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Effervescent Spraying of a Medium to High Viscosity Newtonian Liquid
at High Mass Flowrates

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Effervescent Spraying of a Medium to High Viscosity Newtonian Liquid at High Mass Flowrates

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Summary

Effervescent spraying was evaluated in comparison to liquid-only spraying using a corn syrup at viscosity levels of 100 to 10,000 mPa·s and at flowrates of 30 to 45 liters per minute. Spray characteristics were quantified in terms of average drop size, drop size distribution, and spray angle, and analyzed in terms of the gas/liquid mass ratio (GLR).

A process or nozzle design that enabled independent control of the black liquor spray drop size in a kraft recovery boiler would be of high interest to the chemical pulping industry. Although it is realized that drop size is a critical issue in recovery boiler operation and combustion efficiency, there is little knowledge and understanding of how liquid properties and nozzle design affect spray characteristics at high black liquor solids ($\geq 80\%$). This paper presents preliminary results of an effervescent spraying process applied at liquid flowrates and viscosity levels that may be encountered in a black liquor recovery boiler operating at normal to high liquor solids. Based on experiments with a model fluid, it is concluded that an effervescent spraying process should enable control of the mass median drop diameter to a range typical of conventional recovery boiler spraying (2-4 mm).

Introduction

In the kraft pulping process, the by-product liquid, called black liquor, is fired into a recovery boiler to burn the organic material for its energy value and recover the inorganic chemicals used in pulping. The spray properties of primary concern for recovery boilers are the drop mass median diameter (MMD), size distribution, and the spatial mass distribution. An ideal spray is believed to have a drop size MMD of approximately 2-4 mm, which results in a proper balance of in-flight combustion and char-bed burning. Although the ideal drop size distribution is debatable (narrow or wide), it can be agreed that it is desirable to minimize the production of very small (< 0.5 mm) or very large (> 10 mm) drops. Very small drops often follow the flue gas flow (termed carry-over) into the superheater and boiler tube sections. Very large drops, resulting from poor liquor disintegration, cause poor combustion efficiency and can cause dangerous cool zones in the char bed at the bottom of the furnace. The mass distribution of the spray, which is a function of the spray angle, affects the char bed size and dimensions, as well as the general location of droplet combustion.

Most mills today concentrate the black liquor to 70-75% solids before spraying; however, mills with a recovery boiler capacity limitation and/or environmental emission concerns are often interested in increasing the percent solids to 80% and higher. At these solids levels, however, the viscosity increases exponentially, causing problems with conventional handling and spraying processes. One alternative being applied in several mills is to superheat the liquor to maintain its fluidity during transport; however, as the liquor approaches atmospheric pressure at the spray nozzle, flashing occurs. Previous research (with normal solids liquors) at the Institute of Paper Science and Technology has shown that flashing produces a significantly smaller drop size MMD with an apparently different drop formation mechanism as compared to conventional spraying in which drops are formed by liquid sheet disintegration [1]. Where and how flashing occurs in the spray nozzle is, for the most part, uncontrollable, resulting in spray properties that are unsteady and unpredictable.

In this study, a different approach to black liquor spraying is investigated - effervescent spraying. Lefebvre [2] describes effervescent atomization as a twin-fluid process in which the atomizing gas is injected into the liquid at some point upstream of the nozzle to form a bubbly two-phase flow. When this mixture exits the discharge orifice, the rapidly expanding bubbles shatter the surrounding liquid into droplets. Based on previous reports [3,4], this process would appear attractive to high solids recovery boiler operations for two reasons:

- relatively large and simple design of spray nozzle orifice; minimizing clogging and its effects;
- potential to obtain present drop diameters (based on conventional solids liquors) with high solids (high viscosity) liquors, which normally would produce large globules or a “rope.”

All previous effervescent spraying studies [3-5] , however, were performed with the objective of producing very small drops ($< 50 \mu\text{m}$) at significantly lower flowrates and viscosity than would be encountered with a full-scale high-solids black liquor spraying operation, where the optimum drop size is believed to be in the 2-4 mm size range. A typical nozzle flowrate for black liquor spraying ranges from 75 - 280 L/min [6]. Black liquor behaves as a Newtonian fluid (mainly) with a wide range of possible viscosities depending on pulping conditions and wood species. One study reports viscosities ranging from 400 to 10,000 mPa·s for 80-85% black liquor at its boiling point temperature [7].

Experimental Approach and Technique

The experiments in this study were performed using nitrogen (as the atomization gas) and corn syrup as a model fluid, with its viscosity adjusted by adding or evaporating water. The details of the spraying facility have been described previously [8], although modifications were made for this study to handle the higher liquid viscosity, gas requirements, and different nozzle designs (Figure 1). Due to entrained gas in the liquid after spraying, experiments were run in semi-batch mode, allowing time for phase separation between runs.

