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Effervescent Spraying: A New Approach to Spraying High Solids Black Liquor

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EFFERVESCENT SPRAYING: A NEW APPROACH TO SPRAYING HIGH SOLIDS BLACK LIQUOR

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ABSTRACT

Effervescent spraying is introduced as an innovative method for spraying high solids black liquor at temperatures below its flashing point. In its simplest form, it involves injecting gas at some point upstream of the nozzle orifice, such that a dispersed-bubbly flow is produced. Upon exiting the nozzle, the gas bubbles explode, shattering the liquid into ligaments and drops. The level of gas required to produce a particular mean drop size varies depending on the liquid viscosity and flowrate; i.e., lower liquid flowrates and higher viscosities require more gas to attain a specified drop size. Liquid viscosities ranging from 100 to 10000 mPa·s were evaluated using a model fluid and industrial-scale, commercially available black liquor nozzles. It is concluded that effervescent spraying enables control of the spray drop size, independent of liquor flowrate, percent solids, temperature, and nozzle orifice size.

INTRODUCTION

This paper introduces an innovative method for delivering high solids black liquor to a recovery boiler - effervescent spraying. Introduced in 1989 (for applications such as aerosol and spray coatings), effervescent spraying can be defined as a process in which a gas (air in combustion applications) is injected directly into the flowing liquid at some point upstream of the nozzle orifice in such a way as to produce a bubbly two-phase flow¹. As the mixture flows through the spray nozzle orifice, the rapidly expanding bubbles break the liquid into ligaments and drops, forming a spray. The relatively small-scale applications previously researched targeted drop sizes in the 10-100 micron range using a liquid flowrate orders of magnitude smaller than a typical black liquor spraying application. The objective of the present research is to develop an effervescent spraying process that will enable spraying of high solids black liquor (>80% solids), at temperatures *below* the liquor's boiling point, with means to control drop size *independent* of varying nozzle size, liquor flowrate, or temperature.

Since the injected gas is the primary force causing liquid break-up, it is understandable that the two-phase flow characteristics prior to spraying should have a direct influence on the observable and measurable spray properties, such as average drop size, drop size distribution, and mass distribution. The injected gas, therefore, is the means by which the average spray drop size is controlled. The amount of gas required to attain a specific drop size will depend on variables such as liquid flowrate and viscosity; however, since the gas flow is controlled independently, drop size should be controllable as a function of gas flow. For black liquor combustion or gasification applications, the gas used could be air or steam.

In the recovery boiler, drop size is an important parameter in order to maintain the proper balance of in-flight and char-bed combustion. Previous research² has shown, for a variety of nozzle types with black liquor of moderate solids (<250 mPa·s), that the spray drop size is most influenced by liquor velocity, producing a drop size with a mass median diameter (MMD) of 2-3 mm. However, with increasing viscosity (>500 mPa·s), the spray drop size is expected to increase, eventually forming a continuous, unbroken stream of liquid from the nozzle (termed "roping"). Present commercial black liquor nozzles do not provide a means for independently controlling drop size distribution.

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 bank sections. Very large drops cause poor combustion efficiency and can lead to potentially dangerous cool zones in the char bed at the bottom of the furnace.

The distinct advantage of effervescent spraying is in its potential to spray black liquor of very high viscosity. Most mills still concentrate their black liquor to 70-75 percent solids before spraying; however, mills with a recovery boiler capacity limitation and/or environmental emission concerns are often interested in increasing the 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 nozzle orifice, flashing occurs. Previous research (with moderate solids liquors) 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^{3,4}. Where and how flashing occurs in the spray nozzle is, for the most part, uncontrollable; thus, using liquor temperature to control drop size may result in spray properties that are unsteady and unpredictable.

EXPERIMENTAL

A schematic of the experimental set-up is shown in Figure 1. The central component of the system is the DOE spray chamber, which has been described elsewhere^{2,3}. Starting at the liquid storage tank (which holds approximately 1500 liters), the liquid is fed to a 4-stage Moyno pump, through an electromagnetic flowmeter, ending with the spray nozzle, which is oriented to deliver a spray sheet in a horizontal direction parallel to the viewing windows. Nitrogen gas is injected into the liquid approximately 0.1 meter prior to the nozzle orifice, with flow being measured by a Hastings mass flowmeter. Pressure transducers are located before gas injection and just before the spray nozzle orifice. Liquid temperature is measured just before gas injection, thereby accounting for any small viscosity changes. Time is required after spraying to allow the entrained gas bubbles to separate from the liquid, after which the liquid is pumped from the spray chamber back to the storage tank for the next experimental run (higher viscosities require more time for phase separation).

