Abstract

The present work consists of a study of spatially resolved secondary atomization characterization (fragment size and velocity distributions). This is especially important, as non-Newtonian liquids lack the depth of research of Newtonian liquids, and fragment size and velocity distributions are mostly unknown. The spatial characterization of a viscoelastic xanthan gum solution undergoing breakup in the bag regime were obtained using both dual- and fiber-mode PDA systems. The xanthan gum solutions were characterized using the Carreau rheological model and Zimm relaxation time model, as these were the best fit to the experimental data. Data were obtained at multiple air mass flow rates (Weber number) and at both fixed and varying radial distances for a set downstream location (location was selected such that the liquid bag had undergone breakup, and the rim had almost completed breakup). Initially, a bi-modal distribution was expected to be seen in the PDA data, as the rim and bag fragments are two distinct sizes; instead, a bimodal distribution was only seen for a few cases, and in those cases, it was attributed to large bag fragments instead of rim fragments after observing corresponding high-speed video of the breakup process. These videos also showed that small fragments from the bag occurred closer to the drop entry into the air stream (early in the breakup process); these small fragments then had time to accelerate to the air jet velocity. The larger fragments, with a larger surface area to volume ratio, took longer to accelerate. Measurements taken at different axially locations showed that the bag breakup process is not symmetric. After again analyzing high speed video, it was seen that the fragments formed from the bag breakup process tend to disperse radially instead of traveling directly downstream with the air flow; this asymmetry was indeed reflected in both the fragment and velocity distribution data.

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Introduction

Fragment size distribution is one of the most important features of any atomization process. By knowing the spatially resolved drop size and velocity data, we gain a better understanding of how the atomization system responds to operating conditions or liquid property changes. Combustion, agriculture, and other applications require knowledge of fragment sizes for optimal atomizer design. Up to this point, fragment sizes have been rarely measured.

In this study, we focus on the fragment sizes and other spatial characteristics of a viscoelastic non-Newtonian solution of xanthan gum and deionized water. Non-Newtonian fluids such as paint, gelled fuels, and thermal barrier coatings exhibit non-linear stress-strain rate relationships. This useful rheological behavior adds complexity to the flow, and causes their secondary atomization behavior to differ from that of Newtonian liquids. This property has been investigated by [1] – [6].

Recent studies have used PDA systems to collect information about atomization dynamics and report their findings using the Sauter mean diameter (SMD). However, many cases focus on dense sprays created by atomizers or spray guns rather than analyzing single drops in cross flow. (See [7] – [9].) Instead of PDA, many groups have used shadowgraphy to record properties of the deforming droplet, but not its fragments, or fragment data focused on Sauter mean diameter and mass median diameter. (See [10] – [12].)

Each experimental method has advantages and disadvantages when collecting spatial data. For this study, the focus was on individual, non-interacting drops breaking up in an air flow, with diameter and velocity distribution measurements the primary goal. The focus was also on a specific location of breakup (10cm downstream of the air nozzle). PDA was selected as the experimental method for this study due to its spatial resolution, equipment availability, and ease of data processing.

Experimental Methods

A total of five solutions of XG (xanthan gum) in DI (deionized) water were prepared with concentrations of 0.1, 0.3, 0.5, 0.7, and 1.0% by weight. Of these solutions, the 0.1 and 0.3% were used in PDA experiments, while all solutions were used with the high-speed imaging system. (For a detailed description of the experimental apparatus, see [13].) A stream of nearly uniformly sized drops, $d_0 = 2.7 \text{ mm} \pm 0.5 \text{ mm}$, were formed and subjected to a high-speed air flow. All experiments were carried out at nominal laboratory conditions of 20°C and 1 atm.

Shear-thinning viscoelastic non-Newtonian liquid rheological parameters were obtained by fitting experimental data with the Carreau rheological model, equation 1:

$$\mu_{eff} = \mu_{inf} + \frac{\mu_{0} - \mu_{inf}}{1 + (\dot{\gamma}/\gamma_C)^n}$$

Drop Size Distribution Results

Drop fragment size and velocity distributions were measured for the bag breakup regime. In this regime, the deformed drop develops two main features: a bag, and a rim. The bag disintegrates before the rim, producing two distinct sets of fragments, one from each feature’s breakup. As shown in Figure 1, the rim and bag fragments are of different sizes, so we would expect this to be reflected in the PDA data as a bi-modal distribution.

