Effects of Fluid Viscosity on the Spray of a Swirl Atomizer in Trigger Sprayers

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Abstract

Swirl atomizers are widely used in both industry and daily life. This work focuses on experimental investigations of the effects of fluid viscosity on the spray development during the transient operation of a swirl atomizer in a trigger sprayer. In the experiments, water-glycerol mixtures were used to simulate different fluids with a wide range of viscosities. The transient dispensing piston displacement was measured by using a linear sensor fixed together with the piston. The trigger sprayer was controlled by an actuator with a given dispensing motion curve. 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 spatial and temporal 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 fluid breakup and atomization. The spray cone angle changes with the variation of the fluid viscosity. Different from the results of constant pressure swirl atomizers, the transient operation of a swirl atomizer results in significant variation of spray structure during the liquid dispensing process. Early stage spray develops very rapidly with a fully developed cone angle. During the late stage of the dispensing process the spray cone angle becomes smaller and the wave length of the surface waves on the spray cone surface becomes longer. For fluids with different viscosities, it is found that more viscous fluid leads to a smaller spray cone angle. The surface wave temporal frequency decreases with the increase of fluid viscosity.

Introduction

Swirl atomizers are widely used for many applications in industry and daily life, from fuel injection spray in power generation engines to various liquid dispensing sprayers used in packaging applications. The importance of hydrodynamics behavior of flow within a swirl atomizer has been recognized and studied by researchers for a long time. For example, the instability and breakup of the liquid sheet in a fuel atomizer in combustion engines directly affect combustion efficiency, pollutant emissions, and combustion stability [1].

The instability of liquid sheets and jets has been studied by many researchers. Rayleigh [2] did a pioneering work of classical studies on the stability of liquid jets. The instability analysis of liquid sheets by Squire [3] provided further understanding of the atomization process. Ponstein [4] was probably 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 neglecting the effects of viscosity and the presence of the two gas phases. Ponstein showed that 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 involved in the disintegration process. Some of these factors suppress the disintegration process while others promote it. It is now generally agreed that the aerodynamic instability of the liquid sheet is responsible for the disintegration process. Mehring [9] and Sirignano [10] showed that liquid swirl can enhance wave growth of the unstable mode resulting in shorter breakup lengths using a non-linear analysis of a swirling, annular, axisymmetric liquid sheet in a void.

Trigger sprayers are often used in industrial package aerosols. The viscosity of liquids plays a very important role in controlling the fluid breakup and atomization. The instability of the liquid jet may directly lead to poor atomization quality. Understanding the underlying mechanisms of the atomization process and factors is critical for both atomizer design and improvement. Although, many researchers have done a lot of experiment work to study the spray system, the viscous flow characteristic in trigger sprayers remains a challenge. For example, Liao [11] used an inviscid, swirling annular liquid sheet as the instability model to predict the constant pressure swirl atomizer

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performance, as the result of empirical-basis design. However, it is very difficult to predict the atomization quality based on the empirical equations for different atomizer designs.

The purpose of this study is to investigate fluid viscosity effects on the spray development and disintegration process during the transient operation 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 spatial surface waves on the spray cone and the temporal waves at the cone surface. In the following of this paper, we start by providing the design and construction details for the instrument and sample information. It is followed by spray images obtained from a variety of fluids with different viscosities. The wave frequency for a certain fluid is then calculated by Fast Fourier Transformation to show the temporal wave propagation characteristics. Finally, some conclusions are summarized based on the results.

