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High Mass Flowrate Effervescent Spraying of a High Viscosity Newtonian Liquid

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Summary

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 (≥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 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 (2-3 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 2-3 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 percent 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. After examining 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, however, were performed with the objective of producing very small drops (<50 μm) at different flowrates and viscosity than what would be encountered with a full-scale high-solids black liquor where the optimum drop size is believed to be in the 2-3 mm size range. Black liquor at 80-85% solids and near its boiling point behaves as a Newtonian fluid (mainly) with a viscosity ranging anywhere from 0.3 to greater than 30 Pa*s (300-30,000 centipoise (cp)),[5] and typical nozzle flowrates range from 75-280 l/min (20-75 gal/min).[6]

Experimental Approach and Technique

The experiments in this study were performed using 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,[7] although modifications were made for this study to handle the higher liquid viscosity, gas requirements, and different nozzle designs. Qualitative and quantitative spray results were obtained by analyzing video images produced by a high shutter speed camera. The camera position 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. The image area is 84 mm tall by 112 mm wide, giving each pixel an area of 0.032 mm^2. Image analysis routines were developed to discern drop images, which were then analyzed and converted into equivalent drop diameters. The lower limit of drop detection was set at 4 pixels (0.13 mm^2); below this size, it was impossible to accurately discern drop shape or size. For each set, between 2000 and 10,000 drops were measured (20 frames).

Liquid flowrates ranged from 25-30 l/min, gas flowrates up to 850 SLM (30 SCFM), and nozzle pressures below 20.7 bar (300 psig). Liquid and gas flowrates were measured using electromagnetic and gas mass flowmeters, respectively. Liquid viscosity was measured using a Brookfield viscometer (model RVT). Although most experiments were run at room temperature, the liquid temperature was measured just before spraying thereby accounting for any small viscosity changes.

An industrial black liquor spray nozzle (Spraying Systems Vee-Jet 65/200; equiv. diameter≈8.7mm) was qualitatively evaluated and compared to effervescent spraying using two different gas-injection/mixing methods (termed methods A and B, shown in Figure 2). Method A injects the gas through an inner cylinder (sparger) with many tiny holes (1 mm dia.); the sparger diameter = 13 mm and the inside pipe diameter (ID) = 20 mm. The concept behind this design was that the increased velocity of the liquid through the flow constriction would increase detachment of small gas bubbles from the sparger, subsequently dispersing with the liquid in the mixing zone before spraying. Method B injects the gas through many small holes in the pipe wall (gas hole dia. = 0.74 mm; pipe ID = 25 mm) then distributes the gas through a 10 cm length of static mixer (Koch Eng. Co.; SMX type; 25 mm dia.). Following the static mixer, the gas mixture is passed through a "mixing zone" (of the same length as method A) before spraying. In both methods, the nozzle exit orifice is a circular hole of either 7.5 or 5 mm diameter drilled into a PVC end cap.

Results

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. Images of a V-jet spray for liquids of increasing viscosity are shown in Figure 1. At low viscosity, the liquid sheet breaks up quickly after exiting the nozzle, forming nearly spherical drops (MMD ≈ 2.2 mm) by the time they reach the video imaging area. As viscosity increases, however, the liquid sheet disintegration process is significantly slowed, eventually forming a continuous stream from the nozzle (recovery boiler operators would classify this as "roping").

Effervescent spraying does not rely on forming a liquid sheet for disintegration; rather, atomization is accomplished by the explosion of gas exiting the nozzle; therefore, a plain orifice nozzle can be used. It should be noted that spraying with a plain orifice *without* adding atomizing gas produces a continuous, undisrupted stream (roping), regardless of liquid viscosity (for flowrates and pressures typical of recovery boiler spraying).

Effervescent spraying methods A and B are schematically shown in Figure 2, along with video images of their sprays for nozzle diameters of 7.5 and 5 mm, respectively. The injected gas to liquid mass ratio (GLR) is shown in each case. Method A clearly produced more liquid strands than method B, as well as an apparently larger drop size. This is most likely due to method B better distributing the gas into the liquid (via static mixer) prior to spraying. The relatively smaller drops produced for the 5 mm nozzle diameter sprays are due to the higher operating pressure compared to the 7.5 mm orifice (≈200 psi vs. ≈100 psi).

