Effect of Viscosities on the Instability of Sprays from a Swirl Atomizer

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Abstract

The phenomena of breakup of liquid sheets and jets are encountered in daily life as well as in various industrial applications. The onset of instability has a direct impact on the downstream spray development, and thus it is necessary to investigate the effect of liquid physical properties on this instability. The present paper focuses on the effects of liquid viscosity on the spray instability during the transient operation of a swirl atomizer in a trigger sprayer via experiments. In the experiments, water-glycerol mixtures were used to simulate fluids with a wide range of viscosities. A high-speed digital video camera was used for the near-nozzle spray structure visualization. The axi-symmetric three-dimensional wave patterns were clearly obtained in a conical liquid sheet produced by the swirl atomizer. The digital images of the sprays were further processed to analyze the surface waves on the spray cone. From the experimental results, it is seen that the fluid viscosity plays a very important role in controlling the liquid sheet breakup and atomization. The spray cone angle degrees were also calculated for the experimental fluids. For fluids with different viscosities, it is found that more viscous fluids have smaller average spray cone angles. The spray cone developed very fast during the early stage for less viscous fluids, while for very viscous liquid, a very small cone angle with little breakup and atomization was observed. As the liquid viscosity increases, the cone collapses earlier with larger droplets in the end stage. In addition to the spray cone angles, the surface wave temporal frequency was also calculated from the experimental images. The results show that the surface wave temporal frequency depends on the dispensing time and the fluid viscosity, while it has little dependence on the location in the near nozzle liquid cone.

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Introduction

The stability of liquid sheets plays an important role on spray development in various technological applications, including process industries (spray drying, spray cooling), coating application (surface treatment, spray painting), spray combustion (burners, furnaces, internal combustion piston engines, jet engine combustion, and rocket motors) and medical and printing application. The importance of hydrodynamic behavior of flow within a swirl atomizer has been recognized and studied by many researchers for a long time [1].

A pioneering work of classical studies on the stability of liquid jets was conducted by Rayleigh [2]. Squire [3] provided a further understanding of the atomization process based on his instability analysis of liquid sheets. Ponstein [4] might be the first to carry out an analysis of stability of an annular swirling liquid sheet. He derived the general dispersion relation for the growth of disturbances under the influence of potential liquid swirl flow and uniform axial mean velocity, while his research neglected the effects of viscosity and the presence of two phases. The liquid swirl with non-axisymmetric modes is more unstable than the axisymmetric mode. There is a competition among these forces that determines the stability of liquid sheets. Extensive research has been conducted thereafter, for example Taylor [5], Levich [6], Sterling and Sleicher [7] and Reitz and Bracco [8]. Forces such as the inertial force, surface tension, aerodynamic force, viscous force, and centrifugal force are all involved in the disintegration process. Some of these factors suppress the disintegration process while the others promote it. It is now generally agreed that the aerodynamic instability of the liquid sheet is responsible for the disintegration process.

Trigger sprayers are often used in industrial packaging aerosols. Liquid viscosity directly influences the surface stability of spray sheets and consequently affects downstream atomization quality. Therefore, it is critical to understand its associated underlying mechanisms for both atomizer design and optimization. Although many researchers have done considerable experiments to study spray systems, the viscous flow characteristics in trigger sprayers need more investigation. For example, Y.Liao [9] studied an inviscid, swirling annular liquid sheet in order to predict the performance of a constant pressure swirl atomizer. However, it is very difficult to accurately predict the atomization quality based on the empirical equations for different atomizer designs and for viscous fluids. Mehring and Sirignano [10] analyzed the nonlinear distortion and breakup of a swirling axisymmetric thin inviscid liquid sheet in a void and at zero gravity. By comparing with an annular sheet which is stabilized by a constant gas-core pressure, they showed that it is the swirl that reduces breakup lengths and times. They also showed that liquid swirl can enhance wave growth of the unstable mode resulting in shorter breakup lengths.

The purpose of this study was to investigate the effects of fluid viscosity on the spray instability and surface wave during the transient operations of a swirl atomizer in a trigger sprayer. A high-speed digital camera was used to visualize the near-nozzle spray structure. The digital images of the sprays were further processed to analyze the spray cone angle and the temporal waves at the cone surface. This paper is organized as follows. First of all, experiment facilities and setup are briefly described. Secondly, spray images obtained from a variety of fluids with different viscosities are illustrated and discussed. Then, the wave frequencies for a range of the fluids are calculated by using Fast Fourier Transformation to show the temporal wave propagation characteristics. Finally, conclusive remarks are provided.

