Performance of Algae-Derived Renewable Diesel in a Twin-Fluid Airblast Atomizer

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Abstract
This study considers the atomization performance of an Algae-derived renewable diesel fuel in a twin-fluid airblast atomizer. Two other alternative liquid fuels, biodiesel and ethanol, are considered in addition to conventional petroleum-based fuels (#2 Diesel and F-76 Military Distillate). As the Algae-derived fuel is produced through hydrotreatment, its chemical composition and physical properties are very similar to the conventional fuels; in this study, this fuel was blended with the conventional F-76. To characterize the atomization performance, the breakup process was investigated using high-speed cinematography, and droplet sizes were measured using ensemble laser diffraction. The high-speed video of the spray also provided a basis for a Particle-Image Velocimetry (PIV) analysis, resulting in a velocity-field measurement of the atomizer. All of the fuels exhibited very similar atomization characteristics. Due to the atomizer geometry and flow conditions, prompt atomization was exhibited for all fuels, resulting in a relative insensitivity of liquid properties on the droplet sizes. The traditional jet-breakup effects of wavy-deformation were found to be insignificant, as the high-velocity atomizing air dominated the breakup process. A relevant correlation for Sauter Mean Diameter (SMD) was selected, showing excellent agreement over a range of flow conditions for all fuels except biodiesel, due to its high viscosity. Despite this, at the best conditions all fuels exhibited very small drop sizes (10-25 microns). The velocity fields were very similar for all fuels, suggesting that for the prompt atomization process, the evaporation rates may be primarily controlled by the fuel volatility.

Introduction

The use of alternative liquid fuels in gas turbines has received considerable attention recently, particularly for aviation applications but also for marine applications. Biodiesel and bioethanol are both renewable in nature [1], [2], and though they are reasonable for commerical 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]. As the combustion process for liquid fuels is heavily dependent on the physical process of atomization, this study looks to compare the atomization performance of HRD to early-generation 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, as well as the type of atomizer being used and the atomizer geometry. This particular study uses an a twin-fluid airblast atomizer, which was developed in house for studying the long-term effects of combustion on materials corrosion. The merits of the airblast atomizer have been discussed in the past [7], [8]; it also has the advantage of ease of atomization for low liquid flow rates, which is critical for long-term testing with limited fuel availability. This study looks to characterize the atomization process of this atomizer for the above mentioned fuels. In particular, high-speed cinematography will be employed for a qualitative visualization of the spray. Further quantitative methods are discussed below.

For combustion modeling purposes, the most relevant parameters are the droplet sizes and velocities; these provide a basis for determining evaporation rates. In the past, correlations have been developed to estimate the Sauter Mean Diameter (SMD) for various atomizer types, based empirical studies while considering fundamental breakup effects [7], [8]. Depending on the flow conditions and atomizer geometry, these correlations can be used with considerable accuracy, and can give insight into the performance of different fuels. In this study, the droplet sizes and SMD are measured using ensemble laser diffraction, and a relevant correlation is selected to describe the performance of this atomizer.

In determining the droplet and flow-field velocities, optical techniques such as Particle Image Velocimetry (PIV) and Laser Doppler Anemometry are available with high accuracy; however, the availability of high-speed

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cinematography can give estimates on droplet velocities as well as insight into the breakup process itself.   This study utilizes high-speed shadowgraphy to gain insight into the breakup process for the different fuels in a twin-fluid airblast atomizer, and integrates the high-speed video with PIV software in order to provide velocity field estimates.

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 [9].   The burner is centered around a twin-fluid airblast atomizer, similar to that used by Rizk and Lefebvre [10]; however, rather than employing co-flowing air, the atomizing air converges upon the liquid orifice, similar to that described by Beck and Lefebvre [11].   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.

Table 1: Atomizer parameters

Liquid Orifice Diameter (d_0)	0.3048 mm
Air Orifice Diameter	3.175 mm
Air cone angle	57.79 degrees
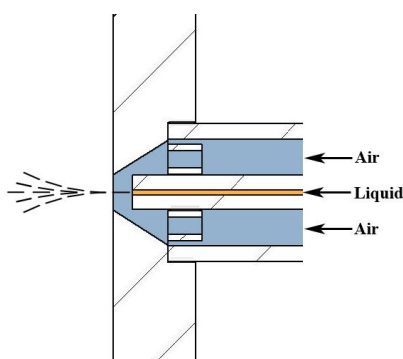
Figure 1 Cross-section of twin-fluid airblast atomizer.

