Pre-filming primary atomization: Experiments and modeling

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Abstract

Primary atomization in a planar pre-filming atomizer has been studied using high magnification shadowgraphy coupled with particle and ligament tracking. From this, mean drop sizes are reported for upstream locations which are inaccessible using PDA techniques. In addition, film thickness measurements and high speed visualizations have been performed. Based on these results, a new physics based model is derived to predict \( D_{32} \). Preliminary results indicate accuracy is within ±30% of the measured values. This model has a number of advantages compared to previous alternatives, including prediction of upstream drop sizes and no reliance on unknown flow properties.

Introduction

Pre-filming air blast atomizers such as those shown in Figure 1(a) are widely used for fuel injection in gas turbine engines and have a number of advantages including fine atomization, relatively little change in performance over a wide range of fuel flow rates, and low pressure losses [1]. Currently, such atomizers are being investigated for use in lean burn combustors which promise the additional advantages of fuel efficiency and low pollution, particularly NO[2]. However, because these designs operate below the stoichiometric fuel to air ratio, they are susceptible to flame instability and extinction. To overcome this, advanced designs are required to precisely control fuel atomization and dispersion.

Much of the previous investigations into atomizers of this type consist of spray measurements at elevated pressures and temperatures using either actual nozzles [3] or simplified planar injectors [4]. Flows are typically non-reacting, and due to limited optical techniques fragment sizes are measured downstream where atomization is complete and drops are approximately spherical.

However, in reacting flows, drop evaporation and combustion is likely to be significant upstream of the cold flow measurement location. Consequently, simulations using inlet conditions from such measurement have limited accuracy. To remedy this, the first half of this work reports measurements of fragment sizes in the upstream dense spray region using a unique image processing routine. Additionally, film thickness measurements are reported along with high speed videos of the primary atomization process.

Currently few models exist to predict initial fragment sizes in pre-film atomizers, and those that are available require knowledge of film properties which are difficult to estimate [5]. As a result, nozzle design must often rely on costly experimental trial and error. To address this, in the second half of this work a new atomization model is derived to predict \( D_{32} \) based on known physics and experimental observations. Particular attention is paid to ensuring that the model is well suited to future implementation in numerical simulation.

Experimental setup

In order to enhance optical accessibility, a two-dimensional abstraction of an axis-symmetric airblast atomizer was used for all experiments. Figure 1(b) shows a cross section of the pre-filming surface and the surrounding duct. To ensure a two-dimensional air flow and avoid interfering corner vorticities, the duct has a wide aspect ratio [6]. The out of plane dimension is \( b = 50 \text{ mm} \) and all measurements were taken at the centerline. Furthermore, the air flowing around the pre-filming surface has no swirl. All measurements were performed at ambient test conditions (\( \rho_g = 1.2 \text{ kg/m}^3 \), \( v_g = 1.5\times10^{-5} \text{ m/s} \)), and the mean air velocity could be adjusted between \( \bar{u}_g = 20 \text{ to } 60 \text{ m/s} \).

Liquid was supplied through 50 small vertical drill holes. Upon exiting the holes air shear caused the liquid to form a thin film travelling in the \( x \)-direction. The film load could be adjusted between \( V/b = 25 \) to 75 mm²/s. For all film loads it was ensured, that the wetting of the surface was uniform and there was no film separation from the surface.

To investigate the effect of different liquid properties on the primary breakup, four different liquids were tested in the experiment. Their relevant physical properties are shown in Table 1.

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Figure 1. (a) typical gas turbine pre-film atomizer, (b) experimental atomizer