Experimental Facility and Samples

The experimental apparatus is depicted in Figure 1. An electronically controlled actuator was used to press the trigger of a sprayer to initiate the liquid dispensing process. The use of this actuator improves the repeatability of the present experimental study. The sprayer and high speed camera are triggered by the same actuator. Near-nozzle region spray was visualized using a high speed digital camera (Phantom v4.3 from Vision Research Inc) at a frame rate of 34000 frames/second with an exposure time of 7 microseconds and a resolution of 112×96 pixels. The near nozzle region is 9×7.7 mm. The working fluids with different viscosities were prepared by mixing distilled water and glycerol with different volume ratios from 0% to 80% with a step of 10%. Wave frequency analysis used 60% to 74% water-glycerol mixture with a step of 2% increasing. Experiments showed that it was difficult to calculate the wave frequency for fluids with glycerol less than 60%. The experiment temperature was the room temperature (74 °F = 23.3 °C). The fluid viscosity is listed in Table 1 for different mixtures. It is seen that the viscosity of the liquid increases sharply when the percentage of glycerol in the mixture is high (e.g. >50%).

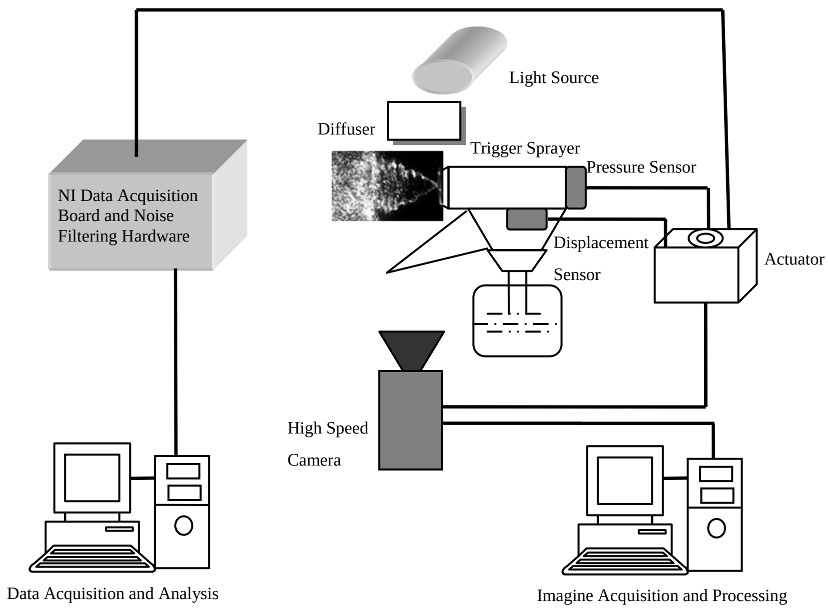


Figure 1. A schematic of the experimental setup

Vol. Ratio of Glycerol	0%	10%	20%	30%	40%	50%	60%	70%	80%
Viscosity (mPa-s)	0.937	1.310	1.888	2.849	4.533	7.828	13.874	29.944	79.488

Table 1. Viscosities of water-glycerol mixture fluids at 23°C

Results and Discussion

SPRAY CONE ANGLE ANALYSIS

It is well understood that the combination of liquid inertia, surface tension and aerodynamic forces affects the liquid breakup. Liquid breakup characteristics such as the spray drop size, the breakup length, and the spray cone angle are related to the unstable wave growing process. Centrifugal forces play a role in the breakup mechanism in pressure swirl atomizers. Liquid enters a swirl chamber tangentially to create a swirling liquid sheet. These types of atomizers usually result in wider spray cone angles than those of plain-orifice nozzles.

Figure 2 demonstrates a representative spray cone angle of a certain working fluid used in this paper. Based on the surface profiles, the spray cone angle can be obtained from the image taken by the high speed digital camera as observed in Figure 3(a) by post-processing the images using Matlab. The cone angle is calculated using curve fitting based on the spray surface profile, which is shown in Fig. 3(b). The transient displacements of the dispensing piston for fluids of 0-80% glycerol are shown in Fig. 4. The time period used for cone angle calculation shown in Figure 4 is from the initial dispensing process (at 290ms) to the time when the piston reaches its maximum dispensing stroke (at 460ms) and the fluid dispensing process is finished. The piston stays at its maximum stroke for a while and then the piston release process starts. There is no conical spray formed after the fluid dispensing process is complete.

