

Generation and Pressure Atomization of Water-in-Oil Emulsions for Gas Turbines

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Abstract

This manuscript describes how the generation of interfacial area in a water-in-oil emulsion influences the pressure atomization of fuel for typical conditions in gas turbine applications. The role that shear plays in initiating the interaction between phases is first identified experimentally in pipe flow. Then, in order to analyze the resulting distribution of water droplets, surface stabilizing agents (surfactants) and a controlled shear device are utilized to control the droplet statistics in emulsions created with similar shear forces. The change in rheological and fluid properties due to the surfactants is then correlated using dimensional analysis to desired flow conditions of a surfactant free emulsion in actual turbine hardware. This approach led to an understanding of the emulsion composition and properties that can be applied to explain the emulsion breakup as it exits a pressure atomization nozzle. Spray properties and discrete phase drop size are measured using laser diagnostic methods and high-speed cinematography.

Introduction

In many practical systems, water is added to the fuel stream (creating an emulsion) and the mixture is atomized. This mixture usually takes the form of water-in-oil emulsions (due to the typical volumetric ratios of water to fuel), especially for lighter fuels. Even if no “inline mixers” are used, emulsification can be expected from the high strain rates present in any valves and/or strainers that might be upstream of the atomizers. Thus, the droplet size distribution of the emulsion entering the atomizers will depend on the number and type of upstream elements and the lengths of tubing, and will be a function of flow rate and water-to-fuel ratio. Furthermore, substantial strain occurs in the atomizer-orifice flow.

Basic macroscopic emulsions consist of one liquid phase dispersed within another. These dispersions may range between an immiscible colloid with a homogeneous consistency at predominately smaller droplet diameters, and a separation of phases with predominately larger droplet diameters. Macroscopic colloids consist of droplets in the discrete phase that are a micrometer in size or greater submersed within the continuous phase [1]. In comparison, microemulsions contain droplets predominantly sub micrometer in size and nanoemulsions consist of a distribution of droplets in the nanometer range. The formation of these emulsions from their parent fluids in their continuous phases requires the increase of the interfacial phase boundary between the two fluids by energy addition. The free energy contained in the interfacial area, $\sigma_I \Delta A_I$, where σ_I is the interfacial tension and ΔA_I is the interfacial area created. The necessary power requirement to produce an emulsion with monodispersed droplets of a given radius (r) in a steady-flow, adiabatic process [single inlet (1) and outlet (2)] can be expressed as Eqn. 1:

$$\dot{W} = \dot{m}_C(h_{C2} - h_{C1}) + \dot{m}_D \left(u_{D2} + \frac{P_{C2}}{\rho_D} + \frac{2\sigma_I}{\rho_D r} - h_{D1} \right) + \sigma_I \dot{N} 4\pi r^2 \quad (1)$$

The first term and second term on the RHS represent the enthalpy change of both the continuous (C) and discrete (D) phases; where (h) is the enthalpy, (u) is the internal energy, (P) is the pressure, and (ρ) is the density. The third term on the RHS captures the power required for the generation of surface area, where \dot{N} is the number generation rate of droplets at a corresponding droplet r . Common emulsifier examples include induced turbulent flow mixers, rotary type shear devices, membranes or micro channel flow systems, and diffusion-type devices [2,3]. In a laboratory environment it is desirable to control the shear rate ($\dot{\gamma}$) applied in the formation of emulsions to manage the droplet size distribution. The addition of surface stabilizing agents (surfactants) allows the emulsion to stabilize and reduces the interfacial tension, which in turn decreases the surface free energy of the system. Surfactants also prevent the coalescence of droplets [4].

With the high level of shearing provided by a mixing device, a narrow size distribution approaches that of monodisperse size distribution [4]. Considering dynamic viscosity ratios of the discrete over the continuous phase (μ_d/μ_c)

near unity, initial $\dot{\gamma}$ on the order of $10^2 - 10^3 \text{ s}^{-1}$ applied at the oil/water interface creates additional surface by first forming large droplets and these droplets quickly rupture into many smaller and smaller droplets due to Rayleigh instability. This development of interfacial area produces predominantly droplet diameters on the order of $10^0 - 10^1 \mu\text{m}$ on a timescale that is less than 1 second [3]. The application of additional shearing to these newly formed smaller droplets is much less effective.

