Atomization and Combustion Performance of Renewable Liquid Fuels in a Swirl-Stabilized Research Combustor

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Abstract
This work considers the atomization performance of alternative liquid fuels for gas turbine applications. Biodiesel and ethanol have been considered in previous combustion studies—however more advanced liquid fuels are being developed. One such fuel is a Hydrotreated Renewable Diesel (HRD), derived from Algae. Field tests have verified that these fuels can be used as a drop-in alternative; this study looks at the fundamental atomization characteristics to provide insight into the physically-controlled combustion process. Five fuels are considered: a 50/50 blend of F-76 military diesel and HRD, Biodiesel (derived from waste vegetable oil), Ethanol, #2 Diesel, and F-76 military diesel. A small-scale research combustor with a twin-fluid airblast atomizer was used. Atomization quality was determined by measuring the droplet size distributions and average drop sizes using an ensemble laser diffraction system. In addition, spray cone angles were determined using high-speed cinematography. The experimental results for the Sauter Mean Diameter were compared to existing correlations for plain-jet airblast atomizers, with excellent agreement for all fuels except biodiesel, due to its high viscosity. At the highest atomizing air flow rates studied, all fuels showed similar atomization characteristics, with slightly higher values of SMD for both biodiesel and DF2; however, the fluid properties and atomization characteristics of the HRD fuel were most similar to those of the petroleum-derived fuels, implying similar combustion characteristics. Combustion tests carried out reveal differences in NOx and CO emissions among the fuels including F76 and the F76/Algae blend. These differences appear more dependent upon relative volatility and chemistry between the fuels than on physical properties.

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Introduction

The development of alternative liquid fuels has recently been a major focus of combustion research, particularly for internal combustion engines. Though there is an abundance of literature concerning reciprocating diesel engines, the use of alternative fuels in gas turbines is relevant for both marine and aviation applications. Biodiesel and bioethanol are both renewable in nature [1,2] and though they are reasonable for commercial applications, they do not meet the rigid specifications for aviation and military fuels [3]. In addition, there are still major barriers to large scale production; thus, research has started to focus on developing advanced alternative fuels that can be used as “drop-in” fuels [4]. One such fuel is Hydrotreated Renewable Diesel (HRD), which can be produced in existing refinery infrastructure [5] and from advanced feedstocks, such as Algae [6].

Several field tests have been conducted on gas turbines demonstrating the viability of Biodiesel [7,8,9], Ethanol [10,11], and HRD fuels [12,13]. More detailed combustion rig tests have examined the emissions from these fuels, including biodiesel [14,15]. Though emissions data are available for the Algae-derived fuel [12], no information is available on the atomization characteristics. As the combustion process is heavily dependent on the physical process of atomization, this study looks to compare the atomization performance of Algae-derived HRD to more common alternative fuels, as well as conventional petroleum fuels. Specifically, this study investigates the atomization of #2 Diesel, NATO F-76 Military Distillate (F-76), a blend of Algae-derived HRD and F-76 (Algae/F-76), ethanol, and biodiesel.

Atomization performance is heavily dependent on the fuel properties and the atomizer geometry. This particular study uses a twin-fluid airblast atomizer, which was developed in house for studying the long-term effects of combustion on materials corrosion. In a combustion rig, the airblast atomizer offers the advantage of simplicity, while providing good fuel-air mixing [16,17]; it also has the advantage of ease of atomization at low liquid flow rates. This study looks to characterize the atomization process of this atomizer for the above mentioned fuels. In particular, the droplet size distributions and average droplet sizes are investigated, and high-speed cinematography provides insight into the structure of the spray. In this study, the droplet size distributions and SMD values are measured using ensemble laser diffraction; the SMD values are then correlated to the fuel properties based on a relevant correlations [18]. In addition, time-averaged high-speed images are presented to determine the relative cone-angle for each fuel. This data can then give insight into the combustion performance of these alternative fuels.