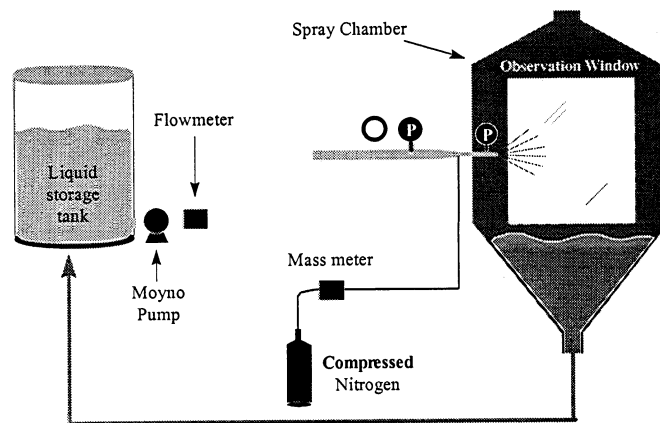


Figure 1: Schematic of experimental spraying system.

Experiments were performed at liquid flowrate levels of 30 and 45 liters per minute (LPM) and gas flowrates from 0 to 1300 standard liters per minute (SLM). Liquid and gas flowrates were measured using electromagnetic and gas mass flowmeters, respectively. Liquid viscosity was measured using a Brookfield viscometer (model RVT). Experiments were run at room temperature, with the exact liquid temperature measured just before spraying to account for any small viscosity changes.

A schematic of the gas injection technique is shown in Figure 2. Gas was injected through many small holes (0.75 mm diameter) in the pipe wall, then distributed into the liquid using a 10 - cm length of static mixer (Koch Engineering; model SMX; 25 mm diameter) before exiting the spray nozzle. Although effervescent sprays were effectively produced previously using a nozzle with a plain circular orifice [9], the experiments reported here were performed using a spray nozzle more commonly used in recovery boilers; namely, a Vee-jet nozzle (Spraying Systems #65200; 8.7 mm equivalent diameter). Pressure was measured (using Ametek model #851 transducers) before gas injection and just before (27 mm) the nozzle exit orifice.

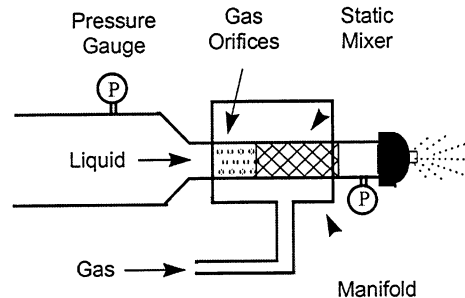


Figure 2: Schematic of gas injection/mixing method and spray nozzle.

Spray Analysis

Qualitative and quantitative spray results were obtained by analyzing video images produced by a high shutter speed camera (Xybion model ISG-250). The camera position for drop size analysis was approximately 1.3 meters horizontally from the spray nozzle end, and a spray separation device was created to limit the quantity of spray within the camera's depth of field. Converting the video images into meaningful drop size data required making assumptions with respect to:

- converting a 2-D image into 3-D drop size information
- measurable size limitations
- defining edge boundaries, noise, and depth of field concerns
- assumptions for strands and other non-spherical shapes

A standardized image analysis filtering and arithmetic operations routine was developed (using Optimas image analysis software) to eliminate noise and define edge boundaries. Because most drops were not perfectly spherical, it was necessary to translate the 2-D drop images into equivalent drop diameters. For an individual drop, the measured area and perimeter can be assumed to be proportional to the actual drop volume and surface area. The applied method uses the area and perimeter of each drop image and converts it into a cylinder with hemispherical ends (because most non-spherical drops appear as such). Then, after calculating its volume, the diameter of a sphere with equal volume is calculated, this being referred to from this point on as the equivalent drop diameter. The lower limit of drop diameter detection was approximately 0.3 mm; below this size, it was impossible to accurately discern drop shape or size. For each set, between 1000 and 10,000 drops were measured (15-25 image frames). The maximum level of uncertainty to be expected in the drop size MMD measurements was $\pm 20\%$.

Spray angles were determined from video images of the near-nozzle spray structure. Due to the unsteady characteristics of effervescent spraying, it was necessary to produce an average image of 32 individual images (using image analysis), thereby allowing a more accurate determination of the liquid trajectory angle from the nozzle orifice. Error in spray angle determination is estimated at $\pm 5^\circ$.

Results

Drop Formation

Conventional spraying (liquid-only) with a Vee-jet nozzle was analyzed in order to make meaningful comparisons with effervescent spraying. Similar to splashplate nozzles, the Vee-jet nozzle operates under the principle of spreading the liquid into a thin sheet, which is disrupted by wave thinning and perforation mechanisms, forming strands and eventually drops. At low viscosity, the liquid sheet breaks up quickly after exiting the nozzle, forming nearly spherical drops by the time they reach the video imaging area. As viscosity increases, however, the liquid sheet disintegration process is significantly slowed, such that strands persist further downstream from the nozzle. Eventually a viscosity is reached where a continuous stream is formed from the nozzle (recovery boiler operators would classify this as “roping”).