The present effort investigates the use of diesel fuel distillate #2 (DF2) and water comprising the oil and water phases of a basic emulsion. With properties similar to DF2, polydimethylsiloxane (PDMS), commonly referred to as silicone oil, is a simulation fuel for unstabilized emulsion formation studies in pipe flow at realistic flow rates and shear conditions to determine an appropriate size for water-in-oil droplets. The spray experiments, however, use stabilized DF2 emulsions of similar character to the PDMS emulsions.

Materials and Methods

In order to stabilize the water-in-diesel-fuel emulsion, surfactants Span 80 and Tween 85 in concentration to attain a hydrophilic to lipophilic balance (HLB) of 6.0 was used. The combination of these two surfactants at HLB = 6.0 stabilizes the emulsion very well for a period of 60 minutes [6,7]. Increasing the concentration of surfactant results in further increasing the stability of the emulsion. According to Song et. al. [6], for a 10 % water in DF2 emulsion, surfactant concentrations of 2.5 % and higher sufficiently slow down water droplet coalescence, which normally increases the mean droplet size, as well as increases the width of the droplet size distribution. However, for surfactant concentrations nearing 6 %, the dispersion becomes saturated, leading to the formation of surfactant micelles throughout the liquid phase, which changes the emulsion's fluid properties [5]. To deter coalescence, generated emulsions were diluted 100 – 500 times with DF2 mixed with the appropriate amount of Span 80 to maintain HLB during the characterization of the water droplet size distribution. The method for creating the emulsion involved the gravity feed of water and DF2 into a high shear device in a batch process. The water and DF2 are poured in proportion to the desired water-to-oil mass ratio, (W/O). W/O near 0.3, 0.45 and 0.6 were used here.

Characterization of Emulsion Produced in Rotary Mixer

A high shear mixer was utilized for surfactant stabilized water-in-DF2 emulsions. A commercial unit, an 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. A schematic of a 3 stage rotor-stator disk configuration showing a flow diagram through the slots of the emulsifier is shown in Figure 1a. Low, medium and high rotary speed was used at 24, 42 and 60 Hz to produce different levels of shear.

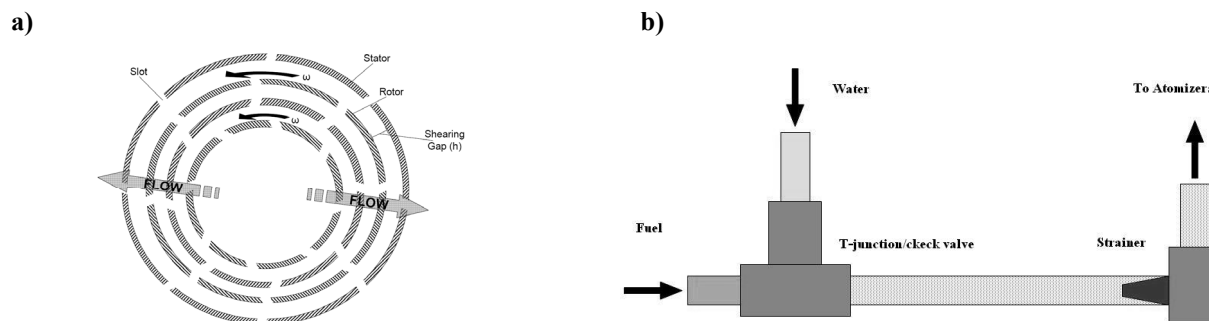


Figure 1. (a) Schematic of three stage rotor-stator disk configuration in respect to outward emulsion flow through slots. (b) Schematic diagram of the T-junction and strainer in a practical system.

In order to categorize the droplet distribution of the discrete phase, (which is water for the W/O = 0.3 case) stabilized emulsions were diluted and digital photographs were captured at 100 -1000 times magnification using a triocular microscope (Nikon Labophot). Image analysis software (Image-Pro Plus version 5.1) was used to count and measure water droplet diameters utilizing a two point method, and representative diameters associated with the resultant size distribution were obtained. The emulsifier shear conditions were compared to those for a surfactant-free emulsion in the industrial flow system that includes a mesh filter following a T-type junction, as shown in Figure 1b. The comparison with the industrial flow system was only qualitative since the unstable emulsion droplets were small and densely populated in that case, making quantitative measurements difficult.

