ILASS Americas, 22nd Annual Conference on Liquid Atomization and Spray Systems, Cincinnati, OH, May 2010

Pressure Swirl Atomization of Water-in-Oil Emulsions

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Abstract

The atomization of surfactant stabilized and natural, unstable water-in-oil emulsions injected into an ambient environment are investigated experimentally. Fuel flow conditions typical in large-scale gas turbine applications are studied. A specialized setup is used to generate controlled emulsions stabilized by addition of surfactants. The emulsion generation process used allows control over the discrete phase droplet sizes within the emulsions. The spray droplet sizes are measured using laser diffraction and the spray pattern is measured using patternation. The results shown that the surfactants do affect the size of the atomized liquids, but in a manner expected based on the change in physical properties. Emulsification can reduce or increase the size of the spray depending upon the amount of water used. Atomization can change the size distribution of the discrete phase depending upon the initial sizes present and the injection pressure used. For the conditions studied, the stabilized emulsions performed very similarly to natural unstable emulsions as long as the unstable emulsion was produced shortly prior to atomization (i.e., <1 sec) and was produced with sufficient shear as to result in a fine discrete phase droplet size. Finally, it is observed that the atomization process also lead to a slight separation of components, with the denser water found preferentially at the outer edges of the spray. This was observed for both stabilized and unstable emulsions. Overall, the results obtained provide significant new insight into how the characteristics of the emulsion affects atomized spray.

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Introduction

In many practical combustion systems, water is utilized to lower emissions of NO_x and soot, improve thermal management, and increase combustion efficiency [1]. Water can be injected into the system air stream, the combustion zone, or together with the fuel as an emulsion. Injection of liquid water or gaseous steam can control combustion temperatures by absorbing heat in the engine. This helps reduce thermal stress and maintains the hardware's structural integrity. In addition, oxides of nitrogen formed via the thermal (i.e., Zeldovich) can also be greatly reduced due to the heat removed from the reaction zone [2]. Use water in form of an emulsion offers the opportunity to overcome limitations associated with physical properties of the fuel itself. An example is "Orimulsion®" wherein water is added to highly viscous bitumen to allow improved flowability and atomization quality [3]. Introduction of water as a emulsion also minimizes modifications to the fuel injection system compared to discrete water injection which requires additional flow manifolds, atomizers, and injection points. In addition, atomized emulsions can promote the onset of "microexplosions", where the water component flash vaporizes prior to the fuel within a fuel droplet or globule causing a secondary droplet breakup [4]. This breakup improves the vaporization and mixing of the fuel and oxidizer within the combustion chamber which can increase both the combustion and thermal efficiencies as well as lower the sooting propensity [1,5]. Thus, introduction of water in combustion systems can have benefits and introduction of water as an emulsion offers additional some further advantages.

Marcroemulsions, which possess discrete phase droplets larger than 1 μm, are thermodynamically unstable due to immiscibility of the oil and water components [6]. This immiscibility is due to the differences in the molecular forces between components. The strong attraction of hydrogen bonds between the polar water molecules compared to the larger non-polar oil molecules (which only have weak London dispersion forces) causes a grouping of like molecules, and results, in continuum mechanics, the coalescence and separation of these components once the liquids are at rest. This instability is represented by a large interfacial tension between the two liquids, where a significant amount of energy is required to create dispersed droplets within a continuous medium. From a practical perspective, fuel emulsions are generally of the water-in-oil type. Such emulsions allowing moderate amounts of water addition and avoid a substantial loss in heating value. These fuel emulsions can be generated quickly and with a reasonable expenditure of shear (experiencing a strain rate on the order of 10^2 - 10^3 s^{-1}) [7]. Separation time scales are on the order of seconds, which poses a considerable challenge in managing a fuel emulsion in a practical system as well as studying it experimentally. For detailed study and convenience, the surface stabilizing agents (surfactants) can be added to significantly slow down the separation of water and oil. The addition of these surfactants decreases the surface and/or interfacial tension between the water and oil, slowing down coalescence [6]. Concentrations are generally below 10 percent (but can be substantially larger depending on solvent) to avoid micelle formation and solution saturation. The addition of surfactant does, however, alter the liquid properties of these solvent fluids and may modify the behavior of the emulsion to some extend once formed.

It is still not well understood how surfactants modify the breakup of stabilized emulsions during atomization and how this breakup compares with that of natural unstable (surfactant free) emulsions. During atomization, the effect of stabilizing surfactants on the emulsion viscosity and surface tension may be similar to that on an unstable emulsion due to surfactant depleted regions where new interface (liquid - liquid) and surface (liquid - gas) is rapidly generated resulting in slow rates of diffusion and limiting wetting [8]. Low interfacial tension enhances the formation of smaller emulsion droplets with a narrower droplet size distribution and overall greater kinetic stability [9]. This can lead to a finer atomization of the emulsion during injection potentially resulting in better engine performance [10]. However, surfactants can be expensive and require an additional aspect of complexity associated with mixing. Hence for high volumetric flows needed for large scale power generation a surfactant free system is clearly preferred.

