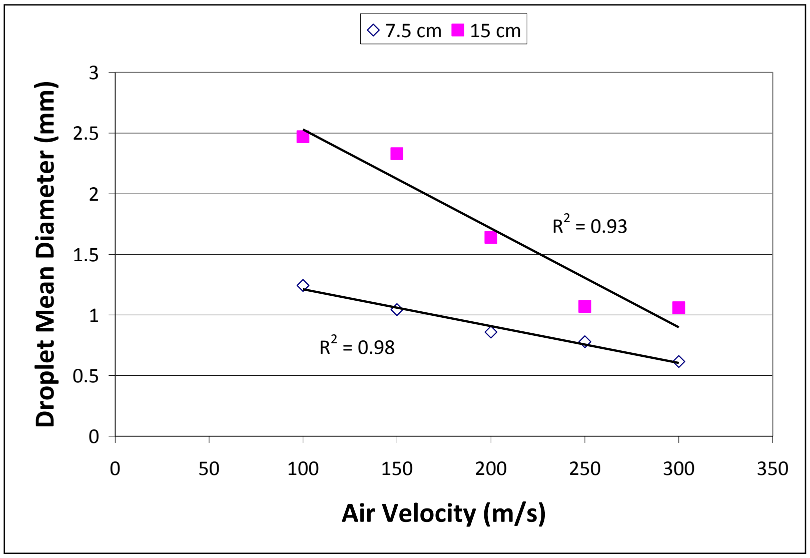


Figure 15. The effect of nozzle proximity on SMD. Q_l = 0.1 L/s, μ_l = 2.5 cP.

PRACTICAL IMPLICATIONS

The results of this lab-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 it easier to shatter lower liquid 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.

While the results are preliminary, it is possible to generalize the results in order to begin to develop correlations that can be applied to actual scale. A common parameter that is often used to character liquid atomization (shattering) is the liquid-to-gas momentum ratio q [6]:

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

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 illustrates median drop diameter normalized by the diameter of the liquid stream at the end of the spout, D_l, plotted against the momentum ratio q:

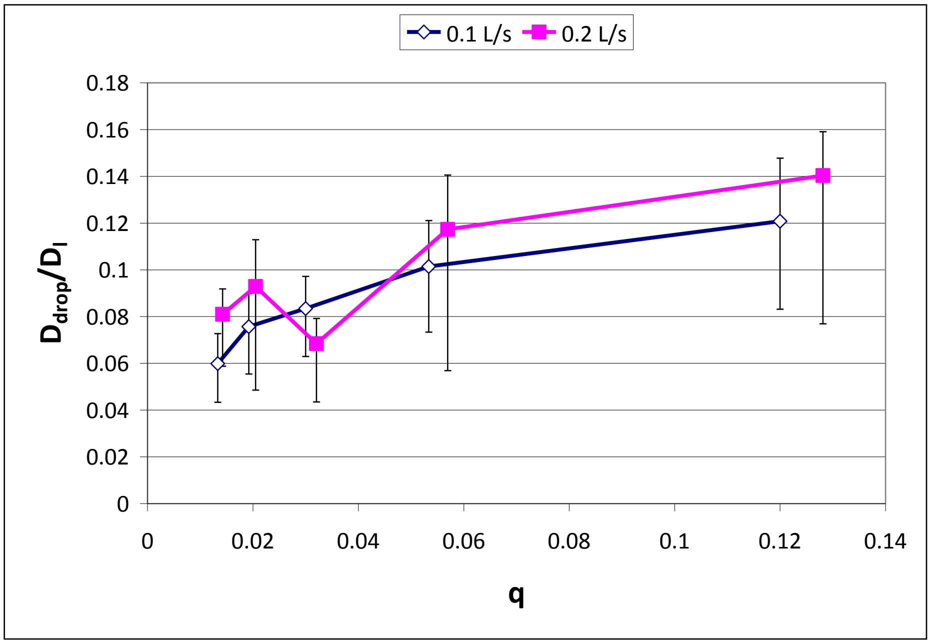


Figure 16. Liquid-to-gas momentum ratio versus normalized droplet mean diameter.

As expected, as the liquid-to-gas momentum ratio decreases, the mean drop size decreases as well. While there is lots of 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, in order to scale up the results.

Additional experiments are planned to examine the effectiveness of different nozzle geometries and positions, and to examine an even larger range of flow rates and viscosities, as might be encountered during boiler start-up and upset conditions.

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