Effect of Viscosity on the Breakup Length of Liquid Sheets
Formed by Splash Plate Nozzles

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Abstract
An experimental investigation has been conducted to determine the effect of viscosity on the breakup length of liquid sheets formed by splash plate nozzles. Corn syrup solution with viscosity ranged between 1.0 mPa.s to 170 mPa.s is used. Four different atomization regimes can be described based on the flow Reynolds number: aerodynamic surface wave, laminar edge instability, turbulent edge instability, and sheet perforation atomization regimes. Furthermore, the breakup length increases with the increase of the nozzle flow velocity and then decreases. The breakup length is correlated with the splash plate nozzle diameter, and the flow velocity, as well as the kinematic viscosity of the sprayed liquid.
Introduction

Splash plate nozzles are used in a wide variety of industries. For instance, in the pulp & paper industry, the splash plate nozzles are used to spray black liquor into Kraft recovery boiler. It consists of a flat plate of rounded cross-section attached at an angle to the end of a pipe. Black liquor flows through the pipe, and when it exits from the pipe, it strikes the flat surface of the plate at an angle. The flow then turns and spreads into a thin liquid sheet. As the liquid sheet leaves the splash plate, it breaks up into small, discrete droplets.

Black liquor is a high viscosity liquid from wood pulp with up to 85% solid contents and it is utilized in combustion processes as an alternative to gas and oil. The spraying process of black liquor is different from other liquid processes as an alternative to gas and oil. The spraying up to 85% solid contents and it is utilized in combustion. Black liquor is a high viscosity liquid from wood pulp with small, discrete droplets.

Introduction

Numerical studies concerning the break up process of a black liquor sheet into individual droplets have been conducted by McKibben and Aidun [7], Fard et al. [8], Foust et al. [9], and Levesque et al. [10]. Viscardiet et al. [11] developed a black liquor spray calculator program to provide a visual representation of the destination of large liquid droplets that are deposited onto the char bed and the wall of the boiler.

Despite considerable numerical and experimental work on this type of nozzle, it is not currently possible to scale measurements made on small laboratory nozzles to help design larger industrial nozzles, nor is it possible to predict the effect of liquor viscosity and nozzle design on droplet spray patterns. The objective of this work is to determine a scaling criterion for splash-plate nozzles, to obtain the same break-up regime and the breakup length for different scaled nozzles. This will allow one to characterize small scale nozzles and use that information for the larger full scale black liquors sprays. By using small scale nozzles, it is possible to investigate the atomization regimes and the break-up lengths.

Experimental setup and procedures

The experimental setup to measure various spray characteristics for different nozzles is shown in Figure 1. It consist of splash plate nozzles, a pressure tank, a three dimensional scanning mechanism, a flat bed, and experimental work on droplet breakup lengths. A sectional view of the splash plate nozzle is shown in Figure 2. The liquid viscosity used in the experimental setup ranged between 1.0 mPa.s to 170 mPa.s. Corn syrup and water inside the tank equipped with pressure gage and safety valve.

Figure 1. The experimental setup

A sectional view of the splash plate nozzle is shown in Figure 2. The nozzle diameters were 0.5, 0.75, 1, and 2 mm. These nozzles were geometrically similar in dimensions with constant splash plate angle of 55° as shown in Figure 2. The liquid viscosity used in the experiment ranged between 1.0 mPa.s to 170 mPa.s. 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 properties and stability. Therefore, a solution of corn syrup with water is used to achieve a large range of viscosities in the measurements.

![Figure 2. A sectional view of splash plate nozzles with different diameters (d = 0.5, 0.75, 1, and 2 mm)](image)

The viscosity of solution was measured using (RheometricsARES-RFS3 mechanical spectrometer using the 50 mm cone and plate geometry). By knowing the density of corn syrup at room temperature ($\rho = 1450$ kg/m$^3$), the density of the solution of corn syrup and water is calculated based on mass conservation law. In addition, the variation of surface tension of the solution is measured (Kruss K100MK2 Tensiometer). A high-speed video camera, was used to image the liquid sheet produced by splash plate nozzle.

The breakup length of liquid sheet was determined by averaging values obtained from many photographs. The flow velocity in the splash plate nozzle ranges from 5 m/s to about 44 m/s. A rotameter is used to measure the flow rate of water from the pressurized tank to the splash plate nozzle. The measurement extent of the two rotameters ranges from 0.1 to 1.8 L/min, and from 2.0 - 7.0 L/min. For the solution of water and corn syrup, a graded cylinder and stop watch is used to measure the flow rate by collecting a specific volume of the solution for a known definite time.

**Results and discussions**

**3.1 Break-up regimes**

Visual appearances of the break-up mechanism of liquid sheet formed by splash plate nozzle are presented in Figures 4 to 7. Figure 4 shows the sheet breakup due to aerodynamics surface waves for 1.0 mm nozzle, with the values of Reynolds numbers varying from 200 to about 570. This regime is defined as the wavy regime in which disintegration occurs due to aerodynamic surface waves on the sheet growth of unstable modes. When a disturbance reaches some critical amplitude, the sheet breaks at half wave length intervals and forms bands of fluid. Surface tension rapidly contracts this fluid into cylindrical strands that ultimately break up into droplets. This usually occurs at high viscosity and low values Reynolds numbers as shown in Figure 4.