Experimental Methods

This study used the atomizer from a burner that was developed in house to simulate the effluent from a typical gas turbine combustor operating on alternative fuels to support advanced materials testing. As these materials tests require continuous operation ranging from 500 to 1000 hours in duration, the atomizer was designed with a nominal flow rate of 3.53 g/min in order to satisfy the fuel demand in 55-gallon batches [19]. The burner incorporates a twin-fluid airblast atomizer, similar to that used by Rizk and Lefebvre [20]; however, rather than employing co-flowing air, the atomizing air converges upon the liquid orifice, similar to that described by Lefebvre [18]. There is an additional cylindrical component that centers the liquid tube within the air stream. The relevant parameters are shown in Table 1, and the atomizer is shown in Figure 1.

![Figure 1. Cross-section of twin-fluid airblast atomizer.](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Orifice Diameter</td>
<td>0.305 mm</td>
</tr>
<tr>
<td>Air Orifice Diameter</td>
<td>3.175 mm</td>
</tr>
<tr>
<td>Atomizing Air Contraction Angle</td>
<td>58 degrees</td>
</tr>
</tbody>
</table>

Table 1. Atomizer parameters.

Five fuels are considered for this study, listed in Table 2 (along with the supplier). The conventional fuels (Ethanol, Biodiesel, and #2 Diesel) were supplied locally; the military fuels (F-76 and Algae/F-76 blend) were supplied by the Office of Naval Research (ONR). The physical properties for each fuel were measured experimentally. Density was measured using a mass balance and a graduated cylinder. Surface tension was measured with a stalagmometer, and viscosity was...
To determine the parameter that "tune" the combustion efficiency, a comprehensive factorial experimental design was selected to gain a comprehensive map. The atomization air flow rate was metered by a sonic orifice. In order to estimate the air velocity through the orifice, a differential pressure transducer was attached to the atomizing air flow line to measure the pressure drop across the injector. A schematic is presented in Figure 2.

Rather than considering a constant mass flow rate among all fuels, the firing rate is chosen as to be constant for all fuels; this is done to simulate the power demand when using fuels with different heating values. A global equivalence ratio of 0.5 is selected for the petroleum fuels (#2 diesel, F-76); the equivalence ratio for the other fuels is then set to match the adiabatic flame temperature at this condition (1527 K). To determine the fuel composition for all fuels (except Ethanol), Gas Chromatography/Mass Spectrometry (GC/MS) was employed using a Finnigan 2000 series Trace MS Trace GC. From these results, an approximate chemical formula was derived based on the average composition. This approximate chemical formula was then used with equilibrium software provided by Turms [23] to calculate the adiabatic flame temperature; given the enthalpy of reactants for the different fuels [23,24]. The nominal fuel flow rates are presented below in Table 4.

### Table 2. Physical fuel properties (Fuel supplier in parentheses).

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Density (kg/m³)</th>
<th>Dynamic Viscosity (kg/m s)</th>
<th>Surface Tension (kg/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol (Gold Shield)</td>
<td>784.8</td>
<td>1.231 x 10⁻³</td>
<td>0.02286</td>
</tr>
<tr>
<td>#2 Ultra-Low Sulfur Diesel (UCI North Campus)</td>
<td>828.6</td>
<td>2.881 x 10⁻³</td>
<td>0.02876</td>
</tr>
<tr>
<td>F-76 Naval Distillate (ONR)</td>
<td>830.3</td>
<td>2.593 x 10⁻³</td>
<td>0.02862</td>
</tr>
<tr>
<td>Algae HRD/F-76 Blend (ONR)</td>
<td>811.1</td>
<td>3.699 x 10⁻³</td>
<td>0.02771</td>
</tr>
<tr>
<td>Biodiesel (Extreme Biodiesel)</td>
<td>884.8</td>
<td>7.409 x 10⁻³</td>
<td>0.02794</td>
</tr>
</tbody>
</table>

### Table 3. Atomizing Air Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Low</th>
<th>Mid</th>
<th>High</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow Rate (g/min)</td>
<td>3.42</td>
<td>4.33</td>
<td>5.22</td>
</tr>
<tr>
<td>DP (kPa)</td>
<td>9.89</td>
<td>17.5</td>
<td>24.8</td>
</tr>
</tbody>
</table>

### Table 4. Atomizing Air Parameters

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Flow Rate mL/min</th>
<th>Global Eq. Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>7.03</td>
<td>0.525</td>
</tr>
<tr>
<td>#2 Diesel</td>
<td>4.21</td>
<td>0.501</td>
</tr>
<tr>
<td>F-76</td>
<td>4.21</td>
<td>0.499</td>
</tr>
<tr>
<td>Algae HRD/F-76</td>
<td>4.31</td>
<td>0.495</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>4.59</td>
<td>0.505</td>
</tr>
</tbody>
</table>

measured using a falling ball-drop viscometer. The fuel properties are presented in Table 2. Of note is that the military specifications for the viscosity of F-76 require a value between 1.7 and 4.3 x 10⁻³ kg/m s at 40 °C [21]; both Biodiesel and Ethanol do not meet this requirement at ambient conditions.