Interfacial Tension Measurement

The interfacial tension for the two-phase fluids under investigation was calculated by the “pendant drop method.” The pendant droplet was formed by injecting the DF2 phase into the denser water phase through a 0.089 mm ID tube. A digital image of the droplet in equilibrium was obtained (Casio Exilim EX-F1 camera) and the interface between the water and the oil was traced using image processing routines (Mathematica). A normal stress balance (Young-Laplace equation) was applied to the traced interface to compute the interfacial tension. The addition of surfactants produced smaller static droplets and required the use of additional magnifying optics to define accurately the droplet boundary.

Atmospheric Pressure Atomization Rig

The prepared emulsion produced by emulsification system was flowed into one of three separate accumulators where the batch was pressurized from 100 to 600 Psi and switched to a return circuit via a T-junction to the atmospheric atomization rig. A mass flow meter (MicroMotions Coriolis type) was used to measure the mass flow and density of the emulsion and a pressure transducer measured the differential pressure upstream of the nozzle exit. The pressure atomization nozzle was a Parker-Hannifin Macrolaminate Injector with an overall exit diameter of 1.905 mm. Laser diffraction (Insittec RTS) measured the spray Sauter Mean Diameter (SMD) and Mass Mean Diameter (MMD). The laser system was calibrated prior to testing. The laser measurement area (9 mm beam diameter) was positioned 3 cm below the nozzle exit. The reported test results are averages of 60 test points acquired at a sample rate of 1 per second. Post processing corrected for low light scattering signal due to the denseness of the spray as well as beam steering due to the spray vapors.

The parameters measured from laser diffraction were compared to a correlation equation calculating SMD for pressure simplex atomizers proposed by Lefebvre [8] to check its applicability to the current atomizer.

$$SMD = A \sigma^{0.25} \mu_L^{0.25} \dot{m}_L^{0.25} \Delta P_L^{-0.5} \rho_A^{-0.25} \quad (2)$$

Results and Discussion

The σ_I of water-in-diesel fuel was measured for 0, 1, 2, 3.5 and 5 % surfactant addition for an HLB = 6.0. Figure 2 shows σ_I changing from 26.8 ± 0.04 dynes/cm without the use of surfactant to $1.8 - 1.2 \pm 0.05$ dyn/cm with 1 to 5 % addition of surfactant. These differences in interfacial tension indicate that the barrier to droplet breakup has been decreased, which will lead to smaller water droplets for the same amount of shear applied. The addition of the surfactant also changes the fluid properties. Specifically, the dynamic viscosity of water (μ_d) increases 46% (from 0.0014 – 0.0020) with a 5 % addition of surfactant; for DF2, it increases 19 % (from 0.0029 – 0.0035 kg/m-s) for the same 5 % addition of surfactant. The increase in density for both fluids is less than one percent.

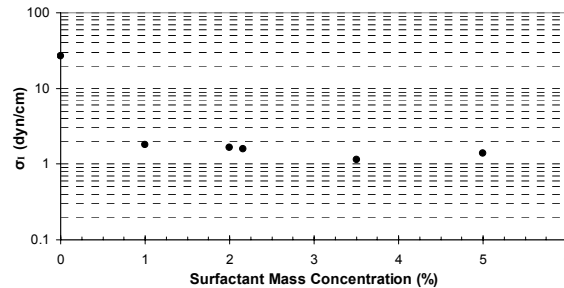


Figure 2. Effect of surfactant addition on interfacial tension for water-in-DF2 emulsion.

Water-in-Oil Droplet Size Determination

An adequate sample size was determined using the approach used by Lemenand et al. (2003) for the determination of the mean droplet size [2]. This method was utilized to establish a representative sample size in order to generate statistics for the water droplet distribution produced in the rotary mixer emulsifier. Increasing the sample size demonstrates an overall asymptotically decreasing trend in SD_n to less than 0.1 % and is in good agreement with the study by Lemanand et al. [2]. Sample sizes greater than 600 droplets for high-shear cases and 800 droplets for the low-shear case provide a good statistical representation of a continuous distribution for water droplet size in DF2 when the shear-strain rate in the present case is on the order of $10^3 - 10^4 \text{ s}^{-1}$.

Using the single rotor-stator disk stage, three stabilized emulsions (adding 5 weight % surfactant) at a W/O = 0.3 were prepared at different rates of shear (characterized by spinning rates of 24, 42 and 60 Hz) in the rotary mix-

er. The resulting stabilized emulsion was sampled, diluted and photographed under a microscope. The resulting water droplet diameter (d_w) frequency % and volume % distributions were determined using a bin size of $0.4 \mu\text{m}$ and are presented below in Figure 3(a-c). Increasing shear for 24, 42 and 60 Hz produced corresponding maximum shear strain rates of 1.5×10^4 , 2.7×10^4 and $3.8 \times 10^4 \text{ s}^{-1}$ at the rotor wall.