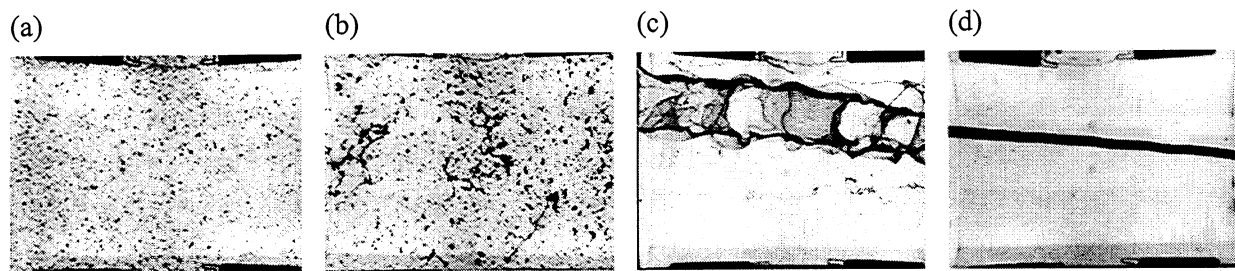


Figure 3: Images of liquid-only spray showing viscosity effect (a) 100 mPa·s; (b) 750 mPa·s; (c) 2800 mPa·s; (d) 10,000 mPa·s, (liquid flowrate = 45 LPM; images 1.3 meters from nozzle with dimensions 280 x 210 mm).

Effervescent spraying does not rely on forming a liquid sheet for disintegration; rather, atomization is accomplished by the explosion of gas exiting the nozzle. Images of the near-nozzle spray structure illustrate this effect, as shown in Figure 4. Initial addition of gas (indicated by the gas/liquid mass flow ratio: GLR) causes the liquid sheet to disappear, being replaced by liquid strands exiting immediately from the nozzle orifice. As shown for the lowest GLR levels, the curved-shaped strands are oriented perpendicular to the direction of flow with fairly uniform spacing. As discussed by Crapper *et al.* [10] - the appearance of these “waves” of liquid strands indicates a frequency imposed by some external force - in this case, the unsteady release of bubbles from the nozzle orifice. Pressure fluctuations, as measured just before the nozzle orifice, verify the unsteady forces being imposed on the liquid by the rapidly expanding bubbles.

For each tested viscosity level, increasing the GLR causes thinner strands with a more disordered orientation (as shown in Figure 4). The thinner strands are most likely the result of: 1) increasing number and size of bubble explosions, and 2) increasing liquid velocity, caused by the gas reducing the effective cross-sectional area for liquid flow. The thinner strands result in smaller drop sizes. At the highest GLR level evaluated, drops appear to form immediately upon exiting the nozzle orifice.

The rate at which the strands disintegrate into drops depends on the liquid viscosity. Increased viscosity causes strands to persist further downstream from the nozzle. At high viscosity levels (2800 and 10,000 mPa·s) and low GLRs, strands do not breakup into spherical drops before reaching the end of the spray chamber (1.8 m downstream of nozzle). At the highest evaluated GLR level, however, the differences between sprays of different viscosity are minimized.