Corn syrup was used as a model fluid for black liquor, since preliminary testing showed its rheology to be very similar to black liquor, but with much better physical property uniformity and stability. Using charts provided by Zaman and Fricke⁵, a wide range of viscosities can be calculated for high solids black liquor; ranging from 400 to 10000 mPa·s for 80-85% solids at its boiling point temperature. Thus, four levels of viscosity were evaluated (100,

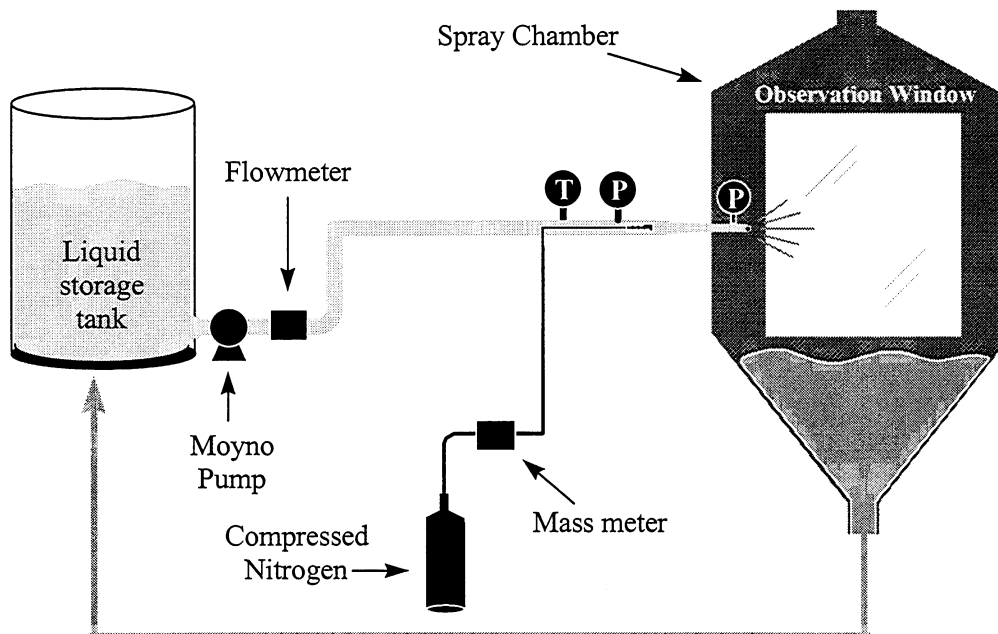


Figure 1: Schematic of Experimental Spraying System.

750, 2800, 10000 mPa·s), in addition to two liquid flowrates (30 and 45 liters/min) and a range of gas flowrates for their effects on the spray properties; including the drop size MMD, drop size distribution, and spray angle.

Initial experiments showed that the location of gas injection was critical to the quality of spray produced. Injecting gas too far upstream from the nozzle resulted in slug/plug two-phase flow, which subsequently caused intermittent bursts of fine drops and large globules of liquid exiting the nozzle. The optimum point of gas injection was determined to be as close to the nozzle orifice as possible, while still allowing a uniform gas/liquid dispersion before spraying.

Two different methods of gas injection/mixing were evaluated (Figure 2). The sparger method simply injects the gas through a cylindrical sparger, allowing the velocity of the liquid to detach bubbles as they form on the sparger walls and disperse them into the liquid before spraying. The static-mixer method injects gas through many small holes in the pipe wall, then distributes the gas through a 10 cm length of static-mixer (Koch Engineering SMX 25mm diameter) before the mixture exits the spray nozzle. Although effervescent sprays were effectively produced using a nozzle with a plain circular orifice, the majority of experiments were performed using spray nozzles more commonly used in recovery boilers; namely, a vee-type (Spraying Systems Vee-Jet 65200; 8.7 mm diameter), and splashplate (Babcock & Wilcox 12/35; 9.5 mm diameter).

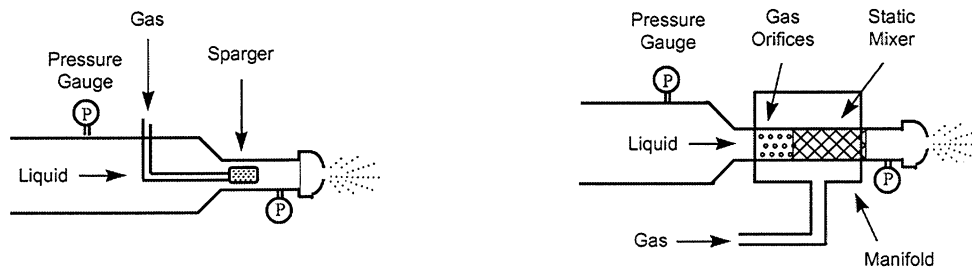


Figure 2: Gas Injection/Mixing - Sparger and Static-Mixer Methods.