The Algae HRD/F-76 blend is similar in properties to the conventional petroleum fuels (Diesel, F-76), with minor differences in viscosity and density. Granted that there is a substantial amount of petroleum fuel in this blend, the production of Algae HRD involves a process called hydrotreatment. Very generally, this process involves the reaction of a triglyceride feedstock (in this case, oil from microalgae) with hydrogen at high pressure and temperature in the presence of a catalyst. Further refinery processes (such as cracking and isomerization) result in a liquid hydrocarbon fuel that is chemically (and physically) similar to conventional petroleum fuels [22]. This eliminates the high-viscosity and density associated with the other vegetable-oil based feedstock (biodiesel), which should theoretically lead to finer atomization.

For the measurements of droplet sizes, a 3-level factorial experimental design was selected to gain a comprehensive map. Three parameters were varied: fuel type, atomizing air flow rate, and atomization air pressure differential (DP); mass flow rate of fuel was kept constant for each individual fuel. The atomizing air flow rate was used to vary the Air/Liquid Ratio (ALR). Recall in Figure 1 that the liquid is supplied via a tube. This can be moved in order to “tune” the combustor; this changes the effective area for the atomizing air within the nozzle, changing the atomizing air velocity for a constant flow rate. The atomization air DP provides a direct measurement of the air velocity, based on Bernoulli’s equation. The numerical values are listed below in Table 3.
Two optical methods were used to study the spray characteristics: ensemble laser diffraction, and high-speed shadowgraphy. A Malvern Insitec Spraytec was used to determine droplet size distributions and SMD values. Because this instrument records data in real time and reports the distribution at a rate of 1 Hz, data was taken over a period of 1 minute to obtain a sufficient average of data. A Vision Research Phantom 7.1 digital high-speed camera was used to obtain shadowgraph images and high speed video of the spray. These high speed videos were extracted and converted to a format which could be read in the MATLAB Image Processing Toolbox. The process of determining an averaged image is discussed below.

200 frames of video were extracted for each case. In the Vision Research CineViewer 675 software, the spray images were pre-processed using an Edge Sobel Vertical filter to enhance the contrast and isolate the droplets from the noise. The individual frames from then converted into binary images in MATLAB using thresholding, further eliminating background noise. These frames were then numerically averaged, and a Canny method within the MATLAB was used to find edges in the spray outline. Using these edges and the average spray images, a spray cone angle could then be inferred.

Results and Discussion

The time-averaged images of the spray for each fuel are presented in Figure 3, along with select stills. These provide a representative comparison between the different fuels at the high-DP/mid flow rate conditions for atomization (4.33 g/min of air, 24.8 kPa ΔP), where emissions data had previously been recorded [19]. The red lines represent the spray boundary as determined by the edge detection. Though it is difficult to define a rigid boundary for this spray, this edge detection method is able to encapsulate most of the volume of the spray. Note that for all of the fuels except biodiesel, there is a blurred mist of very small droplets; these are moving at a relatively high velocity, compared to the larger, more discreet drops.

The spray cone angle for all the fuels is reported in Table 5. Interestingly, both F-76 and the Algae HRD/F-76 blend both have high angles relative to the flow of diesel. In the high-speed images, both of these sprays are slightly canted to one side. Though this doesn’t affect the SMD behavior (discussed below), the effect of a larger spray cone angle would increase the exposure of droplets to the surrounding air, improving secondary atomization as well as mixing and heat transfer [25]. Though there are some stray droplets that do travel beyond the measured spray cone, the bulk of the fluid flow in this atomizer is close to the central axis, and this spray angle doesn’t appear to be dependent on the angle within the atomizer itself.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Spray Cone Angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>23.4°</td>
</tr>
<tr>
<td>#2 Diesel</td>
<td>20.2°</td>
</tr>
<tr>
<td>F-76</td>
<td>38.8°</td>
</tr>
<tr>
<td>Algae HRD/F-76</td>
<td>36.4°</td>
</tr>
<tr>
<td>Biodiesel</td>
<td>28.2°</td>
</tr>
</tbody>
</table>