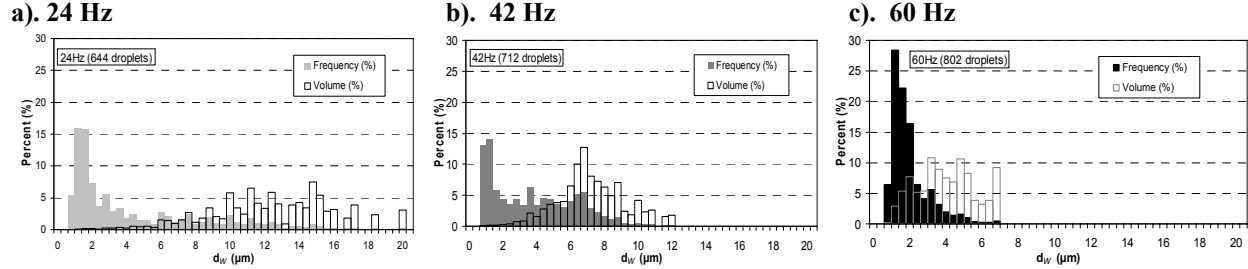


Figure 3 (a-c). Water droplet diameter frequency and volume distributions in % in DF2 ($W/O = 0.3$) for three cases of rotational shear.

From Figure 3 (a-c), the droplet distribution is representative of a well-sheared fluid and is very similar to skewed distributions of droplets of other shear generation devices [3,8]. The distribution showed a limit in droplet diameter near $0.7 \mu\text{m}$, which agrees with the typical limit in drop size for macroemulsions [4]. The appearance of these emulsions is a milky white texture/color without the distinction of the two phases. This is characteristic of an emulsion which is predominately composed of droplets $> 1 \mu\text{m}$ [5]. Note also the shift toward a narrower size distribution as well as smaller mean droplet diameter with increasing rotation speeds in the mixer. At 60 Hz, the droplet distribution approaches a very narrow range with a mean $d_w = 1.8 \mu\text{m}$ and a standard deviation of $1 \mu\text{m}$.

The computed distribution and associated statistics allowed a curve-fit. Using the previous 1-stage shear and 5% surfactant, a two-parameter curve-fit model, as proposed by Schwarz and Bezemer, was used.

$$V\% = 100e^{a\left(\frac{1}{d_{w\max}} - \frac{1}{d_w}\right)} \quad (3)$$

Volume is in cumulative volume percentage ($V\%$) at a given water droplet diameter d_w and a is a fitting constant. This model resulted in a good fit for the larger droplets, as is shown in Figure 4 [10]. This result proves useful in allowing the larger droplet diameters to be predicted, which will have the largest impact on the spray behavior. Fitting constants were $a = 21$, 12 and 7 for the 24, 42 and 60 Hz cases, respectively. Also, the divergence of the distribution increases as the droplet diameter decreases. The single intercept point between the three water droplet distributions for a cumulative volume of 280% when $1/d_w = 0$ signifies a proportionality between the maximum droplet size and representative diameters (e.g., the mean or SMD) of the distributions. In the present analysis, the maximum d_w was directly proportional to SMD by a factor of 1.8 with a standard deviation of 0.24 for the three separate distributions: 1-stage shear, 2% surfactant; 1-stage shear, 5% surfactant; and 7-stage shear, 5% surfactant.

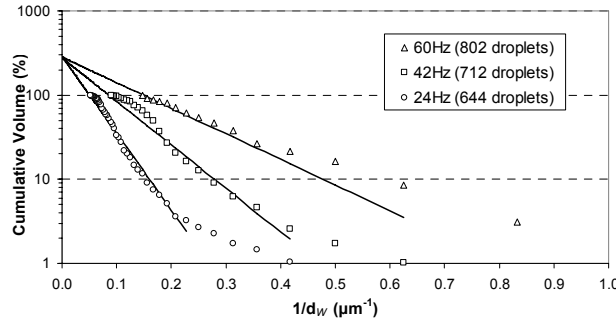


Figure 4. Water droplet size distribution plotted during emulsion generation for three cases of shear for a $W/O=0.3$.