Qualitative and quantitative spray results were obtained by analyzing video images produced by a high shutter-speed video camera (Xyberon model ISG-250). Drop size measurements were made by positioning the camera approximately 1.3 meters horizontally from the spray nozzle end. A spray separation device was created to limit the quantity of spray within the camera's depth of field, and maintain a clean viewing window. 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 nonspherical drops appear as such). Then, after calculating its volume, the diameter of a sphere with equal volume is calculated - this being referred to as the equivalent drop diameter. For each set, between 1,000 and 10,000 drops were measured, providing information to represent the drop size MMD and drop size distribution.

Spray angles were determined by observing the near-nozzle spray from the top and side view perspectives. Since effervescent sprays are inherently discontinuous, an average image of 16-32 individual images was produced for spray angle determination. Images of the near-nozzle spray also provided qualitative information of the drop formation process involved in effervescent spraying, as compared to conventional (liquid-only) spraying.

RESULTS

Drop Size MMD

The primary objective of this research was to determine how drop size MMD was affected by effervescent gas flowrate at various liquid viscosity levels. Figure 3 shows these effects for 30 LPM liquid flow using the static-mixer gas injection/mixing apparatus with the Vee-Jet nozzle. These results indicate that:

- At low viscosity levels (100 and 750 mPa·s), a low level of added gas (represented by the gas/liquid mass ratio) causes an initial increase in drop size, then as gas flow increases, a relatively steady decrease in drop size.
- At higher viscosities (2800 and 10000 mPa·s), increasing gas flow decreases drop size such that at the highest gas flowrate, little difference exists between viscosity levels. With no gas added, a continuous stream of liquid is produced; thus, a certain amount of gas is required to produce individual drops.
- At any particular gas flowrate level, increasing viscosity results in a larger drop size.

It would appear from Figure 3 that the MMD levels out near 1 mm as the gas flowrate was increased, even at the highest viscosity. This is by no means believed to be true; however, video camera and analysis limitations did not allow drops smaller than about 0.4 mm diameter to be accurately detected. Although the mass fraction of these tiny drops is very small at the lower gas flowrates, higher gas flowrates should cause a higher mass fraction of these tiny undetectable drops. Thus, MMD data points that appear to have leveled out at about 1 mm are probably slightly higher than they should be.

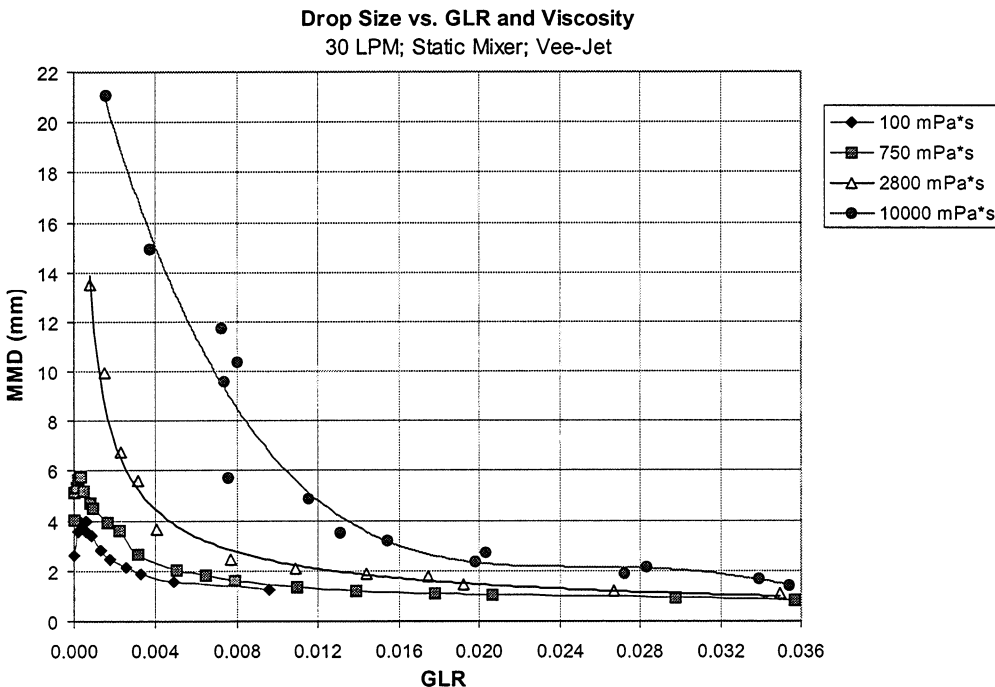


Figure 3: Drop Size MMD as a function of gas flowrate and liquid viscosity for effervescent spraying (30 LPM; static-mixer; Vee-Jet nozzle).

The effect of GLR on drop size at a liquid viscosity of 100 mPa·s is shown in Figure 4. The increase in drop size at low GLRs (compared to conventional liquid-only spraying) was unexpected, since most previous research concerning black liquor flashing reported a smaller drop size than spraying without flashing. However, Helpio

*et al.*⁴ did show a small increase in MMD at the start of flashing using a splashplate nozzle. Qualitative images of the near-nozzle spray structure provides a possible explanation for the increase.