Table 5. Atomizing Air Parameters

Regarding the breakup process itself, Figure 3 shows the impact of the atomizer geometry. Unlike a traditional plain-jet airblast atomizer, in which a liquid jet undergoes wavy deformation before breaking into ligaments and individual droplets, in this atomizer the droplet issue directly from the exit orifice. Some ligaments attach to the lip of the atomizing orifice, particularly for the highly-viscous biodiesel, but the still im-
es reflect the prompt atomization process. In particular, the atomization process is dominated by aerodynamic and surface tension forces, with viscosity taking a reduced roll [16]; however, the viscosity of biodiesel is high enough to impact the breakup process.

Recalling Figure 1, the geometry is such that the atomizing air should impinge on the liquid jet. In the past it has been discussed that this geometry, in which the air is impinging on the liquid rather than co-flowing with it, will result in the breakdown of the classical mode of atomization [18]. Further complicating this process is the presence of a sharp corner in the atomizing air stream at the end of the fuel tube; it is anticipated that this corner will cause some amount of recirculation and turbulence, which may lead to smaller drop sizes issuing from the atomizer. However, there is also a volume of liquid that becomes attached to the face of the injector surrounding the orifice (more apparent for the highly-viscous fuels, Algae/F-76 blend and Biodiesel). This “bulge” has two major issues; the first is that it results in coking in the combustion environment [19]. The second is that it produces large droplets, as sometimes the atomizing air entrains some of this liquid into long ligaments which then break-up and coalesce into larger droplets downstream. This results in a wider range of drop sizes. Also, due to the turbulence just beyond the orifice of the injector, some of these droplets are accelerated away from the central “core” of droplets. This makes it even more difficult to define a rigid spray cone angle.

The results for the SMD measurements are presented in Figure 4. They are plotted against the atomizing air pressure drop; the solid lines represent a correlation developed by Lefebvre for a twin-fluid atomizer [18]. The error bars represent one standard deviation over the 60-seconds of recorded data. For this atomizer the most influential parameter on the drop size is the atomizing air velocity. As can be anticipated, the highest atomizing air velocities result in the finest atomization. The effect of ALR is not as apparent; at low pressure drops, the SMD does decrease with increasing air flow, but at high velocities this effect is limited. Biodiesel does show this effect over all flow rates. The correlation by Lefebvre would indicate this trend, but it indicates a span of around 5 microns at the low flow rates.

The fuels with similar physical properties have similar values for SMD; F-76, #2 Diesel, and the Algae/F-76 blend all produce similar ranges of drop sizes, within the experimental error. The SMD values for ethanol were also very similar, despite the higher liquid mass flow rate and different physical properties. Biodiesel had a higher SMD value for all cases, though at the highest velocities, produced an average SMD on the order of 5 microns larger than the other fuels.

Note also that the numerical correlation shows a very good fit for all fuels with some deviation for biodiesel. For any type of twin-fluid atomizer, the primary goal is to impart the kinetic energy of the atomizing air into the liquid. In the case where the atomizing air is co-flowing in parallel with the liquid jet, it has been discussed in the past that the traditional modes of disintegration for a liquid jet apply [26,27]. However, utilizes air that impinges on the liquid jet, suppressing these effects. The result is a shattering of the liquid jet before it can be deformed by liquid flow phenomena; as a result, this is governed primarily by the aerodynamic forces and the liquid surface tension, producing a side variety of drop sizes. The final correlation is provided by Equation 1. The coefficient C* was determined empirically based on the data for all fuels except biodiesel.
This correlation considers the ratio of kinetic energy imparted from the atomizing air to the energy required to atomize the liquid jet. As such, it mostly considers aerodynamic effects. When it was derived, the lack of a viscosity term was not addressed [18]. From the SMD measurements shown in Figure 4 above, this is acceptable for the low viscosity liquids (ethanol, diesel-like fuels), and this correlation does indeed produce excellent agreement. However, the correlation breaks down for biodiesel. The general trend is captured, but the discrepancy ranges from 30-50%. Compared to the other fuels, this effect is most likely due to the higher viscosity, which resists the breakup process and results in longer ligaments, which form at the atomizer lip [16].