Five different fuels are considered for this study, listed in Table 1 (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 measured using a falling ball-drop viscometer.   The fuel properties are presented in Table 2.   Of note is that the military specifications for viscosity require a value between 1.7 and 4.3 x 10^{-3} kg/m s at 40 °C [12]; both Biodiesel and Ethanol do not meet this requirement at ambient conditions.

Table 2: Fuel Properties (Fuel supplier in parentheses)

Fuel	Density kg/m^3	Dynamic Viscosity kg/m s	Surface Tension kg/s^2
Ethanol (Gold Shield)	784.8	1.231 x 10^{-3}	0.02286
#2 Ultra-Low Sulfur Diesel (UCI North Campus)	828.6	2.881 x 10^{-3}	0.02876
F-76 Naval Distillate (ONR)	830.3	2.593 x 10^{-3}	0.02862
Algae HRD/F-76 Blend (ONR)	811.1	3.699 x 10^{-3}	0.02771
Biodiesel (Extreme Biodiesel)	884.8	7.409 x 10^{-3}	0.02794

As the atomization process is highly dependent on the liquid fuel properties, particularly density, viscosity and surface tension, it is apparent that there will be some differences in the performance between the fuels.   Of note is that 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 [13]. This, for the most part, eliminates the high-viscosity and density associated with the other vegetable-oil based feedstock (biodiesel), which should theoretically lead to finer atomization.

To gain a comprehensive map of the atomization characteristics, a 3-level factorial experimental design was selected. 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). Also, the fuel tube 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.

Table 3: Atomizing Air Parameters

Parameter	Units	Low	Mid	High
Atomizing Air Flow Rate	g/min	3.42	4.33	5.22
Atomizing Air Pressure Differential (DP)	kPa	9.94	17.5	24.8

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 energy demand in practical systems when using fuels with different heating values. To determine the relevant mass flow rate required, the adiabatic flame temperature is set equal. 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 Turns [14] to calculate the adiabatic flame temperature; given the enthalpy of reactants for the different fuels. The nominal fuel flow rates are presented below.

Table 4: Nominal flow rates for fuels

Fuel	Approx. Chemical Formula	Fuel Flow Rate mL/min	Combustor Eq. Ratio
Ethanol	C_2H_5OH	7.03	0.525
#2 Diesel	$C_{15.43}H_{32.22}$	4.21	0.501
F-76	$C_{14.76}H_{30.40}$	4.21	0.499
Algae HRD/F-76	$C_{15.95}H_{33.05}$	4.31	0.495
Biodiesel	$C_{18.79}H_{34.58}O_2$	4.59	0.505

To measure the atomization characteristics the atomizer was mounted in a down-fired configuration to properly exhaust the spray. Fuel flow rates were metered using a rotameter that was calibrated for each fuel. The atomization air flow rate was metered by a sonic orifice. In order to estimate the air velocity through the atomizer, 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.
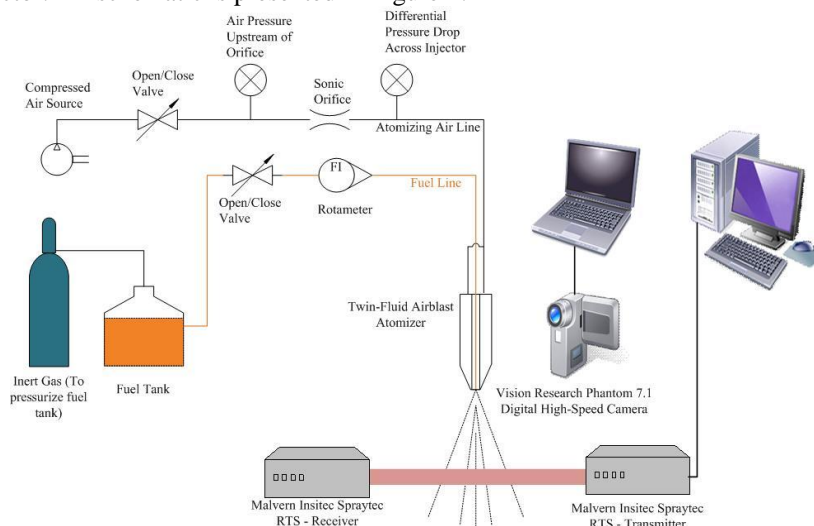

Figure 2 Schematic of test-rig

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Two optical methods were used to study the spray characteristics: high-speed shadowgraphy, and ensemble laser diffraction.   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 LaVision's Da Vis software.   From this software, velocity fields could be extracted.