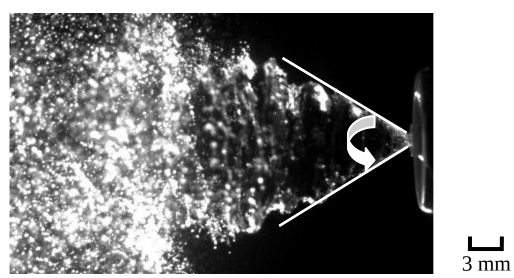
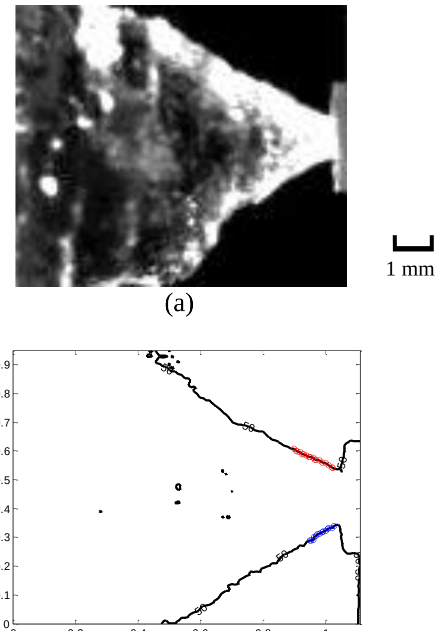


Figure 2. Global spray structure of trigger spray and the calculated cone angle

Figure 5 illustrate the mean spray cone angle as a function of the liquid viscosities of the mixtures. The error bars represent the standard deviation for 5 repeated experiments. The mean values of cone angle under each viscosity are also explicitly given in Table.2. As observed in Figure 5, the spray cone angle decrease as the liquid viscosity increases from 0% to 50% percent water-glycerol mixture, the cone angle changing only slightly decreased about 6.6 degree, which is as expected, since it is seen that in Table 1 the liquid viscosity does not increases too much. However, for fluids with much higher viscosity, such as from 60% to 70%

glycerol, it is seen that the spray cone angle reduced dramatically compared with less viscous fluid. For the most viscous fluid, 80% glycerol-water mixture, the cone angle is only about half of that of pure water.



(a)

(b)

Figure 3. (a) Near nozzle spray image taken by the high speed CCD camera; (b) Surface profile of the spray cone

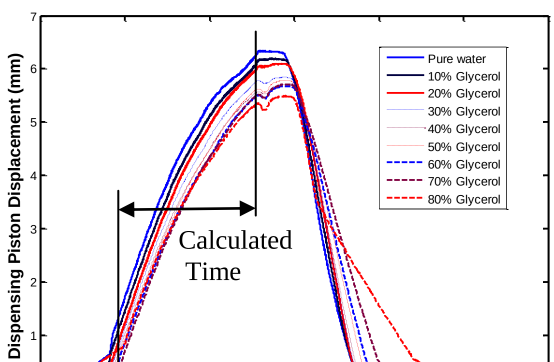


Figure 4. Transient displacement of fluids with different mixing ratios of glycerol

TEMPORAL SURFACE WAVE FREQUENCY ANALYSIS

For an unsteady spray from a swirl atomizer, the surface waves propagate and grow spatially with time, which are determined by wave number and frequency in space and time, respectively. Liquid sheet breakup is controlled by both spatial and temporal instabilities. The wave propagation of a liquid sheet surface can be expressed by

$$D = M \times \exp\left[i(kx + 2\pi ft)\right] \quad (1)$$

where D is the surface wave displacement, M is the magnitude of the surface waves, k is the wave number in space, and f is the oscillation frequency in time.

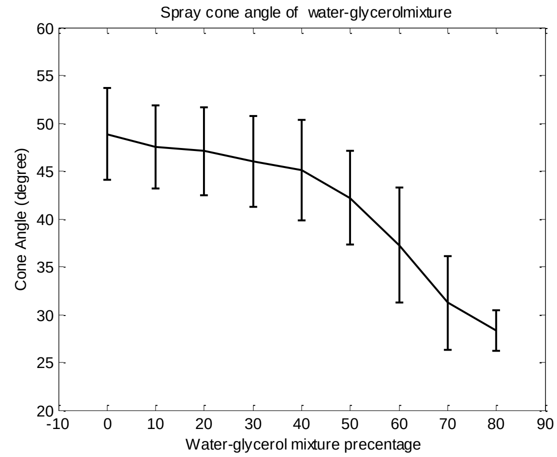


Figure 5. The calculated spray angle and the error bars for fluids with different viscosities