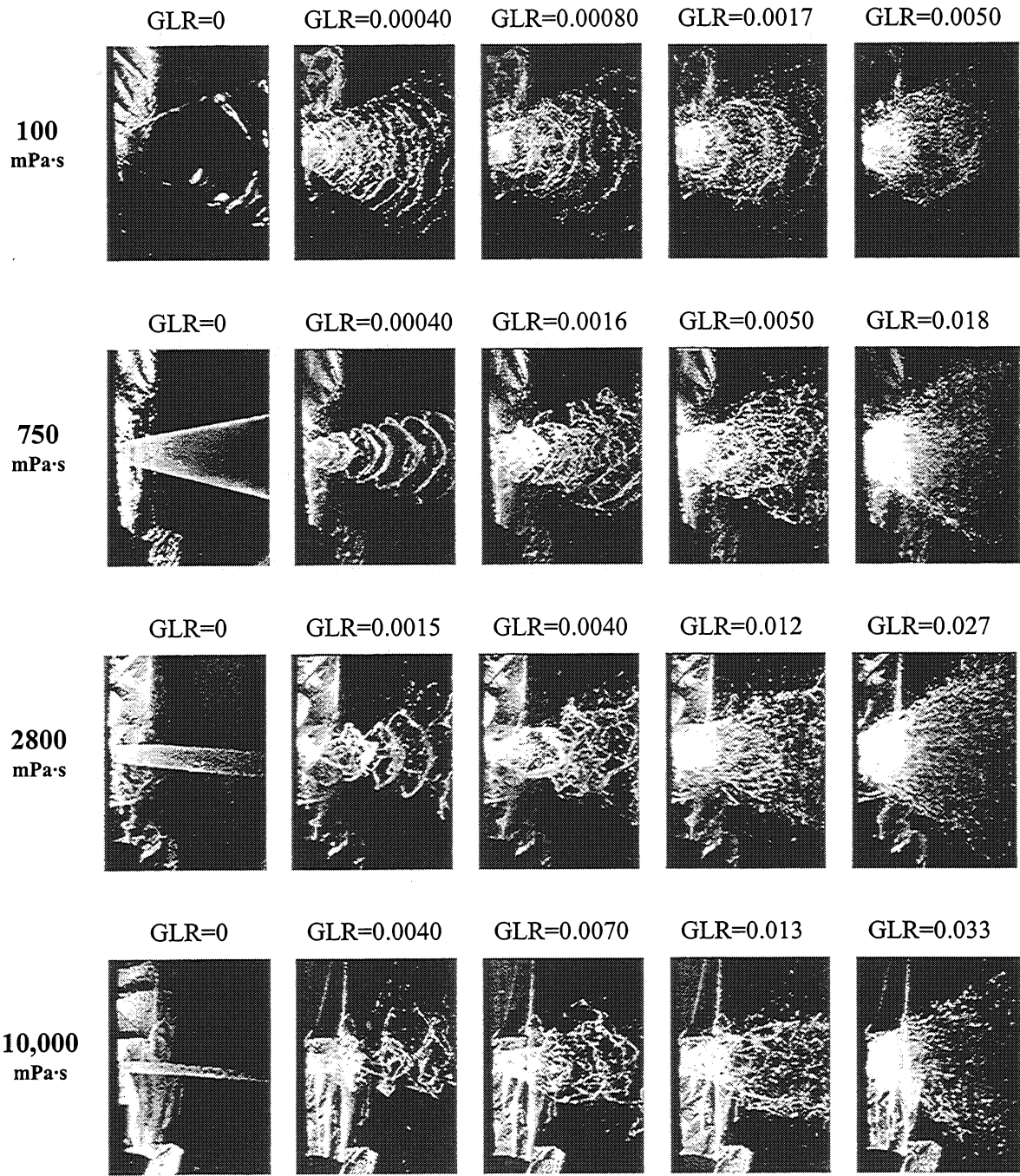


Figure 4: Images of the near nozzle spray structure for liquid-only (GLR=0) and effervescent sprays at increasing gas flowrate and viscosity (liquid flowrate=30 LPM).

Drop Size

For conventional liquid-only spraying, drops do not form above a certain viscosity threshold (dependent on liquid flowrate and nozzle size). As the images in Figure 3 indicate, individual drop distinction becomes indeterminable at high viscosity levels, since all or portions of the spray are a continuous

stream of liquid. The primary objective of this research was to determine if an effervescent spraying process could effectively spray a liquid that is too viscous for conventional spraying methods.

As shown in Figure 5, the gas flowrate has a dramatic effect on the drop size MMD for effervescent spraying. At the highest viscosity levels (2800 and 10,000 mPa·s), adding a small amount of gas (GLR=0.0001-0.0002) disrupts the continuous liquid stream into large drops of 10-20 mm diameter. Further increases in the gas flowrate reduce the drop size MMD to the desirable range of a recovery boiler (2-4 mm), with further increases reducing to a level near 1 mm. Lower viscosity levels require a lower GLR to attain a similar drop size.

Although not shown, increasing the liquid flowrate from 30 to 45 LPM results in the exact same trends as shown in Figure 5, but reduces the drop size MMD by an approximate 20-30%. This decrease can be attributed to the higher flow velocity and pressure experienced in the nozzle orifice, subsequently causing more intense bubble explosions and faster moving liquid strands. Both effects reduce the spray drop size.

Close inspection of the lower viscosity data in Figure 5 (100 and 750 mPa·s, shown more clearly in Figure 6) shows an initial increase in MMD compared to liquid-only spraying. This increase in drop size at low GLRs was unexpected, since previous research concerning black liquor flashing concluded a smaller drop size than spraying without flashing. The larger drops can be attributed to the different drop formation mechanism for effervescent spraying compared to sheet disintegration (as discussed previously). At low GLR levels, the strands that form immediately upon exiting the nozzle orifice are thicker than the strands formed through disintegration of the liquid-only sheet, thus resulting in a larger drop size MMD compared to liquid-only spraying.