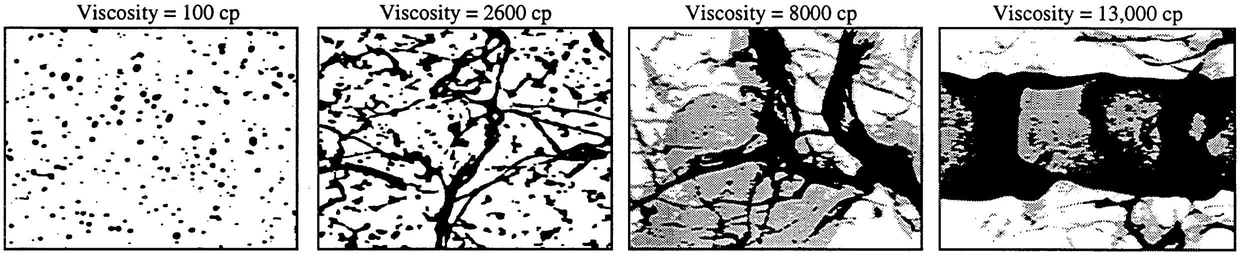

Figure 1: Effects of viscosity on sheet disintegration using conventional spray nozzle (Vee-Jet nozzle; ≈ 30 l/min).

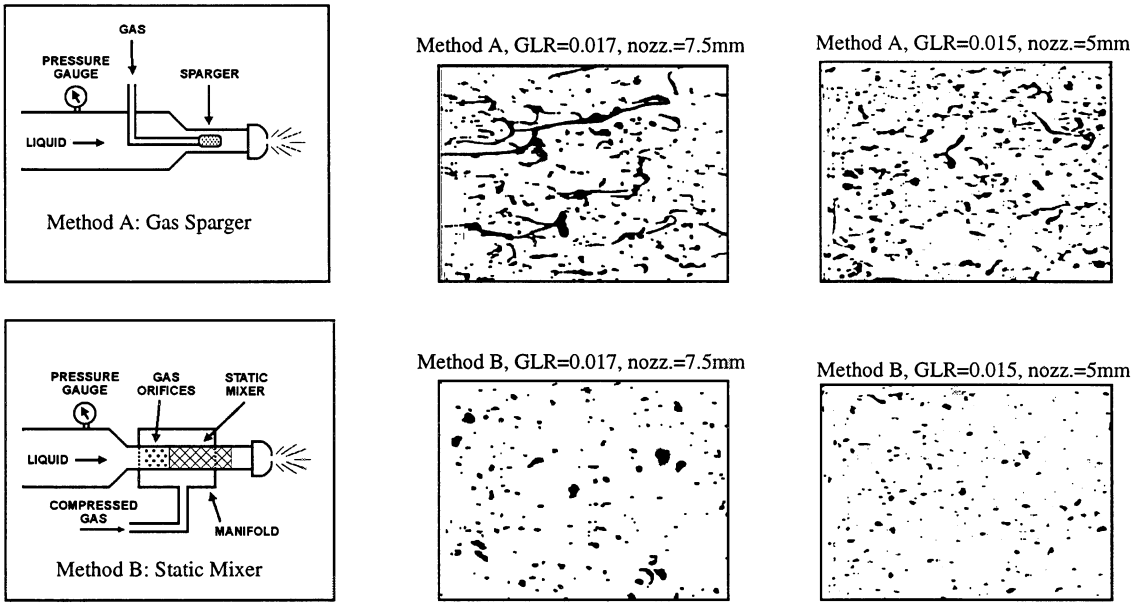

Figure 2: Comparison of effervescent spraying methods A and B (nozzle dia. = 7.5 and 5 mm; visc. = 6000 cp).

The effect of increasing the gas flowrate (holding liquid flow at 30 l/min) is shown in Figure 3 for viscosities of 500, 1000, and 7000 cp (using effervescent spraying method B only). The decrease in drop size with increasing GLR is quite clear; also, for similar GLR, an increase in viscosity produces larger and more nonspherical drops. However, at the highest level of GLR, viscosity appears to have little effect, producing similarly small drops.

Quantifying Spray Image Data

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 nonspherical 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 from this point on as the equivalent drop diameter.