Results and Discussion

High-speed cinematography was employed to visualize the breakup process for the fuels.   Though the process is highly transient, select stills from the video are presented below in Figure 4.   These provide a representative comparison between the different fuels at the mid-range conditions for atomization (4.33 g/min of air, 17.5 kPa DP).   All of the fuels produce a very wide range of drop sizes.   For all of the fuels except biodiesel, there is a blurred mist of very small droplets, which in the video are shown to be moving at high velocity.   Biodiesel, lacking these smaller droplets, will have a larger average drop size.
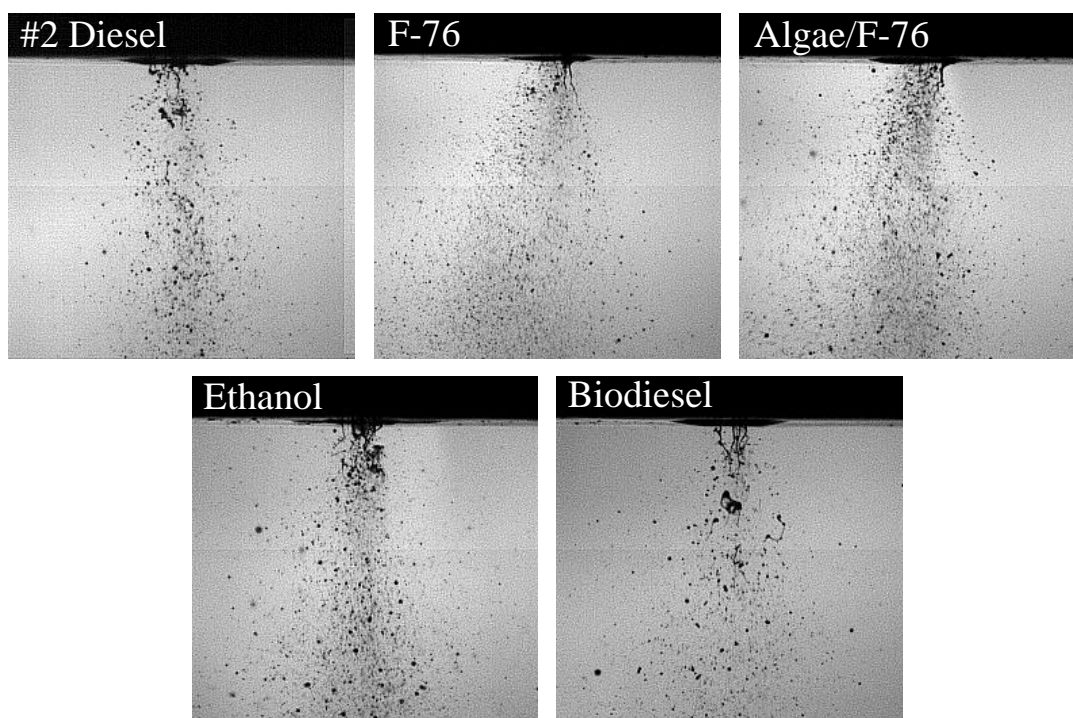
**Figure 3** Still-images of spray, from high-speed video

In a conventional plain-jet airblast atomizer, a liquid jet will extend beyond the exit before undergoing some amount of wavy deformation and then breakup into individual ligaments and droplets.   In the atomizer in this study, there is no liquid jet that issues beyond the orifice.   Instead, droplets and some ligaments are issued from the orifice, characteristic of the prompt-atomization process.   In prompt atomization, the surface tension, density, and ALR are the most important factors that influence the atomization process, with viscosity taking a reduced roll [7].   This is apparent in the high-speed images, in that most of the fuels produce similar sprays. However, the highly-viscous biodiesel is noticeably different.   Though the other fuel property effects (surface tension and density) have been quantified in the past (discussed below), the qualitative effect of viscosity is that it will lengthen the breakup process.   In particular, long ligaments are drawn out from the liquid orifice, resulting in larger drop sizes.