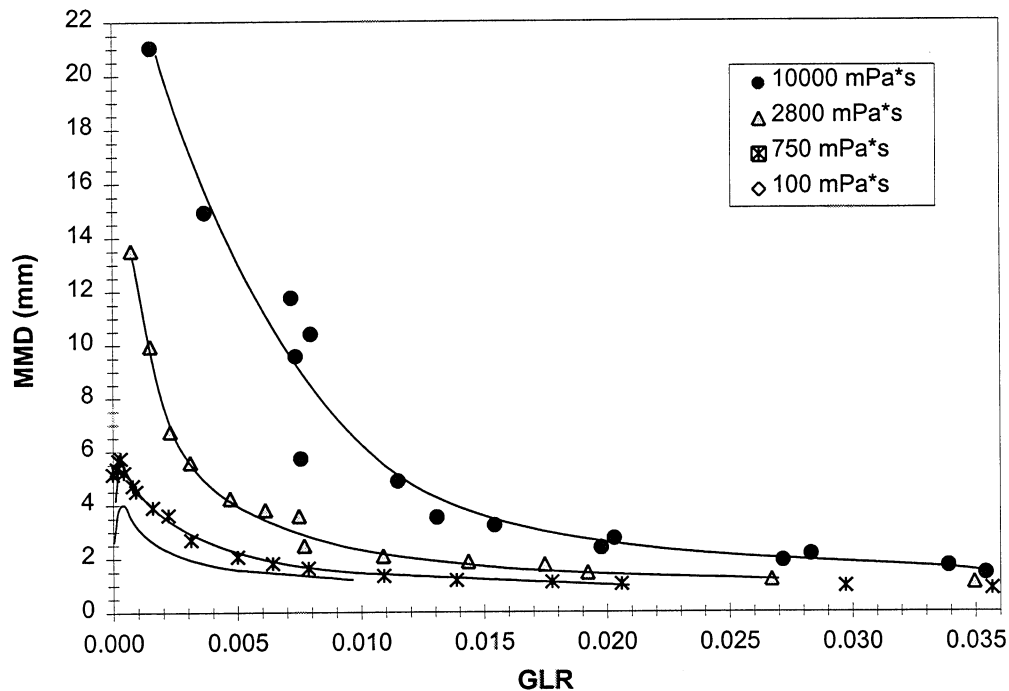


Figure 5: Drop size MMD as a function of GLR and viscosity for effervescent spraying (using Vee-jet nozzle at 30 LPM; uncertainty estimates are $\pm 20\%$ for MMD and $\pm 1\%$ for GLR; trendlines are for graphical purposes only).

It would appear from Figure 5 that the drop size MMD levels out at about 1 mm as the GLR is increased, even at the highest viscosity. This is by no means believed to be true, because other studies show drop sizes below 0.1 mm are possible at very high GLRs [10]. Unfortunately, however, current video camera and analysis limitations do not allow drops smaller than 0.3 mm diameter to be accurately detected. Although the mass fraction of these tiny drops is very small at the lower GLRs, higher GLRs should cause a higher mass fraction of these tiny undetectable drops. Thus, results are probably slightly higher than they should be for MMDs in the 1-1.5 mm range. With respect to recovery boiler operation, knowing the relative quantity of these small drops is critical because they collectively contribute to the carry-over problem discussed earlier.

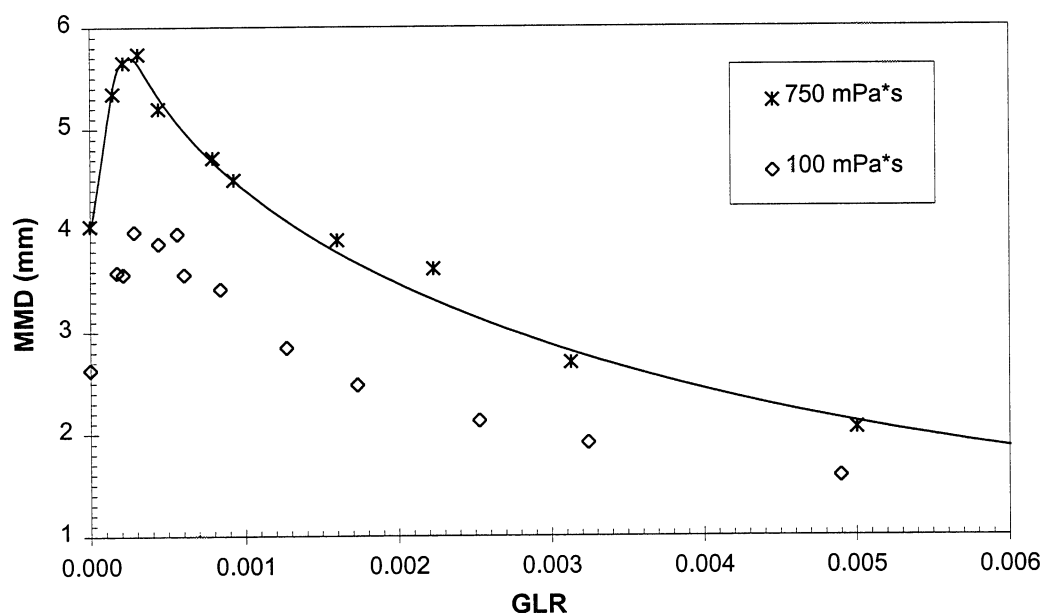


Figure 6: Drop size MMD as a function of GLR for viscosities 100 and 750 mPa*s (close-up view of data in Figure 5).

Drop Size Distribution

Previous research [11] for black liquor spraying has shown that the drop size distribution was best modeled mathematically by the square-root normal distribution, and that the normalized standard deviations (standard deviation divided by the square-root of the MMD) were relatively constant at 0.20 ± 0.03 . After analyzing effervescent spray drop size results, it was determined that the square-root normal function still provided the best overall fit to the data, although sprays containing abnormally large strands and globules (observed at high viscosity and low GLR conditions) were better represented by a normal distribution. However, in order to make meaningful comparisons among drop size distribution data, standard deviation values were calculated based on the square-root normal function for all drop size data sets.

Another important aspect of this study was to determine if the drop size distribution was affected, either positively or negatively, for effervescent spraying compared to liquid-only spraying. Experimental

results of this study showed an average value for the normalized standard deviation of about 0.25 ± 0.02 for liquid-only spraying at 100 mPa·s, and about 0.29 ± 0.02 for 750 mPa·s. Thus, standard deviations that are significantly greater or less than these values should be acknowledged.