Table 1. Liquid physical properties

<table>
<thead>
<tr>
<th>liquid</th>
<th>density, $\rho$ [kg/m$^3$]</th>
<th>dynamic viscosity, $\mu$ [kg/m·s]</th>
<th>kinematic viscosity, $\nu$ [m$^2$/s]</th>
<th>surface tension, $\sigma$ [kg/s²]</th>
</tr>
</thead>
<tbody>
<tr>
<td>50% propanediol-50% water (v/v)</td>
<td>1004.3</td>
<td>0.00627</td>
<td>6.25x10$^{-6}$</td>
<td>0.0454</td>
</tr>
<tr>
<td>Shellsol D100</td>
<td>797.0</td>
<td>0.00255</td>
<td>3.20x10$^{-6}$</td>
<td>0.0380</td>
</tr>
<tr>
<td>Shellsol D70</td>
<td>792.0</td>
<td>0.00156</td>
<td>1.97x10$^{-6}$</td>
<td>0.0260</td>
</tr>
<tr>
<td>Shellsol D40</td>
<td>780.0</td>
<td>0.00089</td>
<td>1.14x10$^{-6}$</td>
<td>0.0250</td>
</tr>
</tbody>
</table>

Shadowgraphy

The disintegration of the liquid was analyzed by means of background illumination technique, using the optical setup shown in Figure 2. A dual cavity Nd:YAG pulse laser provided short time, high power back light illumination. The beam profile was broadened by an expansion lens and homogenized in intensity by means of a diffuser disc. Due to interference effects, laser speckles were generated at the diffuser which had the potential to reduce image quality. To overcome this phenomenon, a cuvette containing laser dye was inserted into the optical path. It absorbed the coherent laser light and emitted incoherent light of a different wavelength [7]. Single frame shadowgraph images were recorded with a PIV camera in the $xz$-plane of the pre-filming surface. The image size was 15.2 mm in the $z$-direction and 7 mm in the $y$-direction. Examples are shown in Figure 3.

The shadowgraphic images were analyzed using the MATLAB® image processing code discussed in [6]. A contouring algorithm performed a thresholding of the pixel array intensities with sub pixel accuracy, and all visible particle outlines were represented by a closed polygon. Open polygons represented particles at the borders of the image or the ligament structure at the atomizer edge and were removed for the analysis (Figure 3). With this it was possible to determine the droplet sizes, positions, and counts as well as the ligament sizes and positions. Furthermore, unlike PDA measurements it was possible to estimate the diameter of non-spherical droplets, which is a great advantage especially in the primary atomization region near the atomizer edge.

A comparison of the MATLAB® code to commercially available shadow sizing codes can be found in [8].

Figure 2. Optical setup for shadowgraphic images
Experimental results

Shadowgraphy

Figure 4 shows $D_{10}$, $D_{32}$, and $D_{90}$ measured using the shadowgraphic technique as a function of mean air velocity for a film flow rate of $V/b = 25 \text{ mm}^2/\text{s}$. Liquid physical properties appear to have a relatively minor effect on final drop sizes. This is theorized to be due to the opposing effects on fluid properties on film development and primary atomization. For example, fluid viscosity specifies the inner frictional forces of the liquid film such that higher viscosity results in a lower film velocity. Likewise, larger inertial forces are required to accelerate a film of higher density. As a result, increased fluid density is expected to lower the film speed. Due to these effects the relative velocity between the liquid and the gaseous phase will increase with increasing fluid viscosity and density, and it is well known that an increase in relative velocity enhances the atomization efficiency. However, it is also well known that high fluid viscosity and density act to stabilize a fluid against atomization [9]. Therefore, as a result of these offsetting effects the final change in drop sizes with fluid properties appears to be relatively minor and is likely within experimental uncertainty. Future investigations will be needed to reduce the experimental uncertainty such that these effects can be better quantified.

Contrary to the minor effects observed due to liquid physical properties, the gas phase velocity appears to have a major effect on the outcome of primary atomization. Mean diameters decrease with increasing air speed, which can be explained by the increasing aerodynamic forces acting on the surface of the ligaments.

In addition to the influence of the liquid properties on the breakup of the liquid film, Figure 4 shows a comparison of the shadowgraphic measurement at the atomizer edge and PDA measurements taken 50 mm downstream of the atomizer edge for Shellsol D70. $D_{10}$ from the PDA measurements is approximately 60% smaller than that measured with shadowgraphy, and for $D_{32}$ the difference is around 100%. The largest discrepancy between the PDA and the shadowgraphic measurements is for $D_{90}$ (approximately 130-230%). These differences are due to the fact that the shadowgraphic measurements only cover the primary breakup zone whereas the PDA measurements were taken downstream of the atomizer edge where secondary breakup of the largest droplets has occurred. Consequently, the shadowgraphic measurements provide more complete information about the droplet sizes in the primary breakup region. As mentioned in the introduction, initial droplet sizes and positions have a significant impact on the accuracy of numerical simulations, thus the improved knowledge provided here could be used to enhance the accuracy of future simulations.