![Figure 1. 0.1% XG solution, $We = 25$.](image)

However, PDA measurements show a different trend; measurements taken with the dual PDA system at different We for different solutions at one downstream radial position are presented in Figure 2–Figure 7. When Zhao et al. [14] studied fragment sizes, their experimental data showed a gamma distribution instead of the bimodal distribution as reported by Kombayasi et al. [15]. However, Chou and Faeth [16] argue that a bimodal distribution is the result of an undersampling of the small drops formed by the bag, and that there is actually no bimodal behavior for drop size distribution.

It is also interesting to note that for a given solution with increasing We that the peak, or most frequent size range, shifts to the left (smaller fragment diameter). We increases because the velocity of the continuous air jet into which the drop is falling increases; this leads to stronger aerodynamic forces that lead to smaller fragment sizes, which is reflected in the shift of the peak size range.

Solution composition also plays a role in the shape of the fragment size distribution plots. As the XG concentration of a solution increases, the surface tension and viscosity of the solution both increase. The properties both oppose atomization, resulting in larger fragments as the drop breaks up.
In Figure 2, it may be argued that a bimodal distribution is present. High speed videos for this case (DI water, $We = 14$) show a large cloud of very small fragments that is formed when the bag bursts. This cloud forms before the 10cm location where PDA measurements were taken, but it moves downstream with the flow from the air jet and passes through the measurement volume. Closer to the measurement location, the rim of the drop fragments, creating a smaller number of large drops; these are reflected in the increase of fragments in the 130um - 200um range, so this case does present a bimodal fragment size distribution.

The fragment size distribution data in Figure 3 can be interpreted in one of two ways: the increase in the fragment size PDF at 210um is either an anomaly in a monotonically decreasing distribution or evidence of a bimodal fragment size distribution. High speed videos show that the 0.1% XG drop still forms a bag that bursts; this bag forms a larger range of fragment sizes than the water drop did. The rim, however, did not completely break up for this $We$. Instead it had a ‘beads on a string’ type of formation, where the ‘beads’ had a diameter much larger than the size range of the PDA system. This slight increase in PDF (d) at large fragment size is a result of the bag fragments and not rim fragments, and Figure 3 should not be interpreted as a bimodal distribution due to larger rim fragments, but still may be considered bimodal.

This same question regarding the shape of the fragment size PDF can also be asked of Figure 4 when looking at the increase in PDF (d) at sizes around 230um. The high speed videos for this $We$ show the bag bursting approximately 5cm downstream into individual fragments as well as fragments that are connected to the rim by a very thin ligament. By the time the drop has moved downstream to the PDA measurement volume (10cm), these fragments have almost all separated from the ligaments connecting them to the rim. These larger bag fragments cause the slight increase in PDF (d) in the larger fragment size range, so the distribution of Figure 4 should not be considered a bimodal distribution due to rim fragments, but still may be considered bimodal.
The fragment size distribution data in Figure 7 can be interpreted in one of two ways: the decrease in the fragment size PDF at 190µm is either an anomaly in a monotonically decreasing distribution or evidence of a bimodal fragment size distribution. High speed videos show a bag fragmentation process similar to what was discussed with Figure 4. However, the individual fragments produced when the bag first breaks up are larger than the fragments produced by 0.1% XG and DI water. This decrease in PDF (d) seems like an anomaly or the result of noise in the data collection process, and this distribution is not bimodal.

Since these fragment size distribution measurements were taken at only one radial location downstream of the breakup initiation point, it is possible that bag fragments from the edge of the drop were not crossing through the PDA measurement volume located at the center of the breakup area. For the 0.1% XG solution, measurements were taken with a fiber PDA system at the same downstream distance, but at different radial locations (+5mm, ±10mm) in addition to the centerline. These results are presented in Figure 16 (see end of document).

When comparing the fragment size distributions in Figure 16, we may expect that the distributions for ±10mm are very similar to each other, and also that the ±5mm plots are very similar. However, the +10mm distribution shows a peak fragment size that is slightly larger than the peak in the -10mm plot. The +5mm plot also has a higher number of smaller fragments than the -5mm distribution. High speed video shows that the bag breakup process is not completely symmetric. As the bag forms, the rim tends to collect liquid at the top and bottom. The top section of the bag also breaks up be-
fore the lower section does, and the cloud of fragments from the bag breakup process spreads out radially as the fragments move downstream. The bag fragments formed from the top section also appear to be smaller than the fragments from the bottom section, which would explain why the +10mm and +5mm distributions have a larger number of small fragments than the -10mm and -5mm locations. The asymmetry of the bag breakup process is reflected in the fragment size distribution plots.