Vol. Ratio of Glycerol	Cone Angle (Degree)
0%	48.88
10%	47.52
20%	47.11
30%	46.04
40%	45.08
50%	42.21
60%	37.24
70%	31.21
80%	28.34

Table 2. Mean values of the cone angles of fluids with different viscosities

Temporal surface wave oscillation can be obtained by fixing a location and observing the wave change as a function of time. In this way, spatiotemporal diagrams can be obtained for frequency analysis. In the analysis, the location number increases from the picture from the left edge to the right, as illustrated in Fig. 6. Twenty locations are analyzed to obtain the temporal oscillation. Locations 1 to 20 represent the distance from 0.45 mm to 9 mm from the left edge of the image to the nozzle outlet. Figure 7 demonstrates how the domain wave frequency on the spray cone surface is analyzed. Once the wave edge is detected and transformed to a function of time, a Fast Fourier Transformation (FFT) technique is used for this time function to calculate the fundamental frequency, which is scaled to the actual frequency. The image at Location 3 with a time period of 336.4~348 ms after the start of spray serves as an representative example to show how the edge is detected from a spatiotemporal diagram and how the function is constructed.

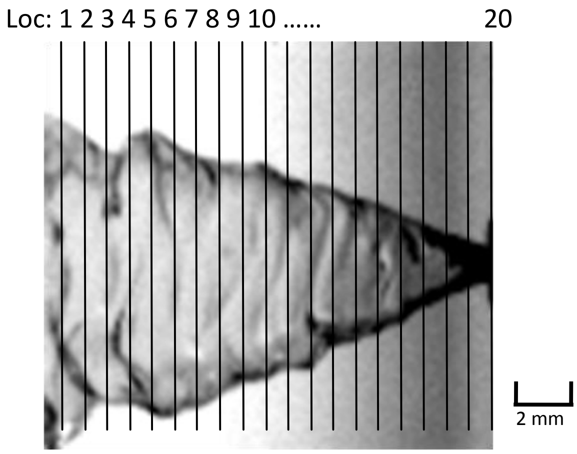
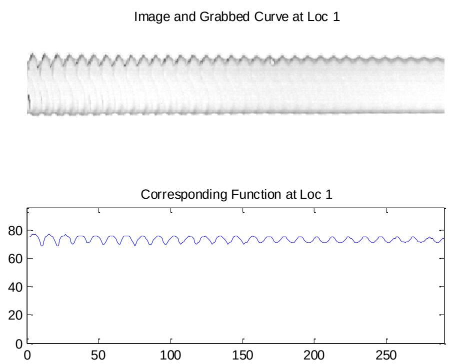
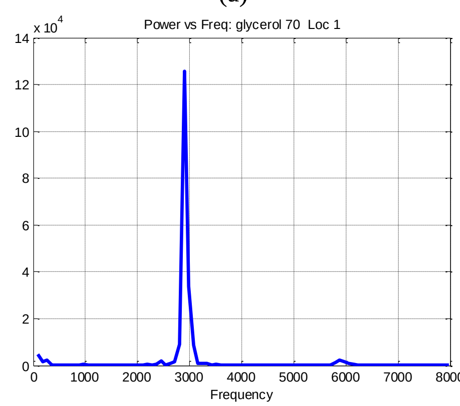


Figure 6. Discretized locations for surface wave analysis



(a)



(b)

Figure 7. (a) A typical detected edge on the original image of 70% glycerol at Location 3 with a time period of 394.4~406 ms (b) Fast Fourier Transformation to calculate wave frequency

The spatiotemporal diagrams for different experimental fluids are illustrated in Figure 8 at different time after the start of the dispensing process. It is seen that the surface wave characteristics can be clearly observed from the post-processed images. Since the liquid viscosity plays an important role on the spray atomization process and the surface wave growth rate, the figures are selected at different time periods for different viscous fluid investigated in the present work. Because this clearly observed wave only occurs at a certain time for a certain fluid, Table 3 illustrates the specified time corresponding to the spatiotemporal diagrams in Figure 8.