Although not taken into account in the drop size analysis, conventional liquid-only sprays contain a relatively thicker portion of liquid in the outer region of the sheet, sometimes referred to as the rim. It is speculated that the rim may have a significant effect on the drop size distribution. At low viscosity (100 mPa·s), the rim forms relatively larger drops and strands compared to the central portion of the spray; however, at 750 mPa·s and higher, the rim is essentially a continuous stream of liquid. In either case, if quantified into an equivalent drop size, the rim would skew the drop size distribution and likely produce a much larger standard deviation value for the total spray (compared to the spray's center-view only). Effervescent sprays, however, do not show a rim effect; thus, the drop size distribution, as measured from the central portion of the spray, is more representative of the entire spray (Figure 7).

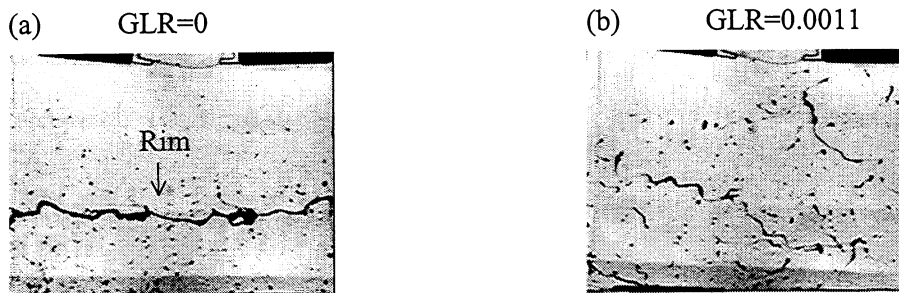


Figure 7: Outer region of spray showing (a) rim effect for liquid-only spray, and (b) no rim effect for effervescent spray (both sprays are at 750 mPa·s viscosity and 45 LPM).

Graphs of normalized standard deviations, as they varied with gas flowrate and viscosity, are shown in Figure 8. At 100 mPa·s, values are comparable to liquid-only spraying (≈ 0.25), decreasing at high gas flowrates due to video measurement limitations (i.e., when the MMD approaches 1 mm, the drop size distribution appears more narrow due to the lower detection limit of 0.3 mm diameter).

At 750 mPa·s, adding a small amount of gas causes a sharp decline in the normalized standard deviation (compared to liquid-only). Increasing the gas flow causes values to become closer to liquid-only spraying, then decline again due to measurement limitations. At low GLRs, the relatively uniform strands disintegrate into drops of more uniform diameter. Increasing the gas flowrate creates more variety of strand size and thickness, thus producing a wider drop size distribution more typical of liquid-only spraying. A similar trend was observed at 2800 and 10000 mPa·s; however, comparison to liquid-only spraying was not possible since a continuous liquid "rope" exited the nozzle. In general, it can be concluded that effervescent spraying produces a similar drop size distribution as liquid-only spraying, and in certain cases a narrower distribution (particularly when the spray rim effect is taken into account).

Spray Angle

Liquid-only spraying with the Vee-jet nozzle distributes the liquid in a sheet that fans out in relatively two-dimensional form. Effervescent sprays exit the nozzle in a more conical form. Increasing the GLR causes an increase in the spray fanning-out angle (shown qualitatively in Figure 4; quantitatively in Figure 9). Liquid viscosity acts as a resistance to changes in momentum; thus, for a given GLR, increasing viscosity causes a decrease in spray angle (as shown in Figure 9).

The spray "sheet-thickness" angle (as measured from a view perpendicular to the fanning-out view) is zero for liquid-only spraying (a flat sheet); whereas effervescent spraying shows a relatively constant

spray angle of about 60° (at a GLR > 0.003) that is relatively unaffected by liquid flowrate, viscosity, and GLR.