Experimental Facility and Fluid Samples

In this paper, the transient linear displacement of the dispensing piston was measured. The experimental apparatus is illustrated in Fig. 1. An electronically controlled actuator was used to press the trigger of the sprayers to initiate the liquid dispensing process. As can be seen in the figure, the sprayer and the high speed camera are triggered by the same actuator. Piston displacement was sampled by using LabView software via a National Instrumentation data acquisition board. The camera and the LabView code were triggered by a trigger pulse from the actuator. Sampling rate of data acquisition is 40,000 points per second. The data was saved to a PC computer for post-processing. Near-nozzle region spray was visualized using a high speed digital camera (Phantom v4.3 from Vision Research Inc.). There were two sets of configurations used in the camera. For the first setting, the camera was operated at a frame rate of 32000 frames/second, exposure time of 7 microseconds, and resolution of 96x112 pixels, which was employed to investigate the details of near nozzle region sprays. The other one used a frame rate of 8584 frames/second, exposure time of 7 microseconds, and resolution of 128x512 pixels to reveal the global structure of the sprays with very high viscosities. The working fluids with different viscosities were prepared by mixing distilled water and glycerol with different volume ratio which is from 0% to 90% with a step of 10%. 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 with the increase of the mixing percentage of glycerol, the viscosity of the liquid mixtures increases sharply. The viscosity of 90% mixture is almost 260 times of the pure water.

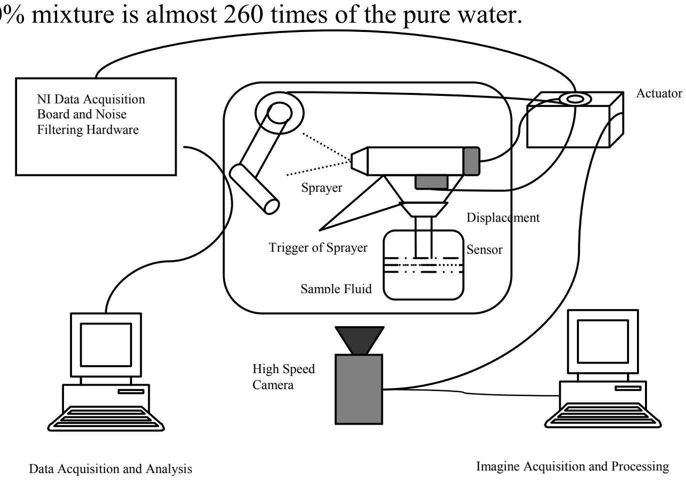


Figure1. Schematics of the experimental setup

Table1. Viscosity of water-glycerol mixture fluids at 74°F

Vol. Ratio of Glycerol	0%	10%	20%	30%	40%	50%	60%	70%	80%	90%
Viscosity (mPa-s)	0.937	1.310	1.888	2.849	4.533	7.828	13.874	29.944	79.488	251.814

Results and Discussion

DISPLACEMENT COMPARISON

The transient displacements of the dispensing piston for fluids of 0-80% glycerol are shown in Fig. 2. As can be observed in Fig. 2, the initial dispensing process, the maximum dispensing stroke, and the piston release process are very different for fluids with different viscosities. With the increase of viscosity, the evidence of a dip in the displacement curves becomes more obvious at the maximum stroke. Viscosity also affects the piston compression, release, and maximum stroke. Higher viscosity leads to less maximum dispensing stroke and the discharge valve opens later for more viscous fluid mixtures. It is also seen in Fig. 2 that the piston release process becomes slower for higher viscosity. Some displacement curves for 90% glycerol are shown in Fig. 3(a). For a very viscous fluid as 90% glycerol, the piston dispensing curves are not very repeatable. The discrepancies in the displacement curve might be due to the hesitation during the piston release process. But for other fluids with mixing ratio from 0% to 80%, the repeatability for different runs isquite good as shown in Fig. 3(b).