In addition to the SMD, the droplet size distributions are presented in Figure 5, for the combustion conditions mentioned in Figure 3. The peak for all of the fuels falls around 20 microns, and it is apparent that there is a very wide range of drop sizes, further reflective of the prompt atomization process. The shift in the curve for biodiesel reflects larger droplets overall. Even though all fuels have very low values for SMD, the presence of these larger drops could have a detrimental impact on emissions for all fuels, particularly for lean combustion conditions.

\[
SMD = \frac{3 \left[ \frac{2}{d_0} + \frac{C^* \rho U^2 A}{4 \sigma (1 + 1/ALR)} \right]}{d_0}
\]  

(1)

In a combustion environment, the use of an airblast atomizer has the advantage of offering some degree of fuel-air mixing before the combustion reaction. However, the liquid fuel still needs to vaporize before it can properly react with the air. In particular, if the evaporation rates are poor, it can lead to issues such as high soot and CO production [25]. Though this paper has shown that comparable spray characteristics can be achieved for several conventional and alternative fuels, the variation in physical properties among the different fuel compositions can potentially lead to differing combustion characteristics.

In terms of evaporation rates, Figure 6 shows the distillation curve for the fuels mentioned; included is
the distillation curve for a pure Algae-derived HRD for comparison. The data for biodiesel was supplied by Bolszo [7], and the remaining curves were supplied by the Office of Naval Research. The petroleum fuels (#2 Diesel and F-76) show similar evaporation characteristics, along with both the pure Algae HRD and the blend. It is noted that F76 has the least volatility of the petroleum fuels and the neat HRD fuel is most volatile. Of the less conventional fuels, biodiesel is the least volatile of all fuels, while Ethanol is the most volatile.

Figure 6. Distillation Curve for all fuels

The rate of evaporation of droplets is governed by the “D-Squared” Law [17]. However, the effective evaporation constant is a function of these distillation curves. A droplet evaporation model was developed by Bolszo and used to compare the evaporation times for biodiesel, ethanol and #2 Diesel. Though the droplet sizes were larger in that study, the evaporation model demonstrated that the evaporation times for biodiesel are the longest, followed by diesel and ethanol. Though the data are not available for the Algae HRD or F-76, based on the distillation curve it is anticipated that these fuels will have similar evaporation times. This is especially important for the HRD fuel, as it avoids the long evaporation times associated with biodiesel.

In a previous study [19], the emissions for these fuels were measured using a swirl-stabilized research combustor with this twin-fluid airblast atomizer. It was observed that biodiesel and ethanol had substantially lower soot formation. Also, a great deal of variation in the gaseous CO and NOx emissions was observed among the fuels. These gaseous emissions are shown in Figure 7. Very generally, it was found that CO emissions were substantially higher for biodiesel, while the NOx emissions were correspondingly lower. Interestingly, the Algae/F-76 fuel produced slightly lower NOx and slightly higher CO than the neat F-76.

Figure 7. Gaseous Emissions for all fuels

Of particular note is that the CO emissions are rather high for these fuels with exception of F-76 (> 100 ppmvd at 15% O2 for all fuels except F-76). This is in spite of the relatively lower volatility of the F-76. The low CO emissions shown by F-76 relative to the other fuels could potentially be due to combustion and evaporation effects. The aromatic content in that fuel produces a very sooty flame, and the high amount of radiative heat transfer could promote evaporation and mixing, though this effect doesn’t seem to transcend to the results for #2 diesel.

As mentioned, the CO emissions for biodiesel are far higher than for the other fuels. Though temperature effects are an integral part of the formation of CO, this dramatic increase in CO also reflects the long evaporation times for biodiesel. In particular, the large droplet sizes coupled with the low volatility of biodiesel lead to a substantial increase in evaporation and vapor mixing time, to which the increase in the CO emissions is attributed [25]. An increase in CO emissions has been seen in other studies [8,11,14,15], but there are some studies that report reductions in CO emissions. It is noted that the present work was carried out at 1 atm without preheat; whereas the high temperatures and reaction rates associated with practical full-scale combustor tests can aid in the destruction of CO, and the oxygen content of biodiesel can lead to reductions in CO emissions [7]. Ethanol and the Algae/F-76 HRD have similar CO emissions, which slightly exceed those of diesel. Though other studies have shown reductions
in CO emissions for HRD fuels [13], again cooler temperatures associated with the low global equivalence ratio could be influencing the CO emissions in the present work.