Considering the mean d_w for 24 – 60 Hz, varying the number of stages from 1 and 7 as well as decreasing the amount of surfactant used from 5 to 2%, the mean droplet diameter, maximum droplet diameter and SMD were calculated. The droplet Weber Number (We_d) will be, $\mu_c \dot{\gamma}_{\max} h / 4\sigma_s$, where μ_c is the dynamic viscosity of the continuous

phase, $\dot{\epsilon}_{\max}$ is the maximum shear strain at the rotor tip and h is the dimensional length of the rotor-stator stage. A trend in maximum d_w was realized and correlated with the maximum shear strain (or velocity) present in the rotor-stator gap h . Physically, this represents the largest space corresponding to the largest droplet which is able to be produced during the emulsification process. The SMD of the distribution of water droplets in the stabilized emulsion prior to atomization was also determined for the different emulsion formation cases. Based on the analysis by F. B. Sprow (1966), a correlation was developed that relates We_d to larger discrete phase droplets where the droplet diameter is larger than the Kolmogorov scale of turbulence. In this inertial range of scales, the turbulence induced breakup is only a function of the energy dissipation [11]. The correlation was verified using a turbine type shear device (where energy dissipation can be assumed to be constant) for emulsion generation shown here with the SMD substituted maximum droplet size based on prior relating of distributions using Equation (3). This correlation is

$$\frac{SMD}{D} = C_o We_d^{-0.6} \quad (4)$$

where D is the geometric parameter and C_o is a proportionality constant dependent on the specific experimental setup. According to R. Shinner (1961), using G. I. Taylor's approach in considering the effect of fluid viscosity in addition to the energy dissipation for emulsions, is important when generating discrete-phase droplets which are smaller than Kolmogorov scale of turbulence [12]. The smaller the droplet's size, the more rigid is its structure. The role of viscosity accounts for the internal and external circulating currents of the fluid both inside and outside the small droplet. The droplet-bursting condition, where the disruptive shear forces are equivalent to the surface tension forces holding the droplet together, is a function of the ratio of dispersed to continuous phase viscosity for the formation of small emulsion droplets [13]. Balancing forces in terms of the We_d for smaller emulsion particles, the local velocity is a function of energy dissipated and kinematic viscosity for the turbulent case. This relationship for emulsion generation in propeller or turbine mixers can be represented for the SMD as

$$SMD = C_1 \sigma_I \rho_c^{-1/2} \mu_c^{-1/2} U_{\max}^{-3/2} D^{1/2} f(\mu_d / \mu_c) \quad (5)$$

where C_1 is an empirical constant, the maximum velocity U_{\max} is chosen due to the correlation with d_w max as well as SMD and μ_d is the discrete phase viscosity. With the function f proportional to the viscosity ratio to the $-3/4$ power for the lowest residual error, Equation 4 and Equation 5 both provided a good fit ($R^2 = 0.877$ and 0.872) to the measured SMD of the water droplets. This predicted SMD with $C_o = 4.82$ and $C_1 = 4.55$ are plotted versus the measured SMD in Figure 5(a). Note that μ_d/μ_c varied from 0.47 for the surfactant free emulsion to 0.58 at 5 % surfactant. Utilizing both equations, the predicted drop size range was calculated by relating fluid properties to Equation 4 and Equation 5 versus We_d in Figure 5 (b). The effect of coalescence was not incorporated in the calculation of SMD during emulsion formation.

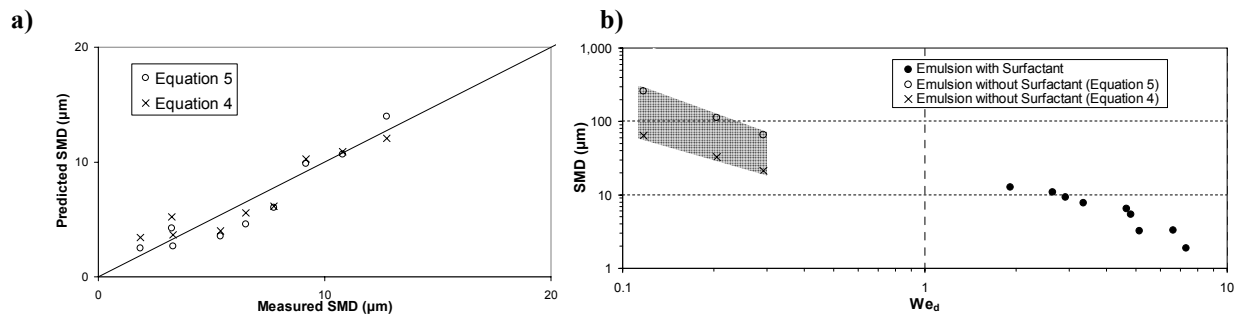


Figure 5. (a) Predicted versus measured water droplet SMD and **(b)** SMD versus droplet Weber Number for 1- and 7-stage shear cases.