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 [11]; this will be discussed in detail with the measurements for SMD.   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 [9]. 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. The overall result is a very wide range of droplet sizes.

The results for the SMD measurements are presented below 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 [11]. 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.
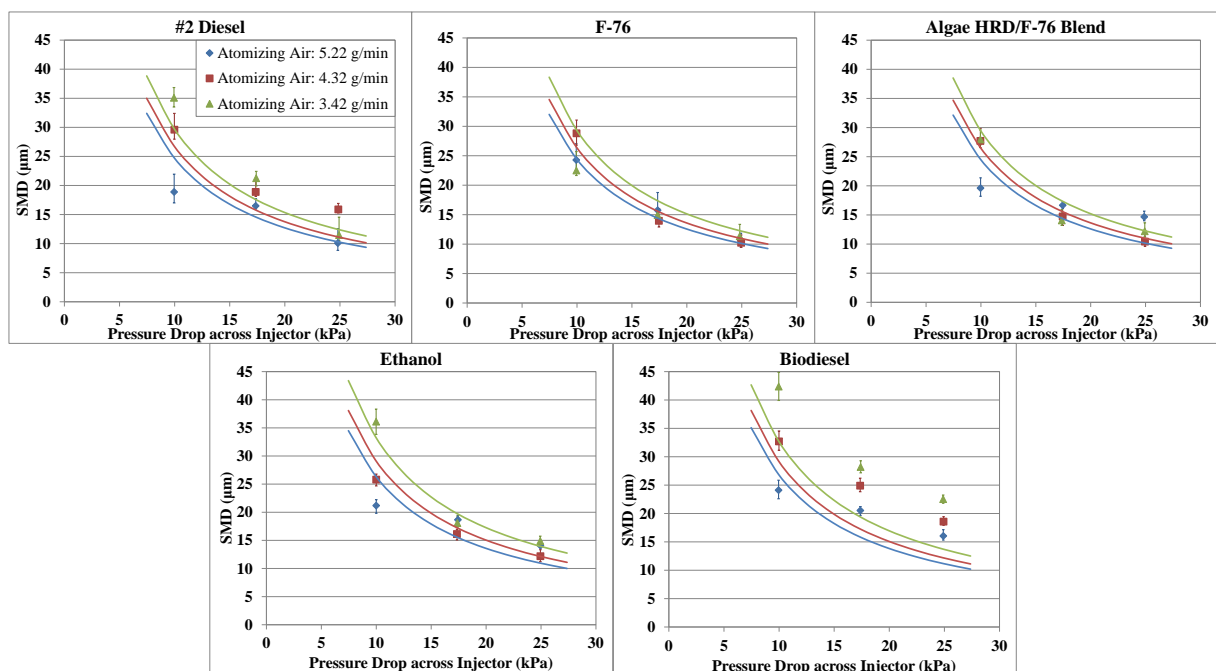
Figure 4 SMD measurements and predictions for all fuels

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. In particular, the liquid flow effects (such as turbulence and cavitation) cause the liquid jet to deform in a wave-like manner ("wavy-surface deformation). As the atomizing air velocity increases, these waves are further sheared into ligaments and fragments which coalesce into droplets downstream of the atomizer [15]. This type of model assumes that for the atomizing air stream, there is no velocity component acting perpendicular to the liquid jet. This type of atomizer has been used in several other studies, and empirical correlations have been developed by several authors to describe the droplet size distributions based on aerodynamic effects (Weber number, We) and viscous effects (Reynolds number, Re).