In conventional liquid-only spraying, strands are formed after the liquid sheet disintegrates, due to aerodynamic and surface tension forces. Both sheet perforation and wave disintegration have been proposed as mechanisms leading to strand formation⁶. However, with a small amount of gas added, the liquid sheet disappears, and is replaced by (somewhat) uniformly distributed strands exiting directly from the nozzle orifice, oriented perpendicular to the direction of the spray flow (as shown in Figure 5). As discussed by Crapper *et al.*⁷, 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, verifies the unsteady forces being imposed on the liquid.

The increase in drop size at low GLRs may be a result of the thicker strands, compared to what are produced from liquid sheet disintegration. Increasing the GLR or liquid flowrate increases the effective velocity of the liquid, and reduces the strand diameter and spacing, subsequently producing smaller drops. Liquid strand disintegration appears to occur closer to the nozzle as GLR increases, and the strands become oriented in a parallel direction to the spray flow. Increasing viscosity causes thicker strands that require relatively higher gas flowrates to disintegrate into drops (as shown in Figure 5).

The two methods of gas injection (Figure 2) were equally effective in controlling drop size with GLR for viscosities up to 2800 mPa·s. However, at the highest viscosity level (10000 mPa·s), the sparger method produced larger drop size MMDs compared to similar conditions using the static-mixer method (Figure 6). The larger drop sizes can be explained by the less uniform gas dispersion created by the sparger apparatus at high viscosity, resulting in less efficient usage of the gas expansion energy on liquid breakup. At lower viscosity levels, sparged gas more freely disperses into a dispersed-bubbly flow-regime without needing a static-mixer.

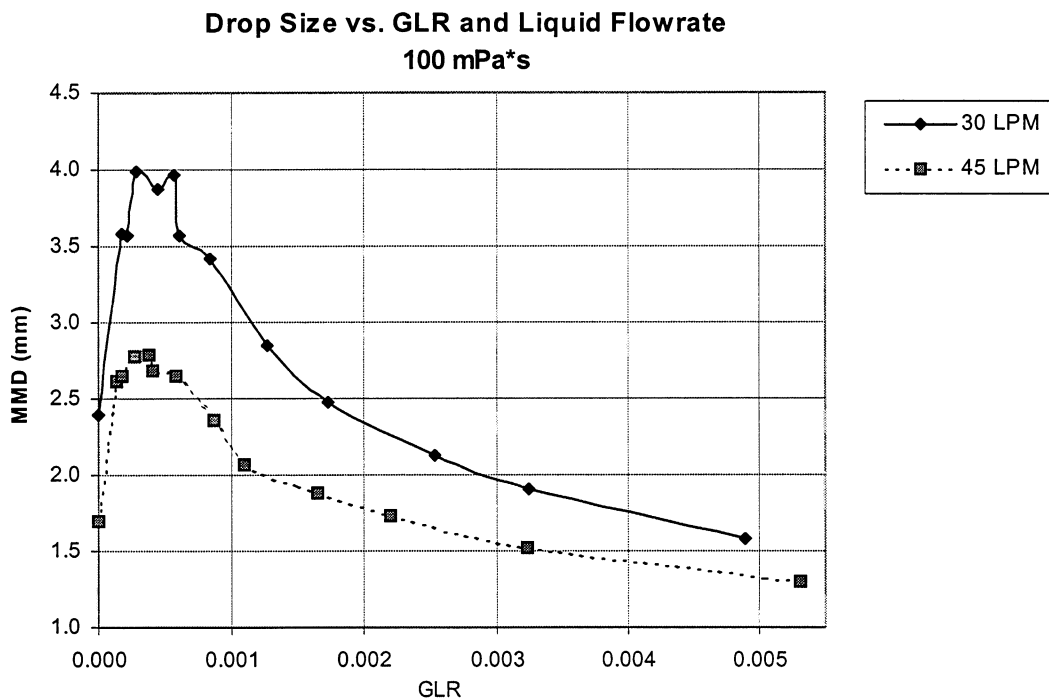


Figure 4: Drop Size MMD as a function of GLR and Liquid Flowrate at 100 mPa·s viscosity (Vee-Jet).