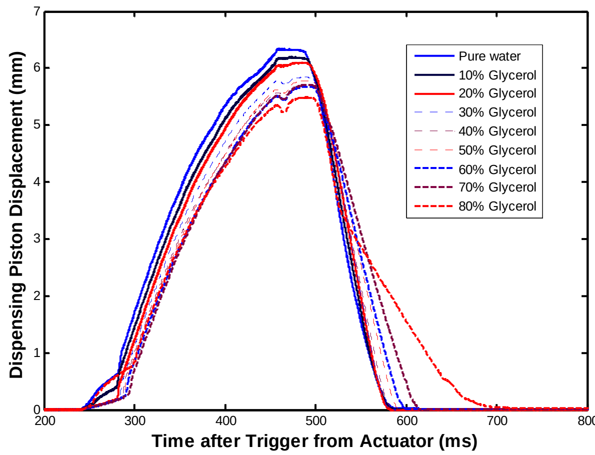
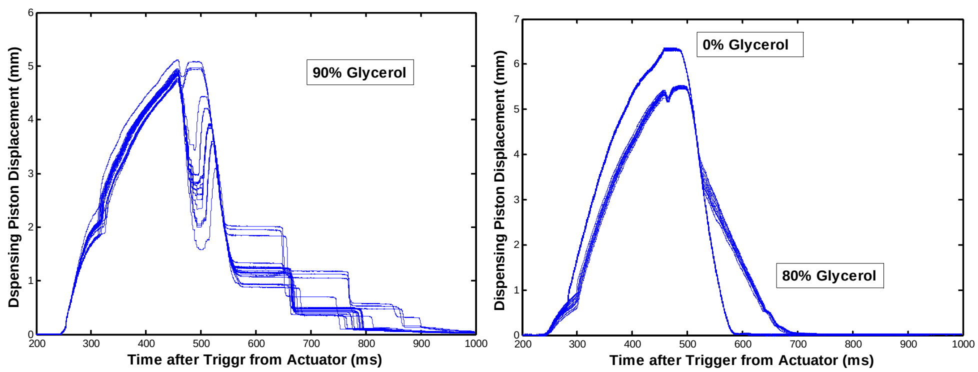


Figure 2. Transient displacement of fluids with different mixing ratios of glycerol



(a) (b)

Figure 3. Transient displacement of different runs for different fluids: (a) 90%; (b) 0% and 80%

SPRAY SPATIAL STRUCTURE

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

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

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.

Since the near nozzle region is critical to the liquid atomization for the downstream sprays, the development processes of the sprays in this region are further investigated in detail from the spray images, namely the start, developed, and end stages, as shown in Figs. 5 to 7. In Fig. 5, it can be seen that the spray structure is similar for 0~40% glycerol, while the structure has a dramatic change for 50-90% glycerol. The cone of the spray for more viscous fluid is smaller than that of a less viscous fluid. For the 90% glycerol fluid, the breakup is very weak. This is due to the effect of viscous force. At the start stage, the initially dispensed liquid does not have enough momentum as the developed stage, as shown in Fig. 6.