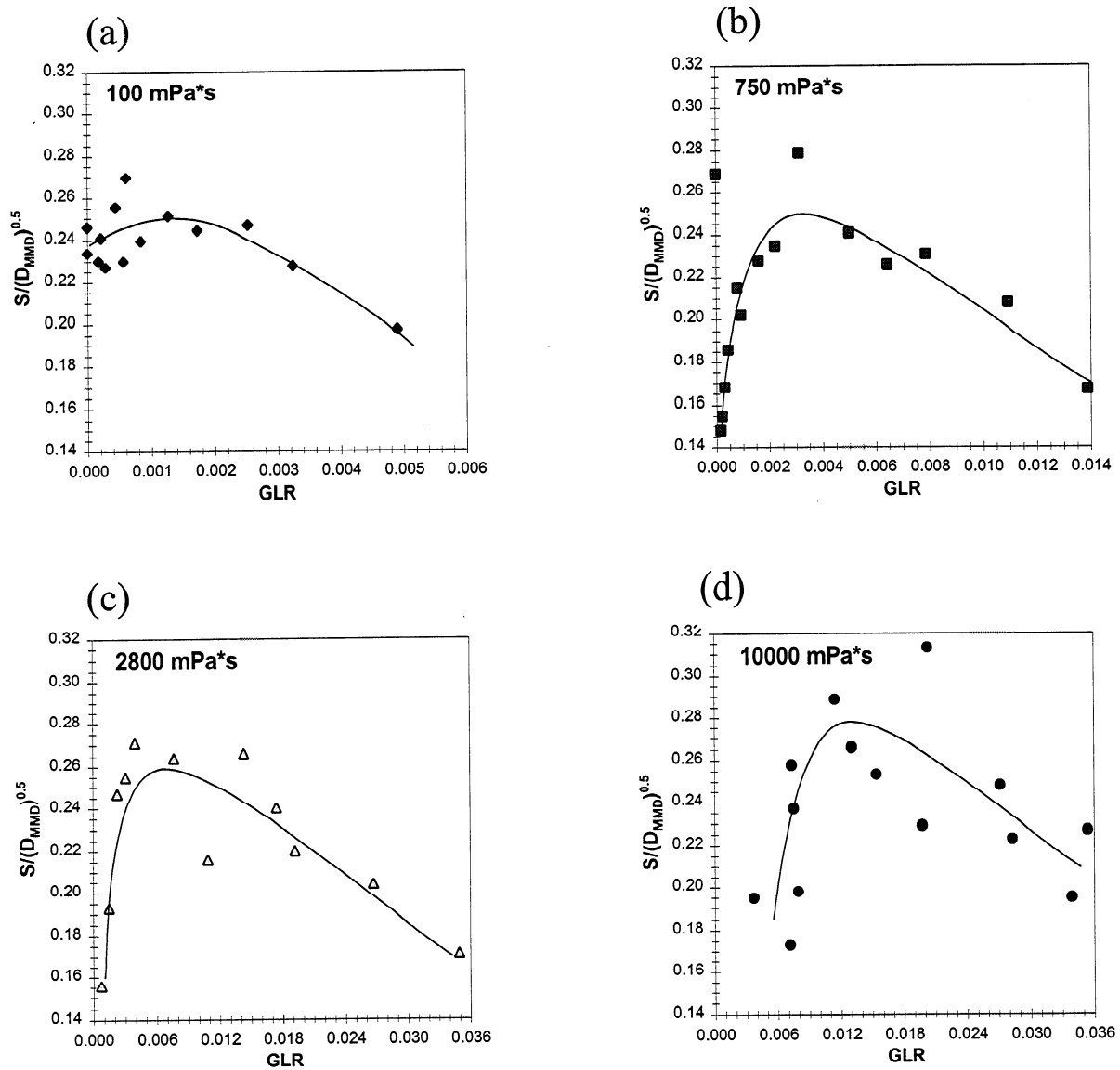


Figure 8: Drop size normalized standard deviation as a function of gas flowrate for effervescent sprays at viscosities of (a) 100 mPa·s, (b) 750 mPa·s, (c) 2800 mPa·s, (d) 10,000 mPa·s (Vee-jet nozzle at 30 LPM; trendlines are for graphical purposes only)

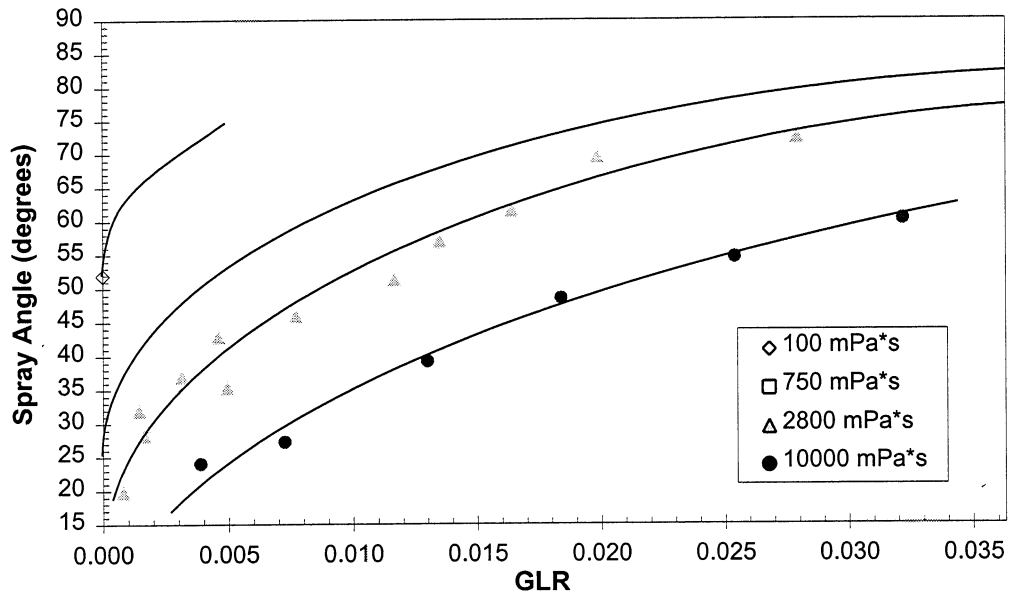


Figure 9: Spray angle (sheet fanning-out view) as a function of GLR and viscosity for effervescent spraying at 30 LPM with Vee-jet nozzle (trendlines are for graphical purposes only).

Nozzle Pressure

Nozzle pressure was measured at a point 27 mm upstream from the orifice; thus, the actual discharge pressure should be considered only slightly less than the measured pressure readings due to unaccounted frictional effects between the pressure port and nozzle orifice. Liquid-only spraying pressures were very stable with time, as opposed to unsteady pressure fluctuations observed in effervescent spraying (caused by bubble explosions at the nozzle orifice).