Spray Characteristics

Preliminary measurements of the spray generated by the pressure swirl injector nozzle were completed at atmospheric conditions. The laser diffraction results for DF2, DF2 “stabilized” with 7.3% Span 80, H₂O, H₂O “stabilized” with 2.6% Tween 85 and stabilized water-in-DF2 emulsions prepared with water droplets using low, medium and high shear with W/O near 0.3, 0.45 and 0.6 are presented in Figure 6. It is noted that for DF2 at full flow conditions (near 600 psid), the laser diffraction system has difficulty recording a drop size due to the opacity of the spray. The measurements for DF2 and H₂O are well described by Equation 2 for pressures above 100 psid (corresponding

to a fully developed spray). The atomization of H₂O results in a larger representative droplet size for a given pressure than does DF2. From Figure 6, it is evident that atomizing pressure plays the dominant role in establishing the overall spray SMD. However, further examination suggests that the atomization of an emulsion results in a lower SMD compared to the pure liquids. The results also suggest that an emulsion with W/O near 0.45 results in a smaller SMD than W/O of 0.3 or 0.6. The results also suggest that the size distribution of water droplets within the emulsion does not strongly affect the spray SMD. Further analysis of variance (ANOVA) is being carried out to establish the relative contribution of injection pressure, emulsion size distribution, and W/O on the characteristics of the spray, including SMD and spray angle.

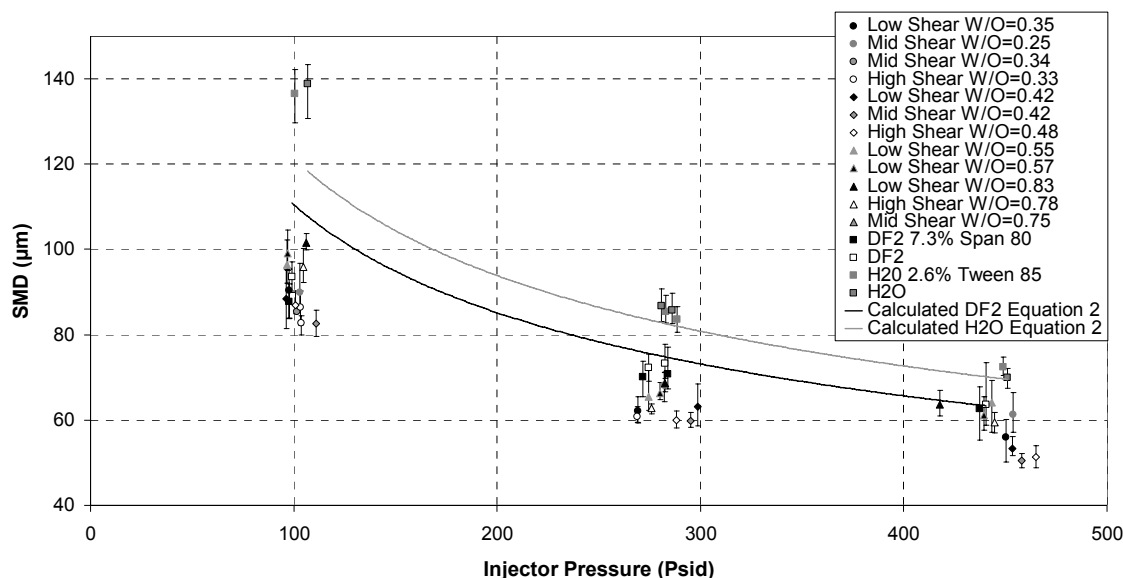


Figure 6. SMD versus nozzle pressure drop measured using laser diffraction for DF2 and water-in-DF2 emulsions.

Finally, it is noted that photographs of the emulsion droplets taken after atomization (under a microscope) reveal that the atomization nozzle further modifies the emulsion droplet size distribution, confirming that the atomizer itself is a strong source of strain for the conditions studied, even more so than the IKA emulsifier itself.

Acknowledgments

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