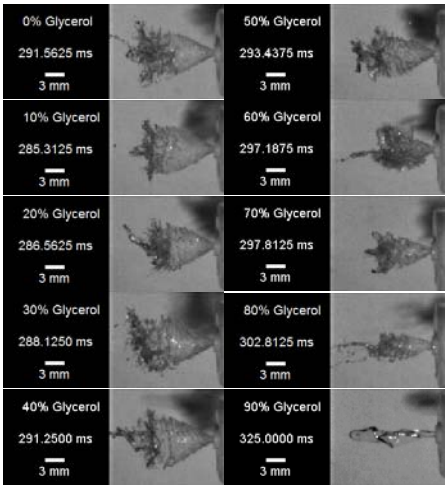


Figure 5. Start stage of spray for different fluids

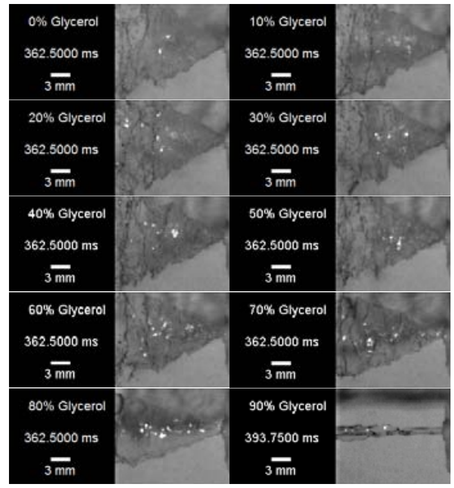


Figure 6. Developed stage of spray for different fluids

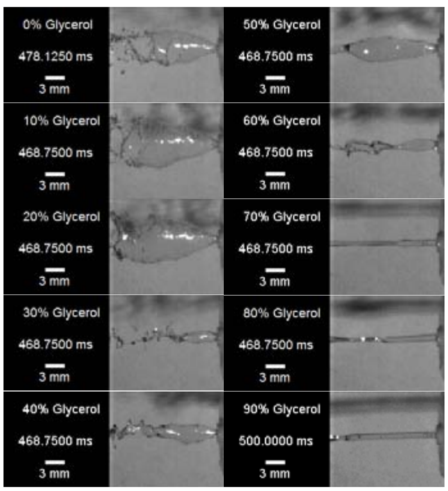


Figure 7. End stage of spray for different fluids

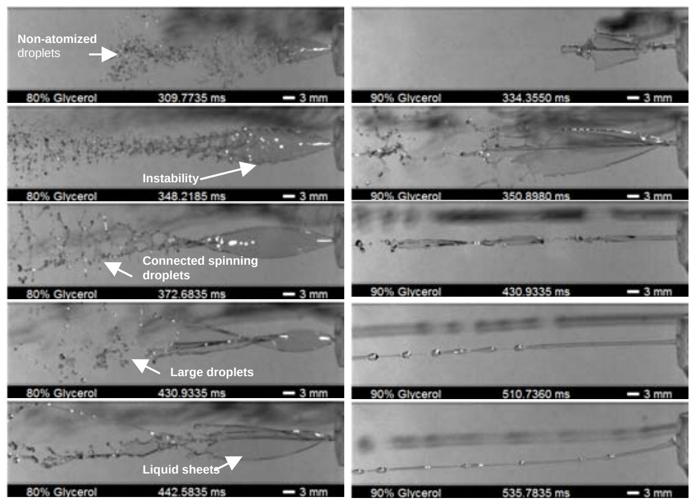


Figure 8. Spray structure of highly viscous fluids

The developed stage of the spray is illustrated in Fig. 6. When the fluid moves out from the nozzle, it forms a cone due to the swirl mechanism in the nozzle, and the surface wave starts to propagates and grow spatially and temporally. As the liquid sheet becomes thinner and surface wave oscillation magnitude increases on the surface of the spray, the sheet begins to break up and atomize to small droplets. The wave breakup length, which is the distance between nozzle outlet and wave breakup point, is found to increase as the fluid viscosity increases. For the mixture of 90% glycerol, the fluid just comes out of the nozzle as a spinning jet or stream and does not break up, which is dramatically different from that of 80% glycerol. This is due to the fact that the viscosity changes dramatically from 80% to 90% glycerol, as listed in Table 1. It indicates that the viscosity has played an important role in determining the structure of the spray and the atomization of the liquid.

The spray images near the end stage of fluid dispensing for different fluids are shown in Fig. 7. Near the end of the injection process, the cone continues to shrink and collapses back to an onion shape by the tip of the spray due to low fluid velocity. This stage is mainly responsible for the poor atomization near the end of the spray. When the volume mixing ratio of glycerol is above 40%, the fluid does not break up due to the loss of the pressure and flow velocity. For 70 - 90% glycerol, a fluid stream is observed at the end stage.