In the rim sheet break-up regime, forces created by surface tension cause the free edge of a liquid sheet to contact into a thick rim, which then breaks up by a mechanism similar to the break-up of a free jet. In this regime, the liquid sheet has two distinct shapes during droplet formation process. First, a smooth sheet is formed at low values of Reynolds numbers ranged from 800 to 1700 and the break up occurs to laminar edge instability as shown in Figure 5. Second, a perturbed sheet is obtained at higher values of Re, usually higher than 3,000. In case of higher Re, Figure 6 shows the selected cases for Re ranged between 12,000 and 18,000. The difference in the sheet surface in the two cases is attributed to the effect of nozzle Re where the perturbed surface is due to turbulent effect in splash plate nozzle. Although the pipe flow turbulence coming out of the nozzle becomes laminar flow after impinging on the splash plate, the sheet has still perturbed and it is not very smooth. This is in agreement with Dombrowski and Fraser [12]. They indicated that turbulence in the orifice can cause two types of disturbance in the sheet, a circumferential waves or a number of local point disturbances.

Figure 7 shows the perforation regime at Reynolds number ranged between 26,000 to 64,000 and nozzle diameter of 1.0 and 2.0 mms. Based on the figure, it is clear that as Reynolds number increased, local disturbances in the sheet become more predominant until holes are formed near the nozzle exit. Spielbauer and Aidun [13] reported that the perforations regime can occur due to number of reasons such as wave disturbance, un-wetatable particles, and air bubbles. In perforated-sheet break up regime, holes appear in the sheet. These holes grow rapidly in size until the rims of adjacent holes coalesce to produce ligaments of irregular shape that finally break-up into drops of varying size. This regime usually occurs at heigh values of Reynolds number and velocity.

**Effect of liquid viscosity**

Figure 8 shows the effect of viscosity on the liquid sheet atomization for three different jet velocities of 15, 21, and 30 m/s and for a splash-plate with 1.0 mm in nozzle diameter. The viscosity of the fluid is changed by changing the ratio of the corn syrup to water. This resulted in a range of viscosities from 1.0 to 170 mPa.s. The higher viscosity range is similar to the viscosity of black liquor. At the low jet velocity of 15m/s and low viscosity of 1mPa.s, corresponding to water, the liquid sheet formed is non-smooth but coherent. The sheet has an open rim, and leaf like shape, which breaks into small droplets at its edges. As the viscosity is increased to 12mPa.s, the sheet becomes smooth, but it still looks like a open rim leaf. Increasing the viscosity to 80mPa.s, clearly shows a contraction of the sheet and the extension of the breakup
point. This indicates that the sheet is becoming thicker; therefore it takes longer for it to break. Increasing the viscosity to even a higher value of 170mPa.s, does not allow the sheet to spread and it forms a closed rim leaf without any atomization. It is therefore concluded that the viscosity not only damps all the surface waves, but also dissipated the lateral spreading of the fluid.

The next row of pictures in Figure 8 shows the spray formed from the same nozzle but for higher jet velocity of 21m/s. The images basically show an increase in the spreading of the sheet. At lower viscosities, the sheets become unstable faster than those at the lower velocity. But at the high viscosity of 170mPa.s the sheet becomes longer and eventually the closed rim opens. A further increase in the jet velocity to 30m/s makes the sheet even more unstable and it breaks up earlier than the previous lower velocity cases. The spread angle increases substantially, spreading fluid in a wider angle.

**Effect of splash plate nozzle velocity**

The effect of splash plate nozzle velocity on the break-up regime at two different nozzle diameters (1 and 2 mm) is shown in Figure 9 (a, and b). Increasing the nozzle velocity results in the increase of sheet velocity and consequently sheet Reynolds number. For low viscosity, it is clear from Figure 9(c) that by increasing the velocity, the break-up length decreases and the sheet break-up mechanism changes from non-perforated to perforated regime. The reason is that the sheet becomes more unstable due to increasing the sheet Reynolds number. Similar trend was found for 2mm except that the transition to perforated regime occurs at low velocity. At high viscosity, the increase of velocity tends to increase the sheet radial velocity which results in the increase of the sheet angle. Moreover, the sheet is smooth and there is no variation in the break-up regime, as in the case of low viscosity, due to low Reynolds number.