One additional parameter used to describe the breakup process for a liquid jet is the dimensionless Ohnesorge number. The Ohnesorge number is defined solely by the liquid properties, but provides a quantitative comparison between aerodynamic forces and viscous forces for a specified liquid and orifice diameter; thus it provides a comparison of the liquid effects among fuels. Ohnesorge's regime map [16] is shown below in Figure 5.
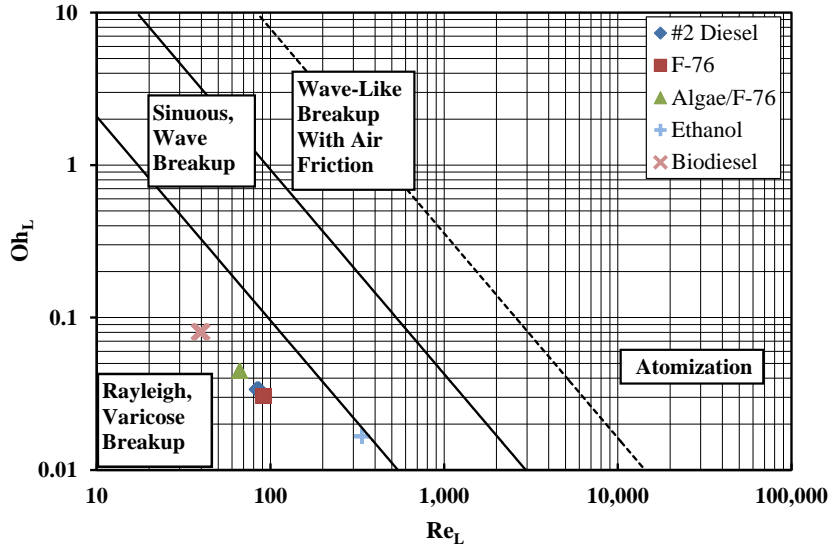
Figure 5 Classification of modes of disintegration, adapted from [16]

For the twin-fluid atomizer in this study, the high-speed images showed the atomization process to be in the prompt regime. In the Ohnesorge plot, all of the fuels fall within the Rayleigh regime. As the liquid jet does not survive beyond the injector orifice, liquid jet effects are less important than the aerodynamic effects in the breakup process for this atomizer. In order to consider the aerodynamic effects, we can plot the Reynolds number with the Weber number. This is shown in Figure 6.
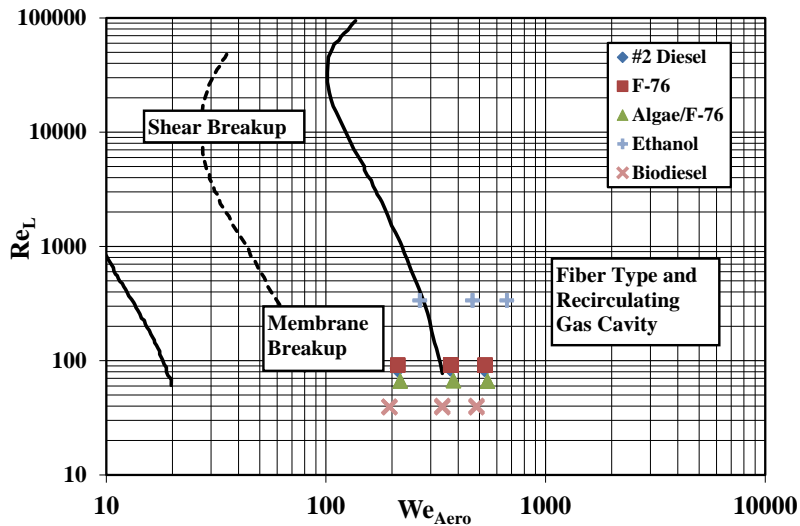

Figure 6 Reynolds number vs. Aerodynamic Weber Number (adapted from [15])

In this figure, the data points for each fuel represent the different atomizing air velocities (increasing from left to right). In the mid-to-high air velocity cases, most fuels would expect to be in the fiber-type breakup regime. A previous study by Bolszo [17] indicated that the Rizk and Lefebvre correlation, though developed using an ALR ranging from 2-8, was valid for low values of ALR (0.25 – 0.65). It was also noted that the Rizk and Lefebvre correlation is only valid in the fiber-type breakup region. In the present study, the application of that correlation resulted in very poor agreement; in particular, it did not capture the sharp increase in SMD at the lower atomizing air velocities. As with the study by Bolszo, the transition between the membrane-breakup and the fiber-type breakup regimes would be the boundary of that application. However, the correlation developed by Lefebvre and used in Figure 4 shows good accuracy even at these conditions, capturing the increase in SMD associated with the transition from fiber-type to membrane breakup.