The global spray structure evolution with time is illustrated in Fig. 8 for very viscous fluid. For the mixture of 80% glycerol, the fluid dispensed out at the very beginning is not really atomized. As the spray develops, a cone is formed and instability begins to take place when the jet develops to a certain distance from nozzle. Beyond this distance, the fluid breaks up into large droplets. When the velocity is high enough, the large droplets break up into smaller droplets. When the velocity is small, the large liquid blobs cannot be atomized. At the end stage of the spray, triple-branched liquid sheets are observed. At this stage, due to the lack of velocity, the fluid cannot form small droplets. For the mixture of 90% glycerol, an interesting phenomenon is that when the flow comes out from the nozzle outlet, it forms three liquid sheets moving forward helically. This is similar to the end stage of 80% glycerol spray. During most of the time of the dispensing process, the liquid comes out of the nozzle as a spinning stream.

TEMPORAL SURFACE WAVE FREQUENCY ANALYSIS

Temporal surface wave oscillation can be obtained when a location is fixed and the wave change is observed as a function of time. In this way, spatiotemporal diagrams can be obtained for frequency analysis at different locations of the spray cone. In the analysis, the location number increases from the picture left edge to right, as illustrated in Fig. 9. Twenty locations are analyzed to obtain the temporal oscillation. Location 1 to 20 representing the distance from 0.7 mm to 14 mm from left edge of the image to the nozzle outlet, while only location 1 to 10 at the time period of 159.7~171.1 ms are analyzed for oscillation frequency because a clear wave shape at these locations allows us to grab the curve which is necessary for the spectral analysis. After the wave edge is detected and transformed to a function of time, Fast Fourier Transformation (FFT) technique is applied on this function to find the fundamental frequency. The image at location 4 and time period of 159.7~171.1 ms after the start of spray serves as an example of how the edge is detected from image and how the function is constructed (Fig.10).

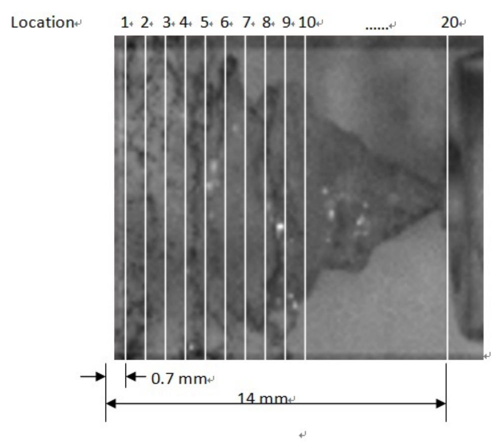


Figure 9 Location specification of the image

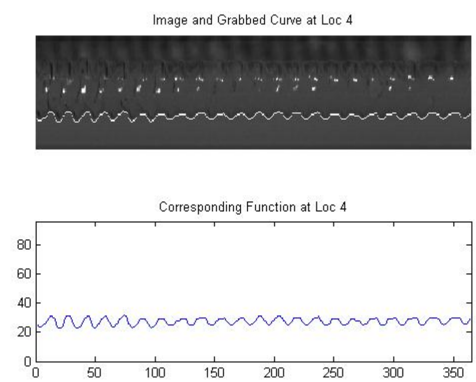


Figure 10 A typical detected edge on the original image and the reconstructed function, location: 4, time period: 159.7~171.1 ms

Table 2 Frequency of fluid propagation temporal oscillation

Location	1	2	3	4	5	6	7	8	9	10
Frequency (Hz)	1929	2018	2018	2018	2018	2018	2018	2018	2018	1929