The same shadowgraphic measurements were performed at a film flow rate $V/b = 75 \text{ mm}^2/\text{s}$ and are shown in Figure 5. Comparing the results for $D_{10}$, $D_{32}$, and $D_{90}$ with the ones at $V/b = 25 \text{ mm}^2/\text{s}$ (Figure 4) reveals small changes in the mean diameters which are likely within the experimental uncertainty of the measurement technique. Future investigations will attempt to quantify and reduce these uncertainties to enable a more detailed investigation on the influence of the film flow rate on primary breakup.

High speed videos

To better understand the breakup process, high speed videos were recorded at frame rates up to 5 kHz using the shadowgraphic technique shown in Figure 2. Due to reduced resolution, fragment sizes could not be accurately determined from these videos. Nevertheless, they provide valuable insight into the atomization physics.

Figure 6 shows typical results for two fluids. In both cases, a mass of liquid, referred to as a ligament, accelerates away from the atomizing edge while indentations appear in the perpendicular direction. The average length of the indentations is given the symbol $\lambda_{\text{lig}}$, and was estimated manually from the high speed videos. Eventually these indentations form bag like structures which break into fine drops in a manner similar to bag breakup observed during secondary atomization [10]. Events such as this appear to occur rather periodically, and manual analysis of the high speed videos was used to estimate the mean breakup frequency, $f$.

Results for $\lambda_{\text{lig}}$ and $f$ are shown in Figure 10 when discussing the new atomization model.
Film thickness measurements

Available models of pre-filming atomization require knowledge of the film thickness [5], which was measured here using a model LT-8100 laser focus displacement meter (LFDM) from Keyence Corporation. In this device, the focusing lens of a 670 nm laser vibrates with a known displacement. Intensity of backscattered light is recorded as a function of time, and it is assumed that peak intensity occurs when the laser focal point coincides with the film surface. To prevent signal corruption due to light reflection from the aluminum pre-filmer, its surface was anodized using a black dye. With this it was possible to measure surface heights within a range of ±1 mm and a resolution of 0.1 μm. Further details on this device and its application to the measurement of film surface heights can be found in [11, 12].

Figure 4. Variation of (a) $D_{10}$, (b) $D_{32}$, and (c) $D_{90}$ for varying mean air velocities and $V/b = 25$ mm$^2$/s

Figure 5. Variation of (a) $D_{10}$, (b) $D_{32}$, and (c) $D_{90}$ for varying mean air velocities and $V/b = 75$ mm$^2$/s

Figure 6. Typical high speed videos for $\bar{u}_g = 40$ m/s, $V/b = 25$ mm$^2$/s, time between images is 0.4 ms.
(a) Shellsol D70 and (b) 50% propanediol
The LFDM principle assumes that the surface to be measured is a diffuse reflector, such that a backscattered signal is achieved regardless of surface angle. Unfortunately, the liquid surface measured here is specularly reflective, and, as a result, liquid height could only be measured when the surface was approximately perpendicular to the laser. Consequently, only the crests and troughs of the wavy film were detectable, and the signal quality was insufficient to calculate the wave frequency. Nevertheless, averaging the signal over time produced a good estimate of the mean film height.

Figure 7 shows the recorded mean film heights. These results are spatially averaged from measurements taken between 15 to 35 mm after the film injection and ±4 mm about the atomizer centerline. In all cases the standard deviation is within 7% of the mean. As expected, film height decreases with increasing gas velocity and decreasing liquid loading.

**Theoretical modeling**

In [5] Dombrowski presents a model for atomization of a liquid sheet acted upon by high speed air flowing over its top and bottom surface. A linear stability analysis is used to calculate the most unstable wavelength for a given sheet thickness, and growth of this wave is assumed to eventually lead to break up into streamwise ligaments. Finally, these ligaments are assumed to form drops due to capillary instabilities.