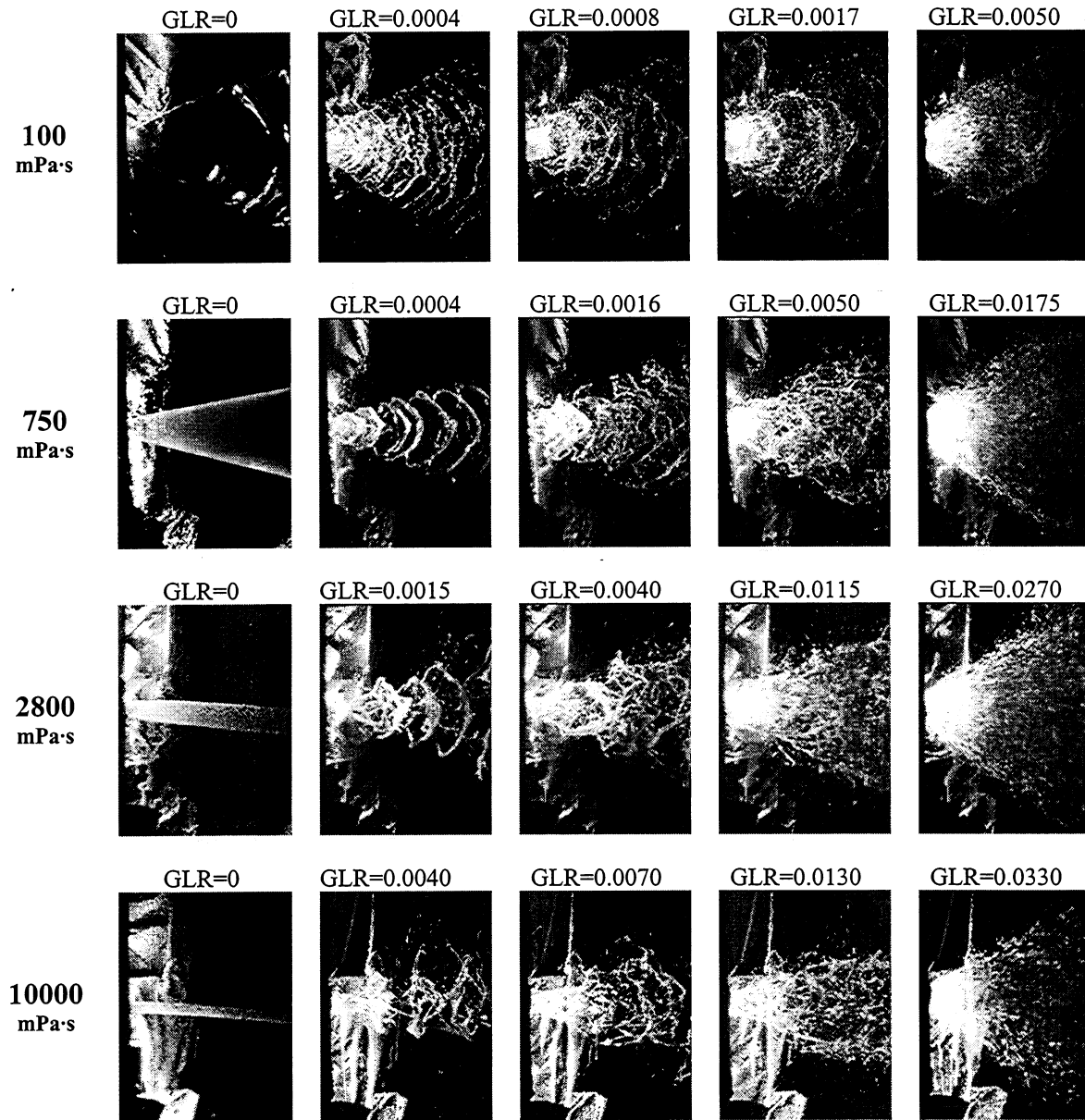


Figure 5: Images of near-nozzle spray at increasing gas flowrate (30 LPM; static-mixer; Vee-Jet nozzle).

Effervescent spraying with the splash-plate nozzle proved to be less effective than with the Vee-Jet nozzle. At low viscosity (100-500 mPa·s), increasing the GLR caused a decrease in drop size; however no initial increase was measured at low GLRs (compared to liquid-only spraying). At higher viscosity levels, drop size control became less effective; i.e., increasing GLR resulted in a relatively smaller change in MMD compared to the Vee-Jet nozzle. Increasing viscosity also caused an increased amount of undisrupted liquid in the form of large clumps (>10 mm) to fall off the bottom of the splash-plate. At the highest viscosity tested (7000 mPa·s), liquid did not adequately break-up, even at the highest gas flowrate tested (GLR=0.04), forming only large clumps that fell before reaching the viewing area in the spray chamber.