Airblast atomizers that employ co-flowing air are subject to the modes of disintegration of liquid jets. As our atomizer utilizes coflowing air that impinges on the liquid jet, these effects are suppressed. Unlike co-

flowing air, in which there is no velocity component normal to the liquid jet, there is now a significant velocity component. Thus rather than the liquid jet being deformed by liquid flow phenomena (e.g. turbulence, cavitation), the air rapidly mixes with the liquid and shatters it into fragments. This prompt atomization process is governed primarily by the air velocity, ALR, and liquid service tension, producing a wide range of velocities and drop sizes [11]. A correlation was proposed by Lefebvre that took these effects into consideration; this correlation is given by Equation 1. The coefficient in this equation, C*, was empirically determined in this study based on the data for all fuels *except* biodiesel; the resulting value was 0.0015. This is considerably lower than the value of 0.007 produced by Lefebvre, representative of a less efficient atomization process; however, that study considered the breakup of a liquid sheet.

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

(1)

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 due to the high-velocity atomizing air. When it was derived, the lack of a viscosity term was not addressed. From the SMD measurements shown in Figure 2 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 5-10 microns. In the regime plot in Figure 6, the biodiesel tests fall outside of the regime boundaries. The high-speed images do show that numerous ligaments form on the lip of the atomizer, which break off and coalesce into large droplets. Compared to the other fuels, this effect is most likely due to the higher viscosity, which resists the breakup process and extends it downstream of the atomizer.

One additional consideration from this study is the use of the high-speed video to obtain a velocity field for the spray. Although this technique lacks the ability to correlate drop size to velocity, it does provide a global velocity field that could be used in the estimation of evaporation rates, due to convective effects. The resulting velocity fields for the different fuels are presented in Figure 7. The flow settings are the same as those shown in the high-speed images in Figure 3.
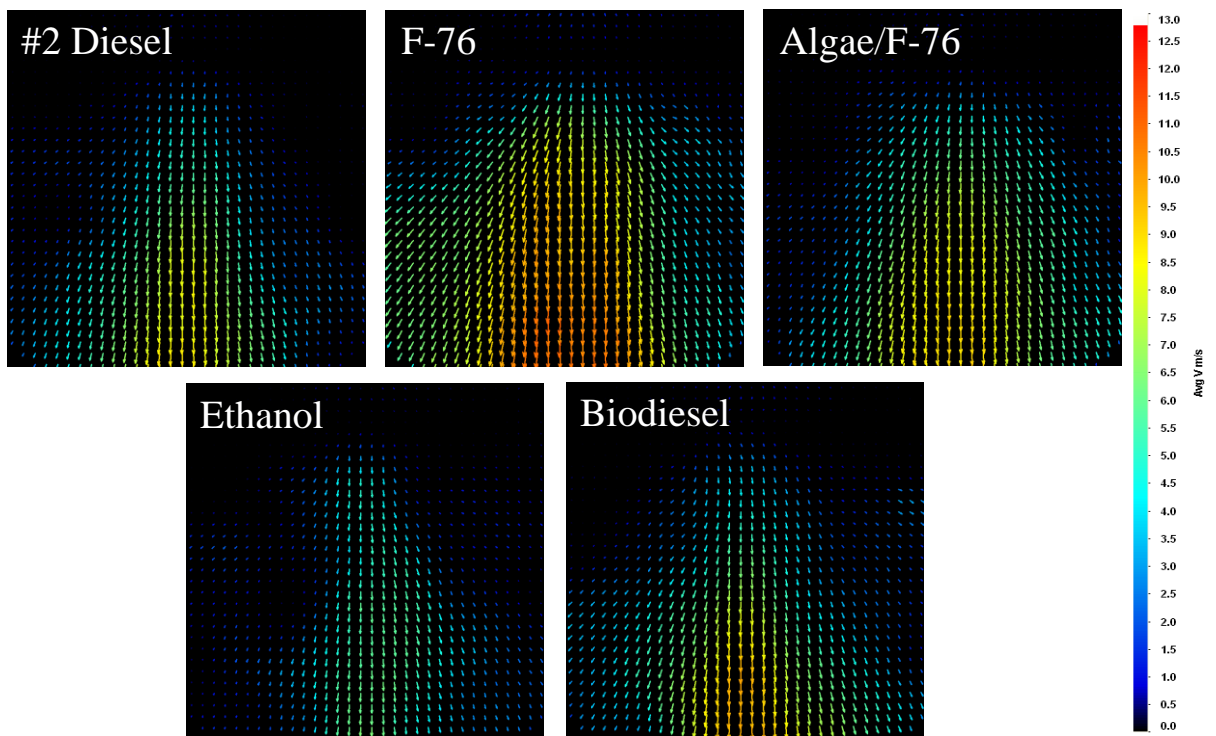
Figure 7 Velocity fields of mid-range spray conditions, based on PIV analysis of high-speed video