Having measured the initial film thickness, this model can be applied here. Figure 8 compares the predictions of Dombrowski for a constant sheet thickness [5] with the downstream PDA measurements shown in Figure 4(b). Agreement between measurement and prediction is quite good. Here it should be noted that Dombrowski’s original work reports a model uncertainty as high as ±20% [5]. Therefore, it is expected that experiments at other operating conditions may reveal larger uncertainties than those shown in Figure 8. Nevertheless, these results show that the Dombrowski model accurately predicts the downstream drop sizes measured here.

Unfortunately, use of this model requires knowledge of the mean film height, a quantity which has proven difficult to predict or measure in realistic gas turbine injectors such as that shown in Figure 1(a). Furthermore, the model predictions do not agree with the upstream drop size measurements reported above. Therefore, to improve upon this, the remainder of this work discusses the development of a new atomization model which does not require film height as an input and is optimized to predict upstream drop sizes.

Figure 9 outlines the proposed process. First, waves develop on the film and periodically transport mass to the atomizing edge. This is assumed to result in the formation of cylindrical ligaments of diameter, $D_{lig}$, and frequency, $f$. These ligaments are unstable due to capillary effects and break apart to form large drops of diameter $D_d$. Finally, these large drops are assumed to undergo secondary atomization via the bag breakup mechanism. In what follows, each process is considered in detail and models are presented to describe their effects.

**Film flow**

In [4] Bhayaraju presents visualizations of the wavy film on a planar pre-filming atomizer similar to that used in the current investigation. Large amplitude surface waves were observed which contributed significantly to the breakup at the atomizing edge. Here it is assumed that these waves result from the Kelvin-Helmholtz instability wherein aerodynamic forces from the high speed, co-flowing gas destabilize the liquid film.

Due to the inlet length, $x_{inlet}$ shown in Figure 1(b), a boundary layer will develop in the air flow before contacting the film surface. As discussed in [13], the presence of such boundary layers dominate the Kelvin-Helmholtz instability whenever $We_{\delta} > 1$ where $We_{\delta}$ is the Weber number based on the gas phase boundary layer and $\delta$ is the vorticity thickness.

![Figure 7. Mean film height for (a) $V/b = 15 \text{ mm}^2/\text{s}$, (b) $V/b = 25 \text{ mm}^2/\text{s}$, and (c) $V/b = 50 \text{ mm}^2/\text{s}$](attachment://Figure7.png)
For all conditions considered here $Re_{inlet} < 5 \times 10^5$ such that laminar boundary layer development can be assumed, and from the analysis of Blasius [14]

$$\frac{\delta}{x_{inlet}} = \frac{3.012}{\sqrt{Re_{inlet}}}.$$  \hspace{1cm} (1)

Using Eq. (1) it can be shown that $We_{k} \rho / \rho_{g} \gg 1$ for all test conditions. Therefore, based on the analysis presented in [13] the initial wave frequency can be approximated by $f \approx (u_{c} / \delta \rho_{g} / \rho_{l})^{1/2}$ where $u_{c}$ is the initial wave convection velocity approximated by $u_{c} \approx \bar{u}_{g} (\rho_{g} / \rho_{l})^{1/2}$. Combining this with Eq. (1) yields:

$$f \approx 0.331 \frac{\bar{u}_{g}}{x_{inlet}} \sqrt{Re_{inlet}} \left(\frac{\rho_{g}}{\rho_{l}}\right).$$  \hspace{1cm} (2)

If it is assumed that all initial waves accelerate downstream at an equal rate, then Eq. (2) can be used to estimate the frequency of waves reaching the atomizing edge. By further assuming that one spanwise ligament forms from each wave, Eq. (2) can also be used to predict the atomization frequency. Figure 10(a) compares the measured frequency from the high speed videos to that predicted by Eq. (2). The solid black line represents the best fit between measurements and prediction. From this it can be concluded that Eq. (2) should be multiplied by a constant 1.45 to account for non-linear effects which cannot be predicted by the linear stability analysis used here. Once this is done reasonable agreement is achieved between theory and experiment.