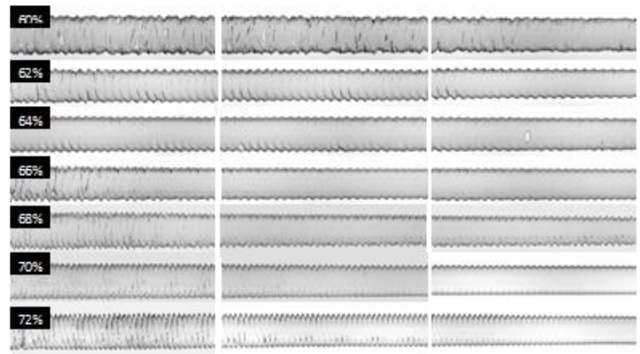


Figure 8. The spatiotemporal diagrams for different viscosity fluids at Location 6 at different time period

Vol. Ratio of Glycerol	Time period
60%	440.8ms - 464 ms
62%	440.8ms - 464 ms
64%	440.8ms - 464 ms
66%	429.2ms-452.4ms
68%	371.2ms - 394.4ms
70%	371.2ms - 394.4 s
72%	348 ms - 371.2ms

Table 3. Specified time period of wave frequency for different viscosity fluids

In Figure 9, 62% glycerol-water mixture is demonstrated as an example to show the relationship between the location and wave frequency. Five different time-period and ten locations were considered for this purpose in Figure 6. With the same viscosity, there is no change on wave frequency at different locations. The surface wave frequency decreases as the spray dispensing time increases, which indicates that higher frequency instability waves are more influential on the instability at the early stage of spray dispensing and breakup processes. Towards the end of the spray development, the wave frequency becomes small.

In Figure 10, there is an observable trend of surface wave frequency changing with time for fluids with different viscosities. Each frequency is an average value for ten different locations. The regular surface wave occurs first for the most viscous fluid. As the viscosity decreases, the observed regular wave forms later. These results show that for a transient spray process, the surface wave instability depends on both the fluid properties and the physical dispensing process such as the fluid velocity and the chamber pressure. The instability of surface wave plays an important role in the atomization process, which also gives an explanation why it is easier for less viscous fluid to atomize when comparing with more viscous fluids of similar surface tension.

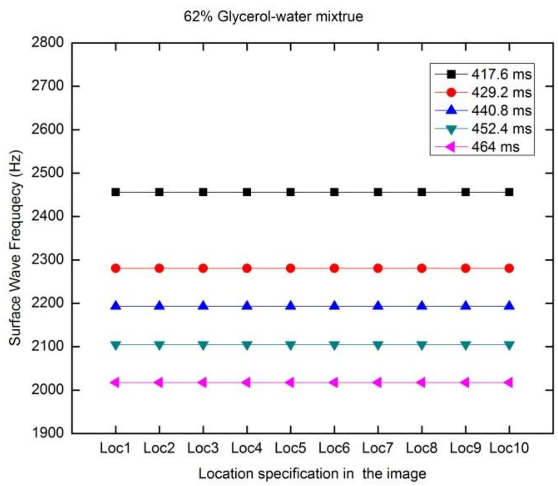


Figure 9. Surface wave frequency at different location for different time period

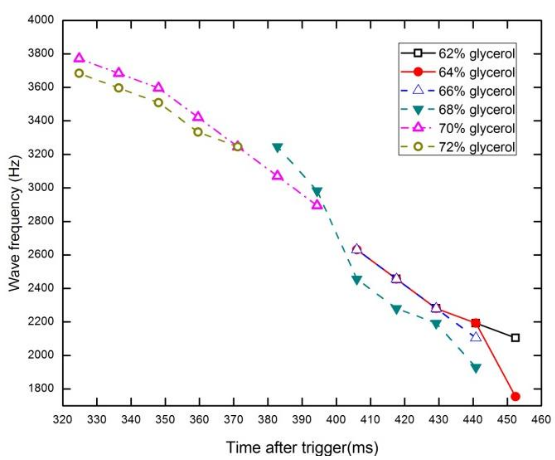


Figure 10. Surface wave frequency of different viscosity fluid at different time period

Conclusion

The near nozzle region of a liquid spray from a swirl atomizer for fluids with different viscosities was investigated experimentally in this work by using a high speed camera. The spray cone angle was calculated for 0% to 80% glycerol-water mixtures to address the effects of fluid viscosities. Based on the experimental observations and calculated spray characteristics, it is confirmed that liquid viscosity has a significant effect on spray cone angle and breakup in swirl atomizers. Higher viscosity prevents fluid from forming a large cone, which results in smaller angles in the liquid cone formation. The breakup of high viscous fluid was found to be more difficult as compared to the less viscous fluid. The frequencies of the temporal waves at the spray cone surface were also calculated for the liquid mixtures with different viscosities. It was found that the wave frequency does not depend on the location on the liquid cone and the frequency decreases with time for all the fluids.

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