**Fragment Velocity Measurements**

Fragment velocity distributions for the xanthan gum solutions (Figure 9 and Figure 10) differ from water (Figure 8) in terms of the range of fragment velocities and the number of fragment diameters at a given velocity. (The graphs for the fragment velocity distributions have been binned by $\text{We}$ – this range or bin is shown as the horizontal bars in the graph – to make viewing and interpreting the data easier.)

The most viscoelastic solution used (0.3% XG) breaks up into larger fragments than both water and 0.1% XG, as shown by the larger number of data points in the 200-300 $\mu$m range. Since the xanthan gum solutions both take longer to both start and complete the secondary atomization process than water, the water drops are further along in this process than the xanthan gum drops at the same nozzle downstream distance; this also accounts for the higher number of larger fragments. Since the larger drop fragments have slower velocities than the smaller fragments, the maximum velocity will decrease as xanthan gum concentration increases since mean fragment size increases with xanthan gum concentration. We also see that the fragment velocity increases with $\text{We}$, which is expected since higher $\text{We}$ correspond to a higher air jet velocity for these experiments.

We also note that the velocity profiles for the 0.3% XG solution (Figure 10) are flatter than the profiles for 0.1% XG and DI water. It takes longer for the more viscous XG solution to start the atomization process, so both large and small fragments are moving at similar speeds, as the small drops have not had sufficient time to accelerate to the flow velocity.
Figure 9: 0.1% XG, We = 11 (T), 14, and 16.5 (B).

Figure 10: 0.3% XG, We = 12.5 (T), 15 (B).

Figure 11 through Figure 15 show fragment velocity with varying radial distance for a 0.1% XG solution at We = 16.5. At first glance, we would expect the ±5mm velocity distributions to be approximately the same, and the ±10mm velocity distributions to be approximately the same as well. However, the fragment size distribution plots showed that bag breakup is not a symmetric process, and the velocity distribution plots are also asymmetric with respect to the centerline. For example, the velocity profile at +10mm is increasing, while the profile at -10mm shows a slight increase, then decrease. Additionally, the profile at -5mm is flat while the velocity profile at +5mm shows a slight increase with diameter. At the edge of the drop breakup area, the
drop fragments are encountering the boundary between the moving air jet and the still ambient conditions. If smaller fragments are more susceptible to boundary layer effects, this would account for their small velocity as compared to larger fragments (Figure 15).

The high speed videos of this breakup process also show that the bag and rim fragments do not move in a straight line downstream with the air flow, but tend to spread out radially. If a large fragment created upstream of the measurement volume has a chance to match the velocity of the air jet as it moves downstream, and it also moves radially, this would explain larger fragments with higher velocities than smaller fragments that may have just formed and have not achieved air jet speed.

Figure 11: 0.1% XG, velocity versus fragment diameter at centerline.

Figure 12. 0.1% XG, velocity versus fragment diameter at -5 mm.

Figure 13. 0.1% XG, velocity versus fragment diameter at -10 mm.
Summary and Conclusions

Dual and fiber PDA systems were used to collect drop fragment velocity and size distribution data at one downstream location at both fixed and radially varying locations. The fragment size distributions show that as xanthan gum concentration increased, the mean fragment size also increased, and the mean velocity decreased. High speed videos showed that small fragments from the bag occurred closer to the drop entry into the air stream (early in the breakup process); these small fragments then had time to accelerate to the air jet velocity. The larger fragments, however, with a larger surface area to volume ratio, took longer to accelerate. Measurements taken at different axially locations showed that the bag breakup process is not symmetric. After again analyzing high speed videos, it was seen that the fragments formed from the bag breakup process tend to disperse radially instead of traveling directly downstream with the air flow; this asymmetry was indeed reflected in both the fragment and velocity distribution data.

Initially, a bimodal distribution was assumed to occur for the bag breakup regime due to the different sizes of rim and bag fragments. Instead, a bimodal distribution was only seen for a few of the cases, and in those cases, the bimodal distribution was attributed to large bag fragments instead of rim fragments after observing corresponding high speed videos of the breakup process.

Nomenclature

\( d_0 \) initial droplet diameter  
\( s \) Carreau consistency index [s]  
\( b \) Carreau rate index  
\( \mu_\infty \) Infinite shear rate viscosity limit [Pa-s]  
\( \mu_0 \) Zero shear rate viscosity limit [Pa-s]  
\( \mu_{\text{eff}} \) Effective viscosity [Pa-s]  
\( \dot{\gamma} \) Strain rate [1/s]

References

Figure 16. Fragment size distribution with varying radial distance: 0.1% XG, We = 16.5.