**Effect of splash plate nozzle diameter**

The effect of splash plate nozzle diameter on the break-up regime at constant velocity of 18 m/s and nozzle diameters ranged between 0.5 to 2.0 mm is shown in Figure 10. As the nozzle diameter increases, the Reynolds number goes up. Consequently, the breakup regime changes from breakup due to turbulent edge instability to perforation regime. Furthermore, since the jet velocity is constant, by increasing the diameter, the flow rate increases. This will result in increasing the sheet thickness and accordingly the breakup length. As the nozzle diameter increases, the lateral spreading is going up due to increase in the flow rate

**Break-up length**

The breakup length (L_b) can be defined as the length of the continuous part of the sheet to the breakup point where spray droplets are formed. It is used to characterize the sheet behavior of splash plate nozzle. The quantities influencing the spraying process can be defined as follows: Characteristics dimension of splash plate nozzle, e.g. nozzle diameter (d), nozzle length (L), plate angle (θ); physical properties of liquid such as viscosity (μ), density (ρ), and surface tension (σ); physical properties of the gas such as gas viscosity (μ_g), gas density (ρ_g); liquid temperature and ambient temperature; liquid velocity (v) and ambient gas velocity (v_g). Here only one nozzle plate angle is considered to be constant. Also, the liquid and gas temperature are kept at room conditions. In addition the ambient gas considered to be quiescent at room temperature. Then, the break-up length can be presented as follows.

\[ L_b = f(v, μ, ρ, d, σ, L) \]  

The sheet breakup regime is classified by two main cases. In the first case, the breakup length is increased with increasing the velocity, whereas, in the second case the breakup length is decreased with increasing the velocity. Then each regime is correlated individually in terms of primitive variables. The dependence of L_b can be written for both regimes as follows:

For the first case, where breakup length increases with the nozzle velocity,

\[ L_b = 50.8 \times 10^6 [d]^{0.56} [v]^{-0.638} [v_g]^{-0.337} \]  

The second case where breakup length decreases with the nozzle velocity

\[ L_b = 1.2 \times 10^6 [d]^{0.832} [v]^{-0.476} [v_g]^{-0.223} \]  

The comparison between measured and predicted breakup length for both cases are shown in Figures 11-a and 11-b. Based on the correlations given in equations (2) and (3), the velocity at the transition from the first case to the second case is developed as follow:

\[ v_t = 0.0348 [d]^{0.6511} [v_g]^{-0.103} \]  

The variation of breakup length with velocity of splash plate nozzle with diameters of 0.5, 0.75, 1 and 2 mm using water is presented in Figure 12-a. It is clear that by increasing the nozzle diameter, the transition velocity (v_t) slightly decreased. The break up length increases until v = v_t and then decreases. Furthermore, increasing the nozzle diameter tends to increase the breakup length. Similar behavior was shown in Figure 12-b, for the variation of breakup length versus the nozzle velocity at varying values of viscosity (1, 12, 15, 80, and 170 mPa.s) and nozzle diameter of 1.0 mm. As shown in Figure 12-b, increasing the viscosity slightly decreases the value of transition velocity, while the breakup length increases with increasing the viscosity.

**Summary**

An experimental investigation has been conducted to
determine the effect of viscosity on the breakup length of liquid sheets formed by splash plate nozzles. It has been observed, based on the visual appearances of the break-up of liquid sheet, that four different atomization regimes can be described based on the Reynolds number where the atomization occurs due to aerodynamic surface wave, laminar edge instability, turbulent edge instability, and sheet perforations. The effect of increasing the viscosity not only damps the surface wave but dissipates the lateral spreading of the liquid sheet as well. Consequently, the breakup length increases. Increasing the nozzle diameter results in an increase of the sheet thickness and accordingly the breakup length. Furthermore, by increasing the nozzle flow velocity, two different trends for breakup length have been observed. The breakup length first increases with increasing the nozzle flow velocity and then decreases. The breakup length is correlated with the splash plate nozzle diameter, and flow velocity, as well as the kinematic viscosity of the sprayed liquid.

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References


Figure 4. Sheet breakup due to aerodynamic surface wave
Figure 5. Sheet breakup due to laminar edge instability

Figure 6. Sheet breakup due to turbulent edge instability

Figure 7. Sheet breakup due to sheet perforations
Figure 8. Effect of the viscosity on the break-up regime at different values of exit velocity using splash-plate nozzle of 1 mm diameter.

(a). Nozzle diameter of 2 mm (μ = 1 mPa.s)

(b). Nozzle diameter of 1 mm (μ = 1 mPa.s)

(c). Nozzle diameter of 1 mm (μ = 80 mPa.s)

Figure 9. Effect of the splash-plate nozzle velocity on the break-up regime at different values of splash-plate nozzle diameters (1, and 2 mm) and two different viscosities.
Figure 10. Effect of the splash-plate nozzle diameter on break-up and atomization regime.

Figure 11-a. The measured versus the Predicted break-up length in the case of increasing the breakup length with velocity.

Figure 11-b. The measured versus the predicted breakup length in the case of decreasing the breakup length with velocity.
**Figure 12-a.** Variation of the breakup length versus velocity at different values of liquid viscosity for 1.0 mm diameter of splash plate nozzle.

**Figure 12-b.** Variation of the breakup length versus velocity at different values of splash plate nozzle diameter for water (μ= 1 mPa.s).