Various methods have been documented in the literature regarding emulsion formation. High strain rates present in the piping, which can include valves, strainers, and/or bends in the flow, provide emulsification upstream of atomizers. Dedicated inline mixers can also provide additional shear to drive the water globules/droplets to a smaller droplet size with a more narrow distributions. The current research produces the emulsions in a rotor/stator mixing device which introduces the water and diesel fuel through small passages to create high shear interactions for stabilized emulsions. Unstable emulsions formed through a T-junction and static screen filter (of 150 μm pore size) at a distance of 0.3 m from the exit of the atomizer nozzle. Not unexpectedly, the atomization process itself also provides very high rates of shear for the emulsion, which modifies the nature of the emulsion [11]. The atomization process depends on the type of injector and the fluid properties of the emulsion spray, which are the two main factors examined in the present study. A pressure-swirl atomizer nozzle is used in the current study to atomize the emulsion with a representative droplet Sauter Mean Diameter (*SMD*).

Lefebvre (1989) formulated a *SMD* correlation for pressure simplex nozzles defined as

$$SMD = 2.25\sigma_L^{0.25}\mu_L^{0.25}\dot{m}_L^{0.25}\Delta P_L^{-0.5}\rho_A^{-0.25} \quad \textbf{(1)}$$

where σ_L is the fuel surface tension, μ_L is the fuel dynamic viscosity, ρ_A is the air density, ΔP_L is the injector pressure drop, and $\dot{m}_L$ is the fuel mass flow rate. Wang and Lefebvre (1989) further expanded the correlation by including the effects of film thickness and spray cone angle.

$$SMD = 4.52\left(\frac{\sigma\mu_L^2}{\rho_A\Delta P_L^2}\right)^{0.25}(t\cos\theta)^{0.25} + 0.39\left(\frac{\sigma\rho_L}{\rho_A\Delta P_L}\right)^{0.25}(t\cos\theta)^{0.75} \quad \textbf{(2)}$$

where t is the film thickness and θ is the spray cone half angle. The extent to which these correlations can be used to determine the SMD of an emulsion spray is evaluated in the present work.

Approach

The current investigation studies the pressure atomization of unstable and stabilized water-in-oil through a large flow capacity pressure-swirl atomizer of a water-in-oil emulsion, both unstable and stabilized with surfactants. The liquids utilized are low sulfur diesel distillate number 2 (DF2) as the oil component and plain tap water as the second liquid component. The discrete water phase droplet size distributions are measured for prepared stabilized emulsions, both at the exit of the emulsion generator and at the exit of the atomizer nozzle. The atomizer tests are designed to garner insight on (1) how emulsion characteristics affect the spray and (2) how stabilized emulsions atomize compared to unstable emulsions. The atomization features measured include the overall spray droplet size distribution and pattern.

Experiment

The preparation of stabilized emulsion and the atmospheric spray rig used for the studies of the pressure-swirl atomizer has been described in detail elsewhere [12]. A brief overview of the setup is presented here.

The nozzle used is a large flow capacity pressure-swirl nozzle (with diameter 1.9 mm and flow number of $9.2\text{x}10^{-7}\ \text{m}^2$) which is oriented downward into a quiescent environment at atmospheric pressure.

Unstable Emulsions For atomizing unstable emulsions, two bladder accumulators; one holding neat water and the other holder neat DF2 are pressurized with nitrogen. The unstable flow circuit is presented above a previously established stabilized emulsion circuit in Figure 1. The separate flow circuits are metered with separate Coriolis flow meters and brought together at a tee-section, with a check valve for the water. Another check valve is provided for the third branch of the tee-junction upon exit. The flow is then quickly passed through a 150 micron screen filter, flows 0.3 m and is ejected through the same atomizer nozzle. A pressure transducer measures the pressure drop across the nozzle and a differential pressure transducer measure the pressure drop across the screen filter element.

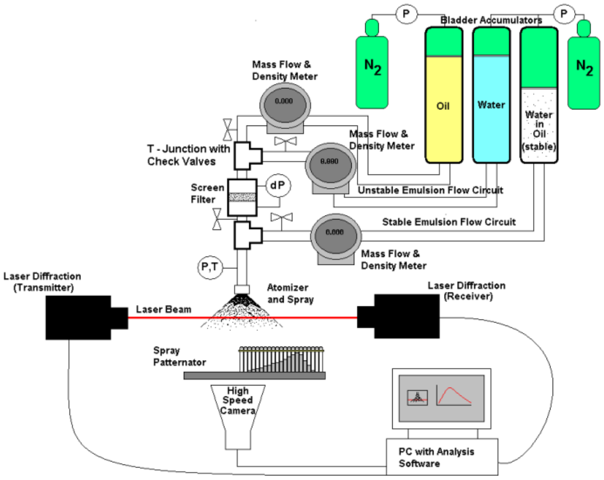


Figure 1: Schematic of pressure-swirl atomizer experimental setup.

Stabilized Emulsions A high shear mixer was utilized for surfactant stabilized water-in-DF2 emulsions. A commercial emulsifier (IKA Labor-Pilot 2000/4), generates strain using a multiple rotor-stator slotted blade type configuration as two immiscible fluids flow outward through the slots due to centrifugal force during the emulsification process. The gap between each of the rotor-stator blades, (h) is 0.28 mm. Low, medium and high rotary speed was used at 24, 42 and 60 Hz to produce different levels of shear. In order to categorize the droplet distribution of the discrete phase, stabilized emulsions were extracted from the system, diluted 100 times, and photographed digitally at 100 -1000 times magnification using a triocular microscope (Nikon Labophot). Image analysis software (Image-Pro Plus version 5.1) was then used to count and measure water droplet diameters utilizing a two point method, and representative diameters associated with the resultant size distribution were obtained.