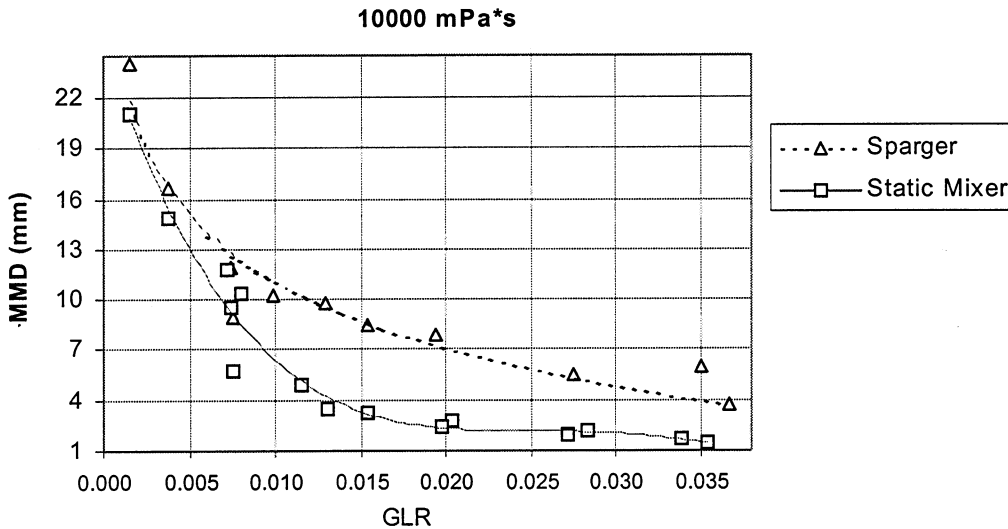


Figure 6: Drop Size MMD as a function of GLR for different gas injection/mixing methods at 10000 mPa*s (Vee-Jet; 30 LPM).

Drop Size Distribution

Previous research for black liquor 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 the drop size data in this study, the square-root normal distribution still provided the best mathematical fit overall for both liquid-only and effervescent spraying.

An 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).

Graphs of normalized standard deviations, as they varied with gas flowrate and viscosity, are shown in Figure 7. At 100 mPa*s, values are comparable to liquid-only spraying ($\gg 0.25$), 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 about 0.4 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. A small amount of injected gas causes liquid strands of fairly uniform thickness and spacing to exit the nozzle orifice, subsequently disintegrating into drops of more uniform diameter. Increasing the gas flowrate appears to create more variety of strand size and thickness, thus producing a wider drop size distribution.