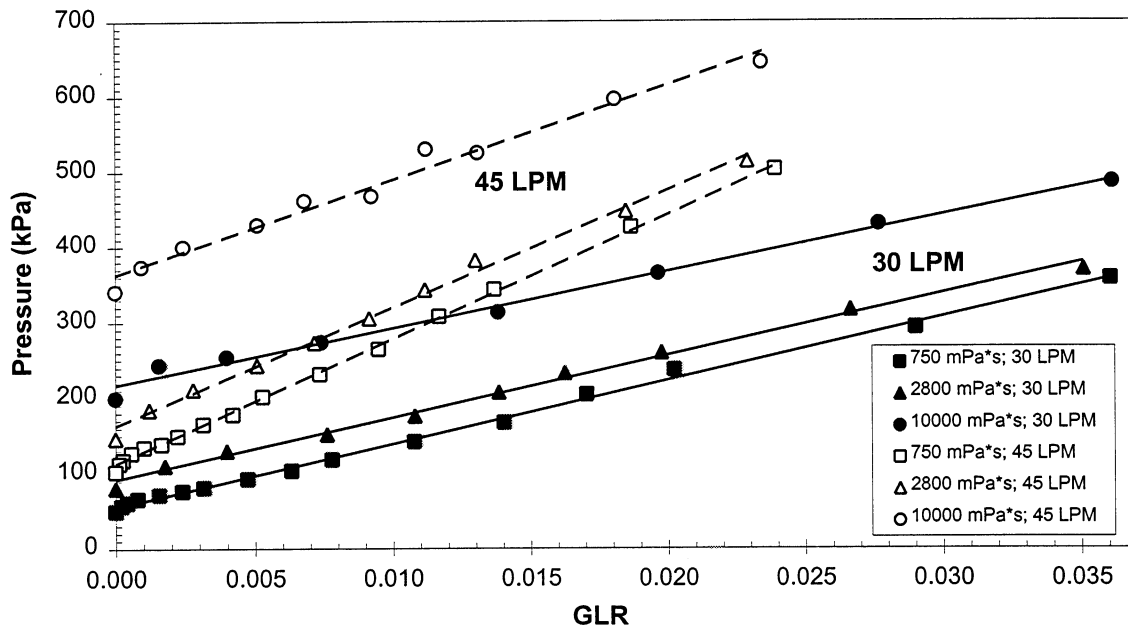


Figure 10: Nozzle pressure as a function of GLR and Viscosity for Vee-Jet nozzle.

Average nozzle pressure results are shown in Figure 10. As expected, nozzle pressure increases with gas flowrate, viscosity, and liquid flowrate. Increasing the gas flowrate causes an increase in nozzle flow void volume, subsequently resulting in less volume for liquid flow, and thus causing higher frictional pressure losses in the nozzle. The slope of the pressure vs. GLR linear curve was found to be relatively constant for the different viscosity levels tested, depending on the liquid flowrate. When spraying with the Vee-jet nozzle and gas injection apparatus, an increase in the GLR by 0.001 caused the nozzle pressure to increase by about 7.7 kPa for 30 LPM liquid flow, and about 15.5 kPa per 0.001 GLR at 45 LPM.

Conclusions

- Results from this study show that liquids that are normally too viscous to spray (using a sheet-producing type nozzle) can be sprayed effervescently to produce drops in the desirable range for recovery boiler operation (MMD = 2-4 mm).
- Effervescent spraying enabled an effective means of independently controlling the spray drop size by adjusting the injected gas flowrate (as indicated by the GLR; the gas/liquid mass ratio). The level of gas required to produce a particular drop size MMD varied depending on the liquid viscosity and flowrate.
- Previous research on black liquor spraying recorded a decrease in drop size when flashing occurred. Results from this study show that effervescent spraying at low viscosity (100 and 750 mPa·s) and at low GLR resulted in an unexpected increase in drop size compared to liquid-only spraying. At a low GLR (≈ 0.0004), the drop size MMD increased by approximately 50 percent compared to liquid-only spraying. The mechanism for producing larger drops appears to be initiated by the gas induced creation of waves of liquid strands that subsequently form larger drops (as compared to the sheet perforation mechanism for liquid-only sprays).
- Effervescent spraying produced a drop size distribution best represented by a square-root-normal function, similar to previous black liquor spraying studies. The normalized standard deviations showed no significant difference between effervescent spraying and liquid-only spraying. It should be noted, however, that liquid-only sprays were observed to have an outer “rim” of liquid not found in the effervescent sprays. Although not included in drop size measurements, the rim would be expected to increase the normalized standard deviation values. Thus, the actual drop size distribution for liquid-only spraying may be wider compared to effervescent spraying in an overall spray comparison at similar viscosity (≤ 750 mPa·s).
- The angle of liquid distribution from the nozzle increased as GLR and/or liquid flowrate increased, and decreased as liquid viscosity increased. Compared to liquid-only spraying, the liquid exiting the nozzle was not in a flat sheet form, but rather an elliptical cone shape.

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