Water and DF2 solutions with corresponding surfactants are fed to emulsifier by peristaltic pumps from two large holding tanks (one for each solution). The water in DF2 emulsion exits the emulsion generator and is piped into a 15 gallon capacity bladder accumulator for holding. When ready for experimental studies, the accumulator is brought up to injection pressure using nitrogen blanketing from high pressure cylinders. An Emerson Coriolis flow meter records the mass flow rate, density and temperature and a pressure transducer measures the pressure drop across the nozzle during atomization. Note that the pressure loss from the accumulator, through the flow meter and to the atomizer is kept as low as possible to minimize further emulsification. A schematic of this parallel, stable flow circuit is also illustrated Figure 1.

Stabilized emulsions were prepared with Span 80 and Tween 85 surfactants in DF2 and water, respectively, to achieve a hydrophilic-to-lipophilic balance of (HLB) of 6.0 at 2 and 5 percent mass concentration. The HLB and concentrations selected achieves maximum stability for the prescribed surfactants based on studies by Song and coworkers [13,14] investigating the temporal evolution in water droplet distribution.

The fluid surface tension was measured with a stalagmometer and the interfacial tension was measured using the pendant drop method. The viscosity was measured with a falling ball method.

Spray Diagnostics. A Malvern laser diffraction system, positioned at 3 cm below the nozzle exit, is utilized to measure emulsion spray Sauter Mean Diameter (SMD), defined below. n_i is the number frequency in a given droplet diameter bin/class i and d_i is the mean droplet diameter of the bin/class. A one minute sampling time, with a 1 second sample rate, provides 60 points temporal average to determine SMD.

$$SMD = \frac{\sum_i n_i d_i^3}{\sum_i n_i d_i^2} \qquad (3)$$

A Phantom 7.1 (Vision Research) high speed camera is used at 2 µs exposure times, with 100 µs interval at 10,000 frames per second (fps) to document the dynamic behavior of the sprays.

A mechanical half spray patternator was fabricated with 21 - 4 mL sampling tubes mounted vertically to measures the volume flux of emulsion from the spray for both stable and unstable emulsions. The patternator is linear in design, measuring 21 cm axially and was positioned 17 cm downstream of the nozzle exit. A schematic of the patternator is provided in Figure 1. A sample run consisted of an umbrella covering being quickly removed during measurement and replaced once the first tube reaches 7/8th filled, to avoid splashing. These sampling tubes are removed and left to settle. Photographs of the separated emulsions are taken and the heights of the tubes are measured and the volumes of both components are calculated.

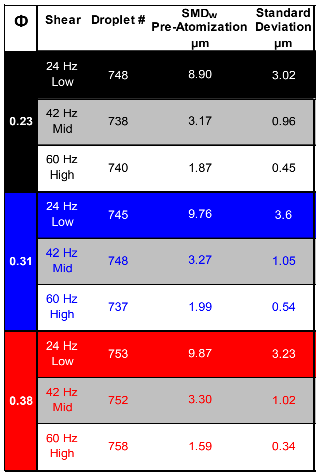
Test Matrix The ranges of the factors associated with the stabilized emulsions studied are shown in Table 1. The atomization pressure and mass flow are provided, the water to total liquid mass fraction ($\Phi = W/(O+W)_m$), the emulsion generator max strain rate (1/s) with accompanying rational speed and finally the discrete phase (water) SMD_w. These stabilized emulsions were also compared to their neat components with and without surfactant added (with 2.6 percent added to water and 7 percent added to DF2). It was noted that an increase in emulsion Φ increased SMD_w by no more than 1 µm in the current range of interest. Table 2 summarizes the resulting statistics associated with the discrete phase size distribution resulting from the generator settings shown in Table 1.

A multi-level factorial statistical experimental design was then developed and carried out for the ranges of values shown in Table 1. The responses evaluated included the spray SMD and angle.

Table 1: Low, mid and high test condition values for stabilized emulsions during atomization.

	Low	Mid	High
Injection Pressure (Psi)	100	300	450
Emulsion Mass Flow (kg/min)	1.3	2.2	3.1
Emulsion Mass Fraction ($\Phi = W/(O+W)_m$)	0.23	0.31	0.43
Max Strain (1/s) Generator Setting [Hz]	15,300 [24]	26,800 [42]	42,100 [60]
SMD_w (µm)	9.9	3.1	1.4

Table 2: SMD_w for prepared emulsions varying water mass fraction and shear during generation.



Φ	Shear	Droplet #	SMD_w Pre-Atomization µm	Standard Deviation µm
0.23	24 Hz Low	748	8.90	3.02
	42 Hz Mid	738	3.17	0.96
	60 Hz High	740	1.87	0.45
0.31	24 Hz Low	745	9.76	3.6
	42 Hz Mid	748	3.27	1.05
	60 Hz High	737	1.99	0.54
0.38	24 Hz Low	753	9.87	3.23
	42 Hz Mid	752	3.30	1.02
	60 Hz High	758	1.59	0.34

For surfactant free unstable emulsions, the same injection pressures of 100, 300 and 450 psi were utilized, with Φ varying from 0.09 to 0.45 and including the neat components (of Φ = 0 and 1).