As for temporal oscillation, most images are too random to be analyzed for less viscous fluids. However, some of them with high viscosity present clear wave characteristics. For example, 70% glycerol shows the wave at the time period of 159.7~171.1 ms, while other fluids hardly show similar characteristics. Noting that the time period is the 15th frame of the total spray time, it is the developed stage of the spray. In Table 2, the frequency is found to be either 1929 or 2018. This implicates that the frequency of the wave propagation is determined by the fluid properites and velocity, but independent of location, at the developed stage. When the location is approaching nozzle, the frequency presents a trend to decrease. However, this cannot be verified since the image start from location 11 does not allow us to obtain a reasonable curve for the analysis. It does not necessarily mean that there is no wave propagation, but the discrepancy in the wave shape is so small for the current experiments setting that the wave shape cannot be recognized. However, the feasibility of temporal analysis is applicable based on the quality of the image. The spatiotemporal diagrams shown Fig. 11 clearly show the effects of fluid viscosity on the surface wave frequency. The results shown in Fig.11 are obtained at Location 6 at the time period of 159.7~171.1 ms. For 70% glycerol fluid mixture, a clear frequency is seen in the diagram. When the fluid is less viscous than 70%, it is expected that the frequency of the surface wave is much higher than those of 70% glycerol and the current camera frame rate is not high enough to capture the oscillation frequency based on the Shannon's sampling principle. However, for a more viscous fluid as shown in the 80% glycerol diagram, the oscillation frequency is much lower than that of 70%. The oscillation period for 80% is about 8 times longer than the 70% glycerol fluid.

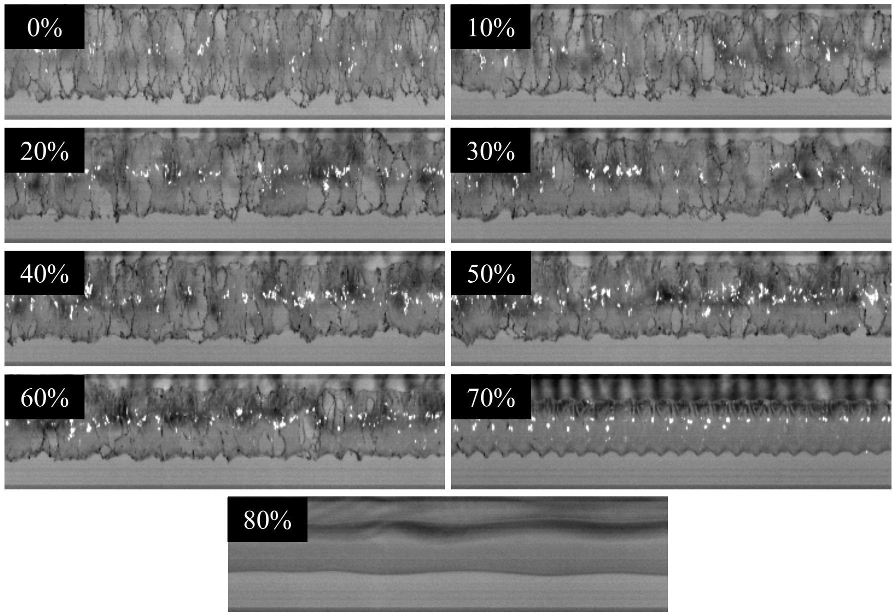


Figure 11 The spatiotemporal diagrams for different fluids at location 6 and time period of 159.7~171.1 ms

Conclusion

Effects of fluid viscosity on the displacement of dispensing piston and the near-nozzle spray from a swirl atomizer are studied in this work. The transient displacement was measured and the spray was visualized by a high speed digital video camera. It is found that the fluid viscosity can greatly influence the piston displacement during the transient fluid dispensing process. The maximum dispensing stroke becomes smaller for a more viscous fluid. From the spray images, it is seen the fluid viscosity can greatly affect the fluid breakup and atomization. Different from the results of constant pressure swirl atomizers, the transient operation of a swirl atomizer results in significant variations of spray structure. Early stage spray develops very rapidly with a fully developed cone angle. During the late stage of the dispensing process the spray cone angle becomes smaller and the wave length of the surface waves on the spray cone surface becomes longer. For fluids with different viscosities, it is found that more viscous fluid leads to a smaller spray cone angle. The surface wave temporal oscillation frequency is expected to decrease with the increase of fluid viscosity from the spatiotemporal diagrams.

Acknowledgement

This work was supported by the MeadWestvaco Corporation. We greatly appreciate the help from Keith Abbott, Douglas Dobbs, and Frederick Renk on the setup of the experiments.

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