The velocities for most of these fuels fall within the same range, with a noticeably has a lower velocity for ethanol. As some amount of kinetic energy from the air is imparted from the atomizing air to the liquid during the breakup process, a further portion of the remaining kinetic energy is available to accelerate those droplets downstream. Recall that the drop size correlation incorporates a constant that describes the efficiency of atomization; the very low value of this constant indicates that most of the energy in the atomization process is instead utilized in the acceleration of the droplets after they have been formed [11]. With the higher mass flow rate of ethanol, if the air-flow conditions are the same, it is expected that the result will be lower velocities, despite producing droplets of the similar size and mass.

Though the evaporation rates have yet to be quantified, the distillation curves for these fuels are readily available. These were provided by ONR for the military fuels (F-76, Algae HRD/F-76 blend, and the pure Algae HRD). The distillation curves for biodiesel and #2 diesel were provided from the literature [17]. As the rate of evaporation is governed by the "D-Squared" Law [8], and the effective evaporation constant is a function of these distillation curves, several qualitative observations can be made. Ethanol is a relatively volatile fuel; as such, this may offset the effect of lower droplet velocities on the evaporation rates, though the extent is still unknown. When considering the other fuels, which have similar velocity fields, the volatility of each fuel may play a greater role. In particular, the high boiling point of biodiesel may lead to longer evaporation times relative to the other fuels. Thus in this prompt atomization regime, it may be possible to isolate evaporation and chemical effects from atomization effects. The natural extension of this study would be to calculate evaporation rates based on the velocity data, in order to further describe the combustion behavior.
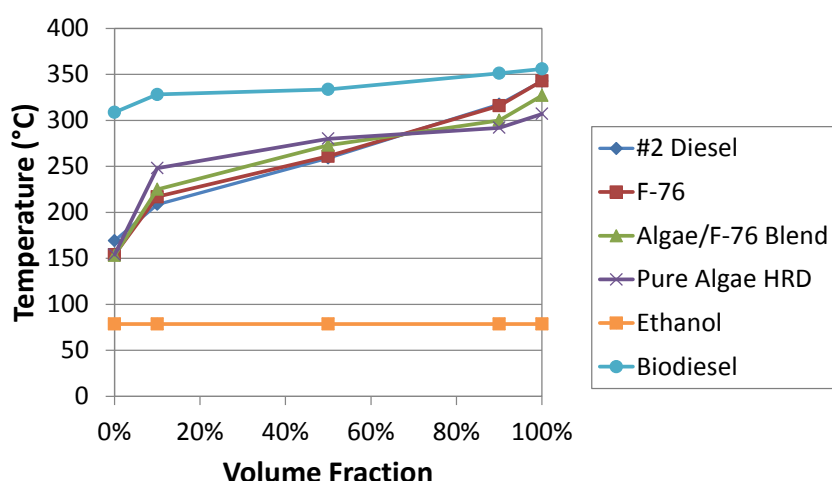

Figure 8 Distillation curves for all fuels

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 was very similar among the fuels. Unlike what is traditionally known as a "plain-jet" airblast atomizer, in this study no liquid jet issued beyond the orifice, due to the low liquid-flow rate and the atomizer geometry. The traditional jet-breakup mechanisms beginning with wavy-disintegration are much less influential in the breakup process, resulting in an overall prompt-atomization process for all fuels. This is seen in the regime plots by Ohnesorge and Lasheras/Hopfinger, in which the aerodynamic effects of the atomizing air stream dominate the breakup process. The correlation by Lefebvre showed that the impinging effect of the atomizer (instead of co-flowing air) imparts more kinetic energy directly into the liquid stream, bypassing the traditional wavy modes of disintegration, and hence traditional effects. Though this correlation showed excellent agreement for most fuels, the high viscosity of biodiesel resulted in larger drop sizes, due to the presence of long ligaments at the atomizer lip.

A PIV analysis was successfully carried out on the high-speed video. This produced velocity fields for all fuels, and it is seen that all fuels have similar velocity fields, save ethanol because of its higher mass flow rate of liquid. The implications are that the evaporation rates may be primarily controlled by the fuel volatility, particularly in this prompt atomization process. Further work to be done includes developing a quantitative evaporation model.

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