Results

The results are presented in this section and describe (1) the effect of surfactants on the liquid properties and spray size distributions, (2) the effect of the properties on the emulsion spray size, (3) the effect of atomization on the emulsion discrete phase size, (4) the comparison of atomized stable and unstable emulsions, and (5) the effect of emulsification on spray pattern.

Effect of Surfactants. The effect of surfactants on spray drop size distribution for DF2 and water was studied at an injection pressure of ~100 psi. To achieve an HLB of 6 with 5 percent overall surfactant addition, 7.3 percent Span 80 and 2.6 percent Tween 85 are added to DF2 and water, respectively. The increased stability is due to a 95 percent decrease in interfacial tension between the DF2 and water with surfactants. The addition of these surfactants alters the fluid properties of these liquids by increasing the viscosity (26 and 13 percent for DF2 and water) and density (less than 3 percent for both fluids) and decreasing the surface tension for the water (42 percent). The fluid properties for the DF2 and water used in this study were measured and are provided below in Table 3.

Table 3: Component liquid properties and modification of fluid properties due to the addition of surfactants to DF2 and water.

	DF2	Water	DF2 Span 80	Water Tween 85
Density (g/cm^3)	0.820	1.010	0.840	1.010
Dynamic Viscosity (g/m-s)	2.9	1.4	3.9	1.6
Surface Tension (g/s^2)	27.9	69.3	27.7	40.3
Interfacial Tension (g/s^2)	27.8		1.4	

The falling ball viscosity method cannot capture the details of emulsified versus pure liquids [15]. As a result, for stabilized emulsions, the dynamic viscosity (μ) and density was calculated from the knowledge of the liquid concentration and water droplet distribution (Table 2) using the approach proposed by Krynke and Sek [16] and is provided in Table 4.

Table 4: Calculated dynamic viscosity and measured density for stabilized emulsions.

		Low Shear	Mid Shear	High Shear
Φ	Density (g/cm^3)	μ (g/m-s)	μ (g/m-s)	μ (g/m-s)
0.13	0.862	3.74	4.20	4.16
0.23	0.879	4.53	5.15	5.01
0.31	0.893	5.47	6.25	6.17
0.38	0.904	6.46	7.47	6.99

The measured drop size distributions are plotted as a volume fraction per droplet size class versus droplet diameter in Figure 2. The SMD for each case is shown in the legend. The addition of surfactant modifies the size distribution for both liquids. The spray SMD decreases for both liquids when surfactants are used, consistent with past experimental spray results on the effect of surfactant by Butler Ellis and coworkers [17]. In terms of liquid breakup, a greater number of smaller droplets are present for the surfactant containing sprays. This is shown by the slight widening of the distribution on the left hand side of the distribution. Secondly, the height distribution peak decreases with the addition of surfactant. For water, the addition of surfactant extends the tail end of the distribution for large droplets, while the tail end of the DF2 distribution subsides. Of course, SMD is most sensitive to the presence of large droplets. In summary, the changes associated with the added surfactant is consistent with behavior expected due to the changes in the physical properties of the liquids. These changes are important to note relative to the differences in sizes due to emulsification and/or when comparing SMD of neat fluids

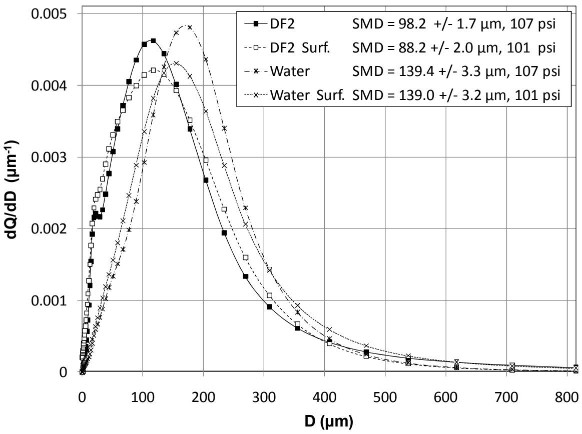


Figure 2: Spray volume fraction per droplet size class versus spray droplet diameter for neat DF2, water, DF2 with 7.3 percent Span 80 and water with 2.6 percent Tween 85

Emulsion Spray Drop Size. The test matrix cases were flowed and measured at a sample rate of 1Hz for 1 minute and the resultant spray SMD's are averaged. These stable emulsion are compared with their neat components with and without surfactant (Figure 2) in Figure 3. The first observation is that the emulsion cases result in a lower spray SMD, specifically for $\Phi \leq 0.28$ when compared to their neat components both with and without surfactants. This effect is most pronounced at the target measured pressures of 300 and 450 psi. The lower measured SMD for the emulsions vs the neat components is thought to be due to an decreese in sheet stability, observed by Ford and Furmidge [11,18,19].