Normalized Standard Deviation vs. GLR and Viscosity

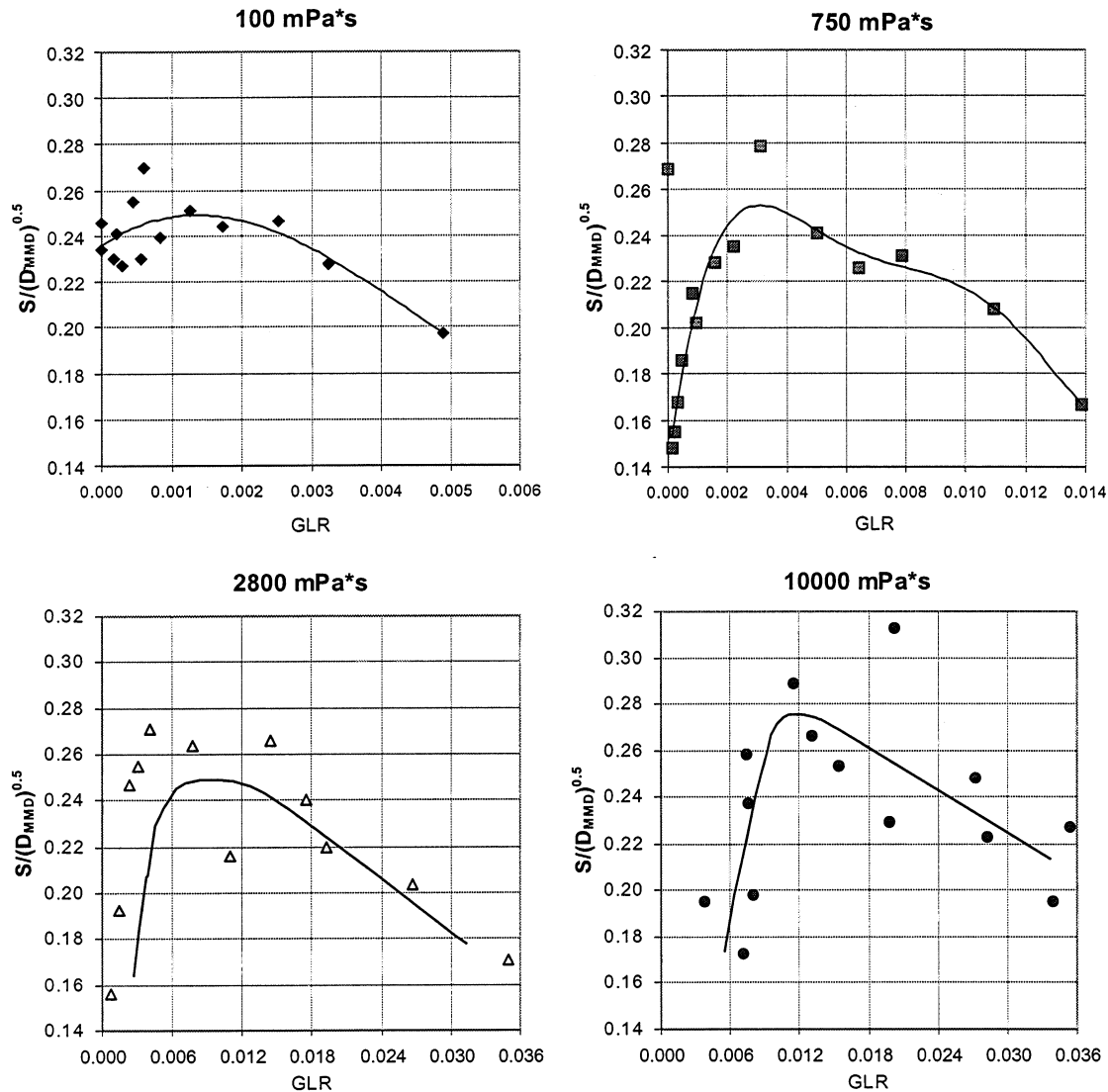


Figure 7: Drop Size Normalized Standard Deviation as a function of Gas Flowrate and Viscosity (Vee-Jet; static-mixer; 30 LPM).

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, but in cases of intermediate viscosity with low GLR it produces a narrower distribution (particularly when the spray rim effect is taken into account).

Spray Angle

Conventional sprays distribute 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 both the fanning-out angle, and the "sheet-thickness" angle. In general, increasing viscosity or decreasing liquid flowrate causes a decrease in spray angles. Figure 8 shows the effect of GLR and liquid viscosity on spray angle for the Vee-Jet nozzle.

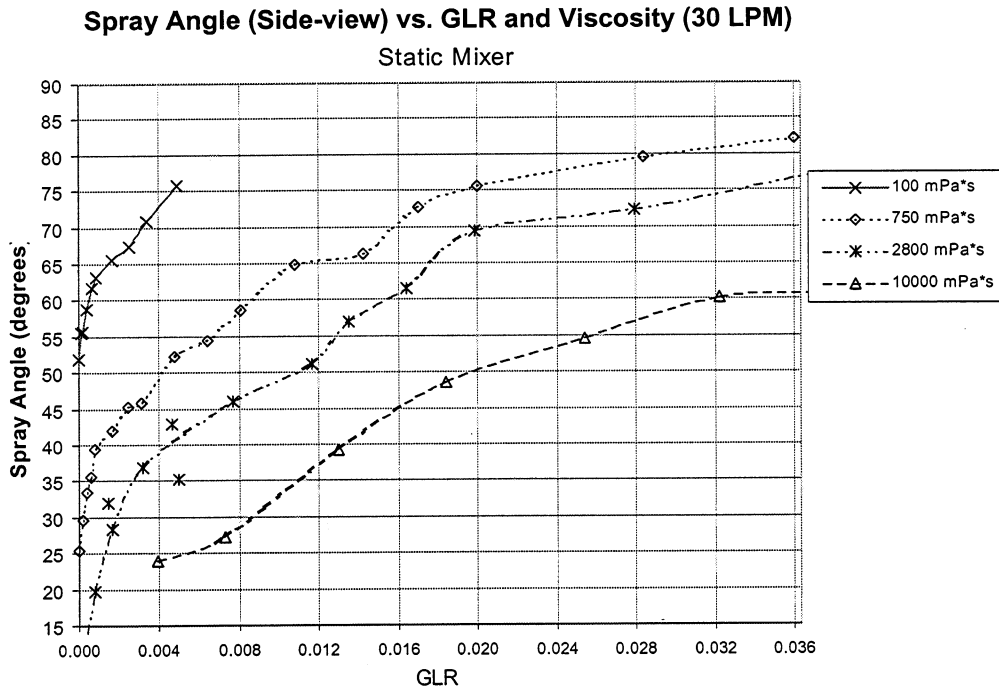


Figure 8: Spray Angle (sheet fanning-out view) as a function of GLR and Viscosity (30 LPM, static-mixer, Vee-Jet nozzle).

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. This section presents the average pressure measured over a 10 second period of time.