The NOx emissions show the opposite trend of CO emissions, which is often the case in combustion systems. Biodiesel produces slightly less NOx than #2 Diesel or F-76, while Ethanol shows a major reduction. In practical systems, which operate at high temperatures, NOx formation is dominated by the Zeldovich (or Thermal) mechanism [25]. In this study the global equivalence ratio is relatively low, corresponding to the modest adiabatic flame temperatures (~1527 K). As such, depending on the degree of mixing and evaporate on, the thermal mechanism may not dominate the NOx formation. This is one of the advantages of lean, pre-mixed, prevaporized combustors. However, in the case where the fuel isn’t prevaporized, the presence of large droplets could lead to individual droplets burning at near stoichiometric equivalence ratios. Though this would be reflected in the higher emissions for biodiesel relative to ethanol, it is not reflected in relative emissions between biodiesel and the petroleum fuels. This would indicate that the NOx emissions at these lean conditions may likely be dominated by the prompt NO mechanism.

The Algae HRD/F-76 blend shows comparable NOx emissions to the conventional fuels, and this has been seen in other studies as well [12,13]. In addition, the NOx emissions for Ethanol are minimal. Though there are some fundamental kinetic differences in the production of pollutants, the atomization and evaporation effects still have a strong influence on the combustion process. As the development of alternative fuels progresses, drop-in fuels such as the Algae-derived HRD will be able to produce similar combustion characteristics in already optimized systems, helping to spur the transition to more renewable fuels.

Summary and Conclusions

This study investigated atomization performance of several alternative fuels in a twin-fluid airblast atomizer. Based on high-speed images of the spray, it was observed that the breakup process and spray structure was very similar among the fuels, with some minor differences for biodiesel. A prompt atomization process was observed for all fuels, resulting in similar values for SMD among fuels. The high viscosity of biodiesel led to slightly larger SMD values, and larger drop sizes were evident in droplet size distribution. A correlation for prompt atomization was used to correlate the data, and showed excellent agreement for the low-viscosity fuels. The spray cone angle was not directly correlated to the internal injector geometry, and also did not appear to correlate with the emissions among fuels.

To gain a better understanding of the combustion performance, the evaporation characteristics of the fuels were qualitatively investigated using previous work. In particular, the Algae HRD fuel had a similar distillation curve to #2 diesel, and it is expected that its evaporation rates will also be comparable. Biodiesel is known to have longer evaporation times, and ethanol is expected to have shorter evaporation times. These effects are reflected in the CO emissions, which seem to be strongly dominated by atomization and evaporation effects. However, at the lean conditions of the research combustor, the effects of atomization on NOx formation is less clear among fuels. It is expected that NOx formation is more dependent on the chemical kinetics, particularly at lean conditions. However, from the results obtained, it appears that the Algae HRD fuel is well suited as a drop-in fuel, and performs quite comparably to conventional petroleum fuels. That this can be observed with a relatively simple test rig has some interesting implications relative to evaluation of candidate alternative fuels.

Acknowledgments

The authors would like to thank Dr. David Shifler of the Office of Naval Research, Bruce Rodman of the Naval Surface Warfare Center, Carderock Division for their support in development of the gas turbine materials testing rig (from which this burner was developed), as well as Professor Daniel Mumm for his leadership in the design and fabrication of the materials testing rig. We would also like to thank Joseph Velasco, Merna Ibrahim, and Zhixuan Duan for their contributions to the burner design and assembly, and for their assistance in the atomization performance tests.

Nomenclature

\[ \text{SMD} \] Sauter Mean Diameter
\[ \text{DP} \] atomizing air pressure differential
\[ \text{ALR}_{\text{Air}} \] to liquid mass ratio
\[ d \] diameter
\[ \rho \] density
\[ U \] velocity
\[ \sigma \] surface tension

Subscripts
\[ o \] liquid orifice
\[ a \] air
\[ l \] liquid

References