The water drop size distribution does not appear to play a significant role. Indeed, the analysis of variance (ANOVA) carried out on the results indicate that the water droplet distribution has no statistically significant effect on SMD compared to the effects of pressure and Φ. This analysis also allowed the significant factors to be associated in terms of an empirical relation shown in Equation 4.

$$\text{SMD}\ (\mu\text{m}) = 112.3 - 42.4\,\Delta\text{P} + 13.4\left(\frac{\Phi}{1-\Phi}\right) + 7.2\,\Delta\text{P}^2 \qquad \textbf{(4)}$$

In addition to this expression derived from analysis of variance, a modified version of the Wang and Lefebvre correlation (Equation 2) was also applied. The modification involved adjusting the leading coefficients to achieve the best fit for the measured SMD for the neat components (water and DF2). The modified expression is:

$$SMD = 1.12\left(\frac{\sigma\mu_L^{\ 2}}{\rho_A \Delta P_L^{\ 2}}\right)^{0.25}(t\ \cos\theta)^{0.25} + 0.81\left(\frac{\sigma\rho_L}{\rho_A \Delta P_L}\right)^{0.25}(t\ \cos\theta)^{0.75} \qquad \textbf{(5)}$$

The calculated apparent viscosity values in Table 4 were used in the SMD predicted by Equation 5. Interestingly, Equation 5, which is based on dimensionless physical groupings of fluid properties, the film thickness and spray cone angle determined from correlations by Lefebvre and spray photographs overpredicts the SMD for the emulsions.

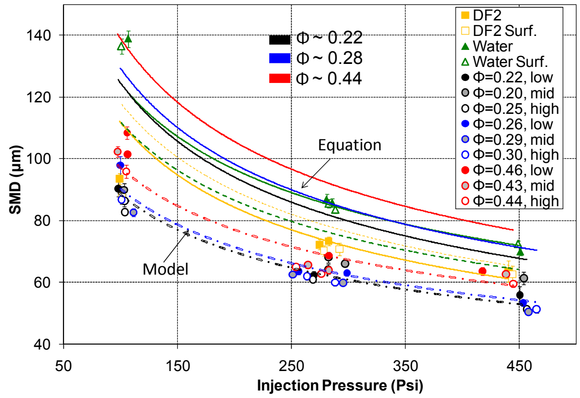


Figure 3: Spray SMD for stabilized emulsion and neat components for the specified test matrix. Equation 4 (model) and Equation 5 are shown overlaid.

To help further assess the ability of Equation 5 to predict the SMD behavior of emulsions, additional analysis was carried out.

Figure 4 compares the SMD results from Equation 4 and Equation 2 (with viscosities from Table 4). As shown, the slope value is very close to unity. Recall that the model (Equation 4) neglects the possibility of the role of shear/water droplet distributions contributing to the spray SMD for the fine distributions investigated. In Figure 4, if the water droplet distribution is consider, based on the three shear setting; low, mid and high or wide, narrow and narrowest droplet distributions, fit of the date for Equation 4 improves when compared with Equation 2 (in terms of R^2 increasing from 0.956), while the slope still remains very close to unity. The results in Figure 4 show a different vertical intercept for each linear trend line, based on three water droplet size distributions, which does indicate the influence of water droplet distribution on spray SMD. However, the offset between the fits for the three distributions further corroborates that Equation 2 (or 5) does not capture the physics associated with the effect of emulsification on the overall spray breakup process. Additional physics are needed in the correlation to account for the atomization phenomena added when spraying emulsions.

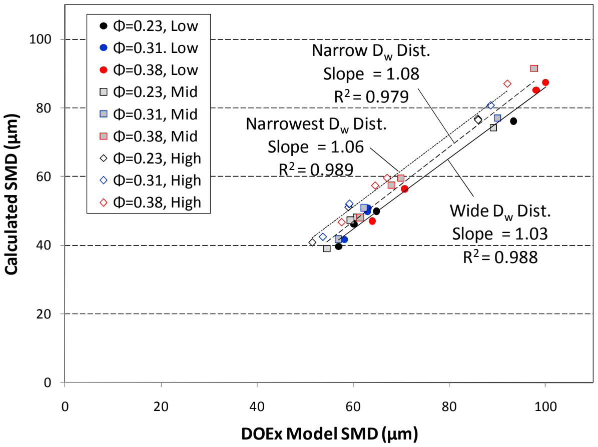


Figure 4: Spray SMD predicted by Equation 2 vs Equation 4.

Atomization Effect on Water Droplet Distribution. As the stabilized emulsion exits the emulsion generator it pumped into a bladder accumulator where it is pressurized to injection pressures. Once the emulsion is flowed back out the accumulator and through 7 meters of 0.5 in tubing and through a Coriolis mass flow meter, it passes through the pressure swirl atomizer. In the atomizer, the emulsion is expected to experience the highest shear in the system and would therefore have the potential to modify the spray most substantially.

To evaluate this, the discrete phase (water) size distribution was determined from counting over 700 droplets from sample taken before and after atomization. The low [24Hz], mid [42Hz] and high [60Hz] setting were used at a mass fraction of Φ = 0.24, 0.31, and 0.38. Table 5 summarizes the SMD_w statistics for both pre and post atomization, along with the associated number of droplets to determine the statistics. As the shear is increase to 42 Hz and 60 Hz, the distribution approaches a narrow monodispersed type near 1 µm. At the highest shear, a very narrow distribution is achieved, signifying good shearing and mixing through the 7 stages in the apparatus.

Table 5: Stabilized SMD_w for prepared emulsions both pre and post atomization, and varying water mass fraction and shear during generation.