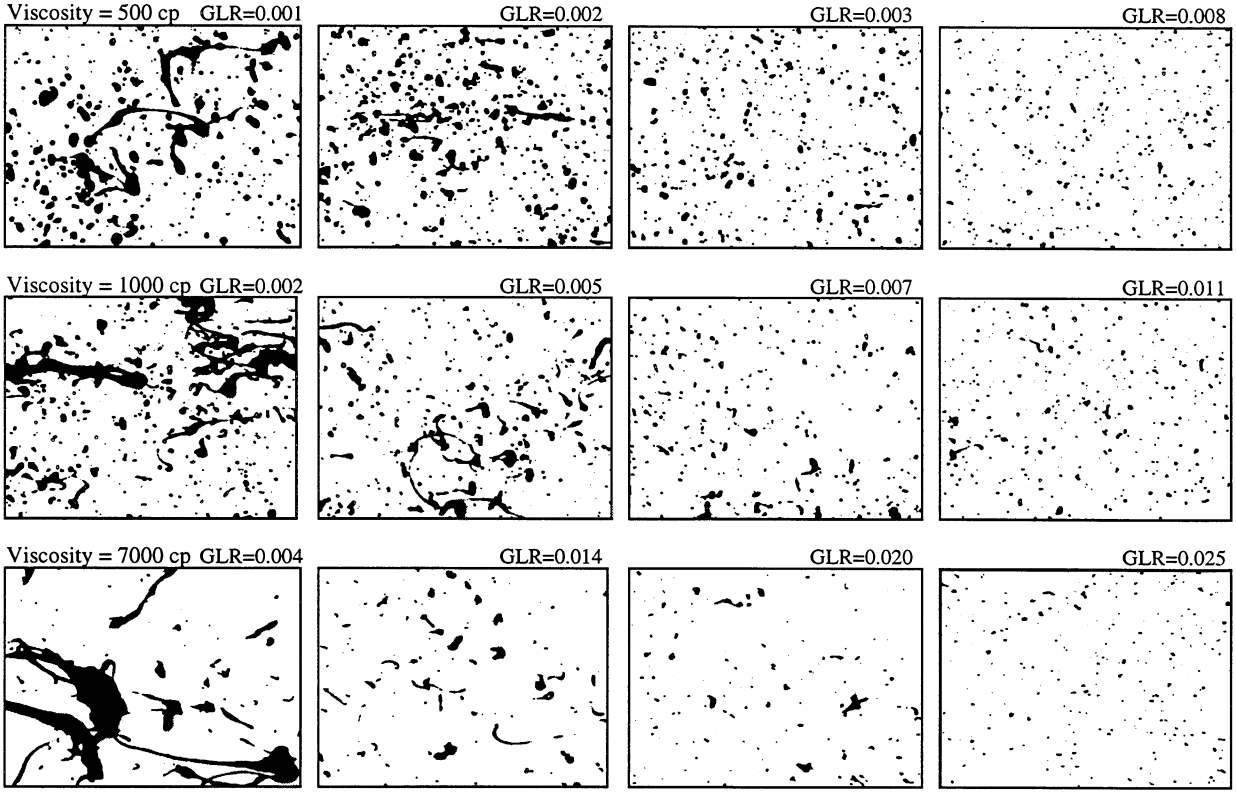

Figure 3: Effect of GLR and viscosity on effervescent spraying (liq. flowrate = 30 l/min, nozzle dia. = 7.5 mm).

Figures 4 and 5 show the spray drop size MMD and normalized standard deviation, as they vary with GLR and liquid viscosity. Results show that by adjusting the GLR, the spray can be controlled to produce a MMD drop size in the range of 1-3.5 mm. This can be compared to previous research (with normal % solids liquors) where a similar size nozzle (Vee-Jet), flowrate (30 l/min), and viscosity (283 cp) produced a MMD of 2.19 mm.[8] Thus, the effervescent process shows the capability of producing larger or smaller drops compared to conventional liquor spraying, independent of liquor flowrate.

The normalized std. dev. shown in Figure 5 is defined as the ratio of the std. dev. to the square root of the MMD for the equivalent drop diameters. This was applied because previous research[8] concluded that the black liquor drop size data (at normal % solids) best correlated to a square root-normal drop size distribution, and that the normalized std. dev. was fairly constant at 0.2. Results from this study show that the normalized std. dev. tends to be higher at low GLR and high liquid viscosity. At these conditions, it appears that increasing amounts of undisrupted liquid globules and strands are contained in the spray. These large globs skew the drop size distribution, and subsequently cause very high standard deviation values. Although not shown in this report, sprays containing a large quantity of glob/strands produce a poor fit to a square-root normal distribution. This suggests that either a different distribution characterization or an improved method for defining and converting globs into equivalent drop diameters is needed.