**Ligament formation and breakup**

Assuming the spanwise ligaments are initially cylindrical, mass conservation yields: $\pi D_{lig}^{2} / 4 = (V/b) / f$. Because aerodynamic forces are negligible in the parallel direction, it is reasonable to assume these cylinders breakup due to capillary instabilities. For this case, Rayleigh’s analysis predicts the most unstable wavelength, $\lambda_{lig} = 4.508 D_{lig}$ [15]. Combining this with Eq. (2) including the 1.45 factor yields:

$$\lambda_{lig} \approx 7.342 \sqrt{\frac{(V/b) x_{inlet}}{\bar{u}_{g}}} \left(\frac{\rho_{g}}{\rho_{l}}\right)^{1/2} Re_{inlet}^{-1/4}.$$  \hspace{1cm} (3)

Figure 10(b) compares the observed breakup wavelengths with those predicted by Eq. (3). The solid black line represents the best fit between measurements and prediction. On average the agreement between experiment and theory is quite good and practically no correction is needed. It is supposed that the large scatter in the data is due to measurement uncertainties, and improved measurement techniques are needed to reduce this uncertainty.

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**Figure 8.** Comparison between predictions of Dombrowski [5] and downstream measurements for Shellsol D70 at $V/b = 25$ mm$^2$/s

**Figure 9.** Atomization model: (a) typical experimental observations and (b) proposed model

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Ignoring satellite drops and assuming that one drop of diameter, \(D_d\), forms from each wavelength, mass conservation yields, \(\pi D_{lig}^2 \lambda_{lig}^2 / 4 = \pi D_d^3 / 6\). Combining this with Eq. (3), results in a prediction for the large initial droplets:

\[
D_d \approx 3.130 \left( \frac{V/b}{u_g} \right)^{1/2} \left( \frac{\rho_t}{\rho_g} \right)^{1/2} Re_{inlet}^{-1/2}. \tag{4}
\]

**Droplet breakup**

According to the proposed model, these large drops immediately undergo further breakup due to aerodynamic effects. This is referred to as secondary atomization, and for drops of low viscosity (\(Oh_d < 0.1\)) previous experimental investigations have shown that breakup occurs when \(We_d > 11\) where \(We_d\) is the Weber number based on the drop diameter [10]. Note that \(Oh_d < 0.1\) for all cases considered here.

Observations of secondary atomization have shown that various breakup modes are possible depending on the level of aerodynamic loading. Bag breakup occurs for \(11 < We_d < 35\), wherein the center of the drop is blown downstream and the periphery forms a thick toroidal rim [10]. A similar breakup process is observed in the high speed videos shown in Figure 6 and Figure 9(a). For this case, Wert provides a model which predicts the fragment \(D_{32}\) based on the initial Weber number [16],

\[
D_{32} \approx 0.324 \frac{\sigma}{\rho_g u_g^2} \left[ We_d \left( T_{tot} - T_{ini} \right) \right]^{1/2}. \tag{5}
\]

Here \(T_{tot}\) is the non-dimensional total breakup time and \(T_{ini}\) is the initiation time, which Hsiang approximates as 5 and 1.6 respectively for \(Oh_d < 0.1\) [17].

When applying Eq. (5), special attention must be paid to the relative gas velocity. In the current model the drops are assumed to break up at the atomizing edge where boundary layers result in a local gas velocity, \(u_g\), that is significantly less than the mean gas velocity, \(\bar{u}_g\). To approximate this, the gas phase boundary layer is modeled using a flat plate solution ignoring the effect of the liquid film. In that case, the appropriate boundary layer development length is \(x_{edge}\) (Figure 1). Using this it can be shown that \(Re_{edge} < 5 \times 10^5\) for all conditions considered here. Therefore, the boundary layer remains laminar, and the relative gas velocity is approximated from the Blasius solution at \(y = 1.45 D_d\).

Figure 10(c) compares \(D_{32}\) calculated using Eq. (5) with the measured values shown in Figure 4 and Figure 5. At the lowest air velocities it was occasionally found that \(We_d < 11\), such that bag breakup is not expected and Eq. (5) could not be applied. For these situations it was found that \(D_{32} \approx D_d / 2\).