Φ	Shear	Droplet #	SMD_w Pre-Atomization µm	Standard Deviation µm	Injection Pressure Psi	Droplet #	SMD_w Post-Atomization µm	Standard Deviation µm
0.23	24 Hz Low	748	8.90	3.02	98	1318	4.59	1.50
					269	1411	2.96	0.90
					450	935	2.93	0.89
	42 Hz Mid	738	3.17	0.96	103	1026	3.04	0.97
					282	722	2.17	0.64
					454	724	2.38	0.69
	60 Hz High	740	1.87	0.45	104	828	2.82	0.74
					269	923	2.02	0.44
					457	961	1.66	0.41
0.31	24 Hz Low	745	9.76	3.6	100	806	2.92	0.89
					299	904	3.25	0.96
					453	934	2.22	0.57
	42 Hz Mid	748	3.27	1.05	111	935	3.61	1.12
					295	946	2.80	0.84
					458	976	2.03	0.54
	60 Hz High	737	1.99	0.54	101	701	2.31	0.68
					288	725	1.60	0.35
					465	726	1.83	0.41
0.38	24 Hz Low	753	9.87	3.23	106	1003	3.75	1.17
					283	1035	3.05	0.91
					418	1036	2.91	0.85
	42 Hz Mid	752	3.30	1.02	97	748	3.12	0.95
					283	719	2.20	0.63
					438	713	1.94	0.51
	60 Hz High	758	1.59	0.34	105	715	1.94	0.43
					276	722	1.98	0.48
					445	915	1.90	0.41

Hence, the atomizer can potentially produce the same effect as the emulsion generator, decreasing the water droplet sizes and narrowing the distribution. As the pressure increases, the droplet distribution becomes narrower. Note that the high shear pre atomized emulsion and the 450 psi atomized emulsion (even with low shear pre atomization) have similar distributions. This implies that the emulsions generated with higher shear do not experience significant changes during atomization, since the shear experienced is at most of the same order as it is when the emulsion is initially produced (assuming negligible coalescence). This result implies that the change in droplet distribution will modify the effective viscosity of the emulsion during atomization [11, 16]. However, since the distributions are fairly fine to begin with, the change is minor, see Table 4.

The variation in SMD_w in Table 5 is displayed graphically in Figure 5. The variation and deviation in SMD_w at a given pressure and Φ highlights the effect of the nozzle on further emulsifying the fuel. Note that at an injection pressure of zero, this is set equal to the pre atomized statistics on the left side of Figure 5.

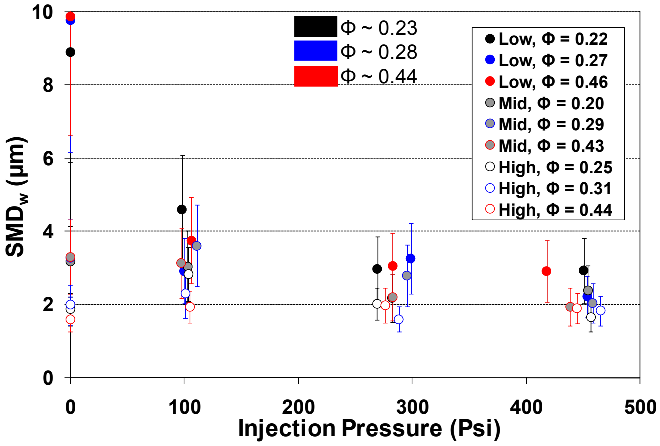


Figure 5: Stabilized emulsion water droplet SMD_w versus nozzle injection pressure with varying Φ and generating shear.

Unstable vs. Stable Emulsions. Although considerable work has been done using convenient stabilized emulsions, the question of how representative the stabilized emulsions are of natural unstable emulsions arises. A study to examine this question was carried out as part of the present work.

The spray SMD of unstable emulsions was studied with two levels of shear. The effect of shear was studied by flowing DF2 and water with and without a 150 micron screen filter located less than 300 mm upstream of the injector. In both cases, the two fluids meet at a checked T-junction, mix/shear, flow through a second check valve and proceed to the outlet of the nozzle.

Visually, little difference is observed between the stable and unstable cases as illustrated in Figure 6 for pressures of 100 and 440 psi at Φ near 0.25 and 0.35. At a given pressure, the neat DF2 and emulsion sprays appear are similar in appearance. The increase mass flow results in a denser, more turbulent spray.

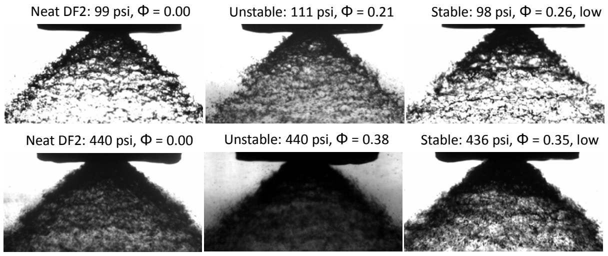

Neat DF2: 99 psi, Φ = 0.00
Unstable: 111 psi, Φ = 0.21
Stable: 98 psi, Φ = 0.26, low
Neat DF2: 440 psi, Φ = 0.00
Unstable: 440 psi, Φ = 0.38
Stable: 436 psi, Φ = 0.35, low

Figure 6: 2 µs snapshots of neat DF2 spray, unstable emulsion spray and stabilized emulsion spray at varying pressure and water mass fraction.

In terms of spray size, Figure 7 presents SMDs for the stable and unstable cases as a function of Φ. Although not shown explicitly because it is discussed in detail elsewhere [20], the insertion of the filter results in a significant decrease in spray SMD at the same Φ values (below that of neat DF2). Without the filter (only the shear introduced by the T-junction) the spray SMD is larger than that of neat DF2. This result does indicate that size of the discrete water droplets (SMD_w) is important in the resultant SMD of the spray and a finer distribution of water droplets can impact the emulsion spray SMD to lower than that of neat DF2. This is in contrast to the finding reported above (see Equation 4). This is an important observation because the stabilized emulsions used all have a relatively fine SMD_w. This implies a "critical" SMD_w likely exists above which the emulsion will behave differently that those below.