Discussion of Minimum Measurable Drop Size

It would appear from Figure 4 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 high GLR's[9]. Unfortunately, however, current video camera and analysis limitations do 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 GLR's, higher GLR's should cause a higher mass fraction of these tiny undetectable drops. Thus, results are probably slightly higher than they should be for MMD's 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.

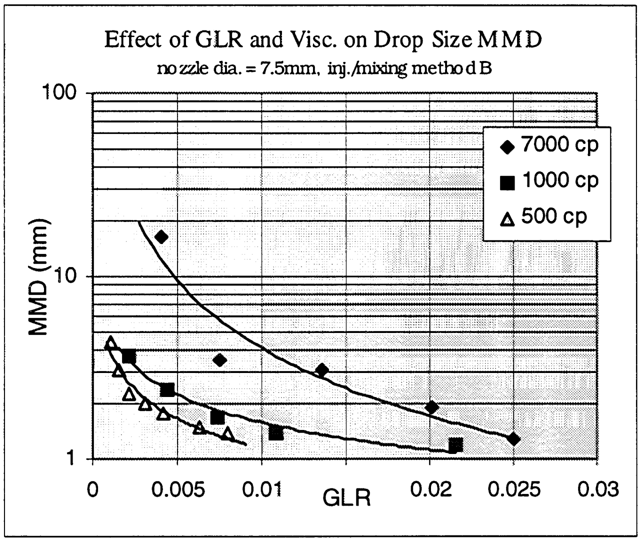

Figure 4: Effect of GLR and viscosity on MMD.

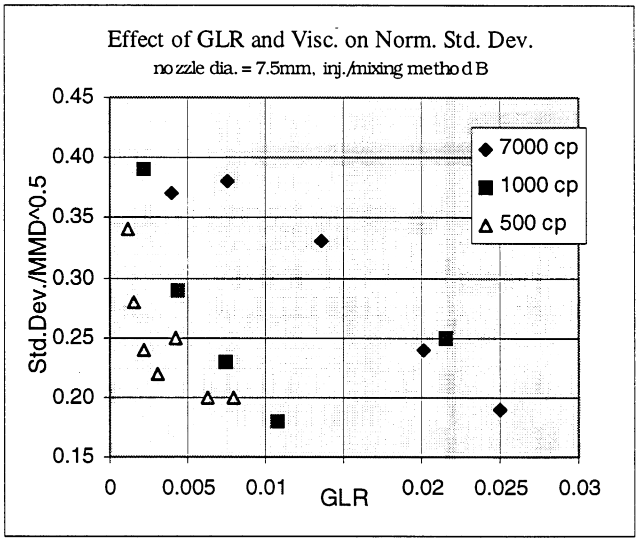

Figure 5: Effect of GLR and viscosity on normalized std. dev.

Conclusions

Although the reported results are only from preliminary testing, several conclusions can made:

- As liquid viscosity increases, forming drops by liquid sheet disintegration (conventional black liquor spraying technique) becomes ineffective.
- It appears that effervescent spraying can be applied at a range of liquid viscosity, to produce drop sizes (as indicated by equivalent MMD) typical of current recovery boiler operation (2-3 mm).

Other conclusions from these effervescent spraying experiments include:

⇒ Drop size is strongly affected by the GLR and liquid viscosity.

⇒ Spray properties appear to be influenced by the uniformity of gas/liquid mixture prior to spraying.

⇒ Drops become more nonspherical as viscosity increases and/or as GLR decreases. This makes it difficult (and possibly more inaccurate) to determine equivalent drop sizes with current techniques.

⇒ Unlike previous black liquor studies (at lower viscosity), the standard deviation (square-root normalized) is not constant at 0.2, suggesting a different drop size distribution characterization may be necessary for effervescent and flashing type sprays at low GLR's and/or high liquid viscosity.

Future research will more closely investigate the drop size distribution (including other spray characteristics) with respect to the interaction effects of the two-phase flow and liquid physical properties.

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