The solid black line in Figure 10(c) represents the best fit between theory and the experimental measurements. For all conditions considered here, agreement is within \(\pm 30\%\), indicating that the proposed model has adequately captured the most important physics.

![Figure 10. Theoretical predictions compared to measurements for (a) breakup frequency, (b) spanwise wavelength, and (c) \(D_{32}\) after primary atomization](image-url)
Future investigations will attempt to reduce the model uncertainty using more precise measurements and incorporating additional physical effects. For example, knowledge of the film flow is currently limited and it is unclear if the model has accurately predicted the actual wave frequency. To address this, future investigations will attempt to measure the wave frequency. Furthermore, Figure 10(a) reveals that the accuracy of the predicted frequency is a function of the material properties, and it seems likely that the uncertainty could be reduced if Eq. (2) were to include the stabilizing effect of liquid phase viscosity.

For practical applications of the proposed model, Eq. (4) would be used to estimate the initial droplet size. Then atomization of these droplets would be predicted using either experimental correlations such as Eq. (5) or numerical atomization models such as the TAB [18] or DDB [19] methods. Therefore, as currently constructed, this model could be incorporated into Lagrangian droplet tracking codes which include computation of secondary atomization. This would then allow for simulation of spray drop sizes and dispersion for a practical atomizer such as that shown in Figure 1(a) without the need to measure initial droplet sizes. Of course, validation is required before this is recommended for design proposes.

Conclusion

This work considered liquid atomization in a planar pre-filming air blast atomizer. The influence of liquid physical properties, air velocity, and film flow rate were studied by means of shadowgraphy, PDA measurements, high speed visualization and film thickness measurements. Particular attention was paid to the mean droplet diameters in the primary breakup zone.

For the range of conditions considered here, changes in the mean air velocity resulted in the most significant effect on mean diameters while modification of the liquid physical properties or flow rate produced relatively minor effects.

Based on the experimental results, a new physics based model was derived to predict \( D_{32} \). The accuracy is within ±30% of the measured values. The main advantages of this model are: prediction of the droplet sizes in the near region of the atomizer edge and no reliance on unknown flow properties, such as the film thickness.

To validate the results presented here, future work is planned to improve the accuracy of the experimental techniques and measure the frequency and size of waves on the film surface.

Nomenclature

\[
\begin{align*}
D & \quad \text{drop diameter [m]} \\
f & \quad \text{wave or atomization frequency [s\(^{-1}\)]} \\
h & \quad \text{mean film height [m]} \\
Oh & \quad \text{Ohnesorge number, } \mu/(\rho_D \sigma D)^{1/2} \\
Re & \quad \text{Reynolds number, } u_{\text{avg}} \theta \rho \gamma \\
T_{\text{init}} & \quad \text{non-dimensional initiation time} \\
T_{\text{tot}} & \quad \text{non-dimensional total breakup time} \\
u & \quad \text{velocity in the } x\text{-direction [m s}\(^{-1}\)]} \\
\bar{u} & \quad \text{mean } u \text{ through a } yz\text{-plane [m s}\(^{-1}\)]} \\
V/b & \quad \text{volumetric film flow rate per unit length in the } z\text{-direction [m}\(^2\) s\(^{-1}\)]} \\
We & \quad \text{Weber number, } \rho u_{\text{avg}}^2 D/\sigma \\
\delta & \quad \text{vorticity thickness, } \delta = \bar{u}_{\text{avg}} \theta (du_{\text{avg}}/dy)_{\text{max}} [m] \\
\lambda_{\text{lg}} & \quad \text{spanwise wavelength [m]} \\
\mu & \quad \text{dynamic viscosity [kg m}^{-1} \text{ s}^{-1}] \\
\nu & \quad \text{kinematic viscosity [m}^2 \text{ s}^{-1}] \\
\rho & \quad \text{density [kg m}^3\text{]} \\
\sigma & \quad \text{surface tension [kg/s}^2\text{]} \end{align*}
\]

Subscripts

\( g \) \quad \text{gas} \\
\( l \) \quad \text{liquid}

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References