For the fine SMD_w produced in both the stabilized and unstable emulsions in the present work, the spray SMD initially decreases with the addition of minor amount of water droplets to the flow for the unstable emulsion. At Φ = 0.3, the SMD begins to increase and again reaches the value of that of neat DF2 at Φ = 0.45 and continues to increase up the end of the range measured of Φ = 0.6. The SMD of neat water is also provided in Figure 7 to show that the SMD decreases once again to an SMD slightly larger than that of neat DF2 (86 versus 82 +/- 2 μm). This same decreasing trend in SMD versus Φ is also present for stable emulsions at higher pressures of 280 psi and 440 psi. The similarities in trend provide significant evidence that stabilized emulsions breakup in a similar manner to that of natural unstable emulsions.

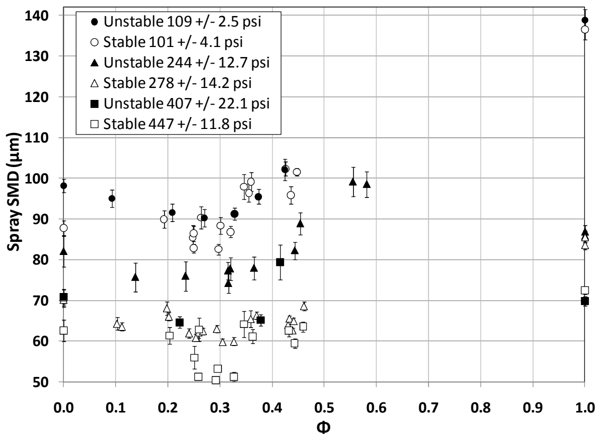


Figure 7: Spray SMD versus water mass fraction for 100, 300 and 450 psi case for unstable emulsions with two shearing configurations and stabilized emulsions.

Another aspect studied with the unstable emulsions is the pressure loss associated with the static screen filter. This was found to be very low, varying 0.3 to 0.5 psi for the range of 100 to 450 psi nozzle pressures tested. Comparing the SMD with and without the filter, this modest pressure drop results in a 10+ μm decrease in SMD. This corresponds to the improvement expected from a 100 psi increase in nozzle pressure! The water fraction of the emulsion was seen to influence breakup to reveal an effect which alters the understood breakup mode for neat liquids. This behavior does not appear to be related to changes in fluid properties of viscosity, surface tension or density [21].

<u>Emulsion Spray Local W/O Ratio</u>. The last aspect studied involves the pattern of the different sprays. In addition to overall spread of the spray, the question of whether segregation of the components might be observed was also of interest.

The results are shown in Figure 8 and Figure 9 for both stable and unstable emulsions. The patternator was set at a vertical distance of 16.5 cm for stable and unstable emulsions at 100, 300 and 450 psi with W/O equal to 0.3, 0.45 and 0.6. The results from the patternation tests are presented in two manners; 1) comparing Φ verses a fixed nozzle pressure drop in Figure 8, and 2) comparing nozzle pressure drop versus a fixed Φ in Figure 9. The stabilized emulsion patternation results were obtained with a nominally fixed Φ (Φ ≅ 0.28) and for a mid-shear prepared emulsion (water droplet distribution SMD = 3.1 μm). This represented the mid range of W/O and emulsion discrete phase droplet sizes in the stabilized case. Pressure was then varied from 107 to 441 psi for a total of 4 cases.

In Figure 8 a) – c), the variation in local Φ for the unstable case is apparent as it is for the stabilized cases and actually results in larger slope for Φ of 0.31 and 0.38 than the stabilized case at Φ = 0.28. A Φ ratio near 0.23 for Figure 8 a) – c) indicates little change in local Φ ratio as a function of radial position. Note that this case was not explicitly studied for the stabilized emulsion. A difficulty was realized in not being able to match the measured mass Φ to the measured volume Φ_v due to complete separation of the components. Oil is believed to persist between the separated stabilized emulsion which remains as a stacked body of droplets with oil interspaced between sedimented droplets, preventing a full separation of stabilized oil and water under the influence of gravity. This flat linear slope for the low Φ cases (very near zero) is depicted better in Figure 9 a). What is interesting to note from comparing the data in Figure 8 is that the water drop size distribution (i.e., with changing pressure drop for the unstable emulsion) does appear to have a substantial effect on local Φ ratio. At greater nozzle pressures, a larger flow rate results in greater shearing and mixing through the T-junction and the screen filter. Also for the stabilized case, a very fine and narrow distribution in water droplets was created through the emulsion generator and the smallest slopes at the pressure range investigated was measured.

In Figure 9, the effect of nozzle pressure is better noted by comparing the unstable emulsions at near constant Φ ratios. Pressure acted to decrease the change in local Φ ratio. This is most noticeable for an overall larger Φ (here near 0.38), shown in Figure 9 c). At Φ's near 0.23, increased pressure did not produce a significant change in local Φ, however notable is a weak negative slope resulted for the 300 and 450psi cases.