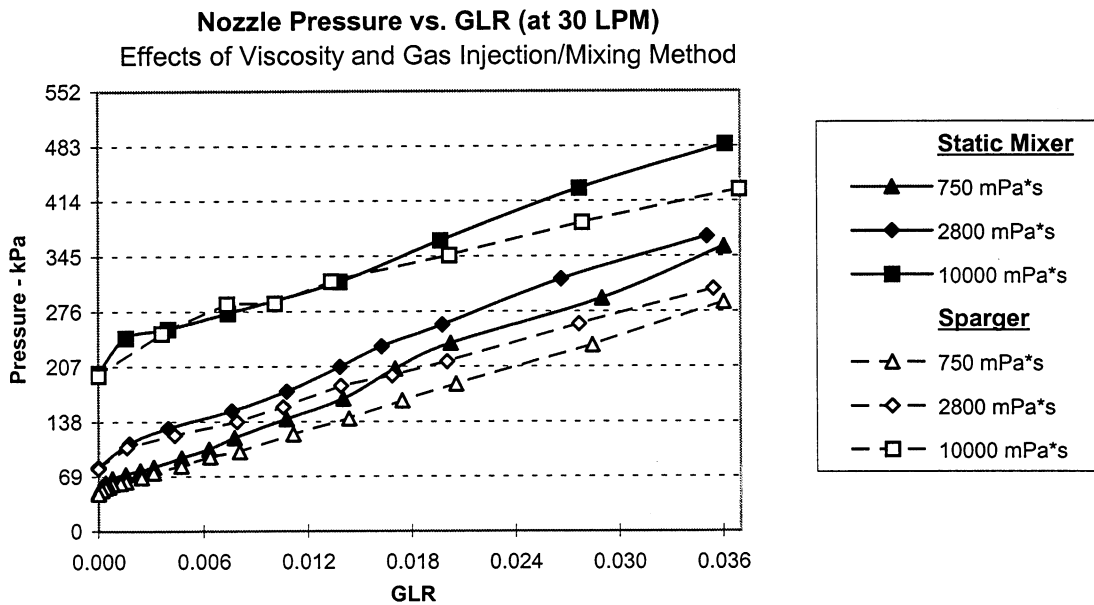


Figure 9: Nozzle pressure as a function of GLR and Viscosity for Vee-Jet nozzle at 30 LPM.

Average nozzle pressure results are shown in Figure 9. As expected, nozzle pressure increases with gas flowrate, viscosity, and liquid flowrate. Increasing the gas flowrate causes an increase in two-phase void volume, subsequently resulting in less volume for liquid flow, and thus causing higher frictional pressure losses. The slope of pressure vs. GLR was found to be relatively constant for the different viscosity levels tested, depending on the liquid flowrate and method of gas injection/mixing. When spraying with the static-mixer 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 liquid flow. Respective slope values for the sparger method were similarly consistent, but about 20 percent lower; most likely due to the less uniform gas/liquid distribution created with the sparger apparatus.

CONCLUSIONS

- Effervescent spraying with the Vee-Jet nozzle enabled an effective means of independently controlling the spray drop size by adjusting the injected gas flowrate. The level of gas required to produce a particular drop size MMD (mass median diameter) varied depending on the liquid viscosity and flowrate; i.e., lower liquid flowrates and higher viscosities require more gas to attain a specified drop size. Experimental results with 10000 mPa·s viscosity show that drop sizes ranging anywhere from large clumps of liquid to a fine mist can be produced by varying the gas/liquid mass ratio (GLR).
- Previous research on black liquor spraying recorded a decrease in drop size when flashing occurred; effervescent spraying was initially predicted to show a similar decline in drop size MMD as GLR increased. Results from this study show, however, that effervescent spraying at a low viscosity (100 mPa·s) and low GLR showed an unexpected increase in drop size compared to liquid-only spraying. At low GLRs (≈ 0.0004), the drop size MMD increased by over 60 percent compared to liquid-only spraying; at higher GLRs, the drop size MMD reduces to a level equal to liquid-only spraying, then decreasing to sub-millimeter size drops as GLR increases above 0.01. 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).
- For effervescent spraying at a low viscosity, a lower liquid flowrate enabled a wider range of drop size MMDs to be produced compared to a higher flowrate. For example, at 100 mPa·s viscosity and 30 LPM liquid flow, drop size MMDs from 4 mm to the minimum size detectable were produced by varying effervescent gas flowrate; compared to a maximum MMD of about 2.75 mm for 45 LPM liquid flowrate. Thus, for optimum control of drop size, it appears important to consider nozzle orifice size with respect to the liquid flowrate desired.
- 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 that was composed of much larger drops and/or a semi-continuous stream of undisrupted liquid. Although not included in drop size measurements, the rim would be expected to increase the normalized standard deviation values of liquid-only sprays. Thus, since effervescent sprays at low viscosity (750 mPa·s and lower) did not exhibit a rim effect, the actual distribution in drop sizes may be narrower than liquid-only sprays, in an overall spray comparison at similar viscosity.
- In general, 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.
- Effervescent spraying with the splashplate nozzle proved to be less effective than with the Vee-Jet nozzle. Although drop size MMD decreased with increasing GLR, a smaller range of drop size MMDs were possible. Also, at higher viscosity levels, increased amounts of undisrupted globules fell a short distance from the nozzle.
- At high viscosity (>2800 mPa·s), a static-mixer is needed for creating a dispersed two-phase flow prior to spraying, thereby resulting in more uniform spray characteristics.

- Extension of the effervescent spraying techniques to black liquor, including validation of the results presented here, awaits conversion of the experimental apparatus back to a black liquor spraying mode.

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