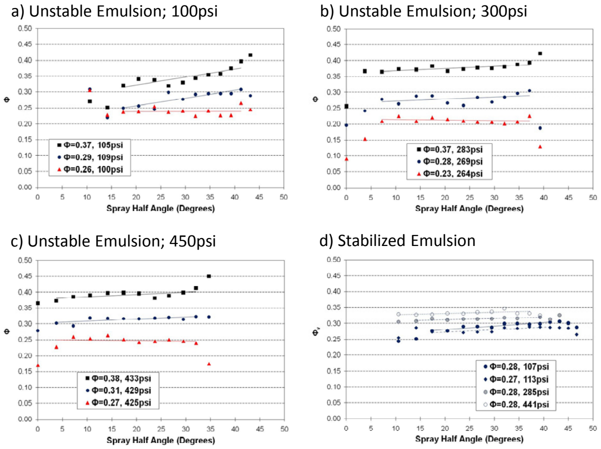


Figure 8: Local Φ ratio versus radial half angle of spray for unstable emulsion at a) 100 psi, b) 200psi, c) 300psi, and d) stabilized emulsion from 100 to 450psi with Φ_v ratio near 0.45.

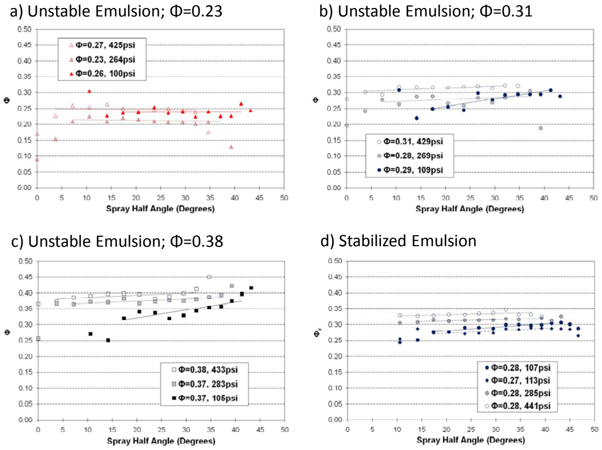


Figure 9: Local Φ ratio versus radial half angle of spray for unstable emulsion at a) Φ =0.23, b) Φ =0.31, c) Φ =0.38, and d) stabilized emulsion from 100 to 450psi with Φ_v ratio near 0.31.

In summary, (1) segregation of components occres as a result of the atomization process, although it seems to also depend on injection pressure with lower pressures resulting in greater segregation and (2) the overall trend in local Φ between the unstable and stabile cases at comparable Φ (0.28 to 0.31) demonstrating that the overall behavior of the stabilized emulsion is quite similar to the unstable case.

Conclusions

A systematic study of how emulsification impacts atomization performance has been carried out for a large capacity pressure swirl atomizer operating from 100 to 450 psi on combinations of DF2 and water. For convenience, surfactants are utilized in some cases to facilitate the detailed study of the emulsions by greatly slowing the separation of the components.

For the conditions studied, the following conclusions are drawn:

- The addition of surfactants modify the atomization of water and DF2 in a manner consistent with that expected based on how the surfactants change the physical properties of the liquids.
- The atomization of stabilized emulsions (i.e., those created with surfactants added) was studied systematically using a statistically derived experiment. Analysis of variance of the results indicates that SMD is dominated by injector pressure drop, however Φ also affects the spray SMD by 5 -10 percent relative to the effect of injection pressure. This results in a 10 micron decrease in spray SMD as Φ is increased from 0 to 0.3. Further increasing Φ results in increasing SMD for both cases back to neat values near Φ = 0.4. Increasing the water fraction further increased the SMD. Interestingly, the role of the discrete phase droplets were found to be statistically insignificant. It was observed that existing physics based SMD correlations could provide correct trends for the emulsion spray size, but did not fully capture the behavior even when using an "apparent" viscosity derived from knowledge of the discrete size distribution and concentration. This analysis also identifies that, while statistically insignificant compared to the injection pressure and Φ, the discrete phase droplet size does play a noticeable role. In the analysis of variance, this role is overshadowed due to the large range of injection pressures and Φ.
- Examination of the discrete phase size distributions before and after atomization establishes that atomization process itself can act as a source of emulsification resulting in a smaller and narrower discrete water droplet distribution.
- In comparing stabilized and unstable emulsions, high speed exposures showed that stable and unstable sprays appear indistinguishable. Examination of the spray sizes produced reveals very similar trends for the stable and unstable emulsions, including the trend with changing SMD as Φ varies. This finding is important relative to validation of the use of stabilized emulsions for the study of the

spray behavior. The study of the unstable emulsions also led to the observation that lower shear (i.e., much less that that used in preparing the controlled stabilized emulsions) results in a larger change in spray SMD. This further reaffirms that the discrete phase size distribution is, in fact, an important factor in the atomization performance of emulsions.

- Finally, for the conditions studied, a noticeable spatial separation of water and DF2 was observed, with the denser water found in greater proportion at the outer edge of the spray. Apparently, the centrifugal forces within the swirl chamber of the injector leads to some separation. Interestingly, the separation tends to be reduced as the injection pressure increases, perhaps a result of the increased shear and mixing associated with the higher pressures.

Acknowledgments

The authors would like to thank Siemens Power Corporation for the sponsorship of the current project and Guillermo Gomez for his contribution in the water droplet statistics and aid in experimentation.

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