Turbulent Fuel Droplet Vaporization and the Initial Size Effect: Experimental Data at Elevated Pressure and Temperature

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1 Introduction

Spray combustion is a complex two-phase phenomenon that occurs at high pressure and temperature in turbulent environments. The rates of momentum, energy, and mass transport govern the sequential processes of droplet formation, vaporization, and combustion. A persistent belief encountered in fuel vaporization studies is that a single, isolated droplet can adequately predict certain fundamental characteristics of atomized liquid emanating from a spray, as the droplets tend to act independently of one another after the rapid breakup of the liquid jet has occurred (e.g., [1,2]). Experimentally and numerically, a significant amount of research has been invested into studying the pressure and temperature effects on droplet evaporation (e.g., [3,4], [5] and the references cited therein), while investigations into the effect of initial droplet size (e.g., [6,7]) and turbulence (e.g., [8–11]) have been less abundant, especially when evaluated simultaneously (e.g., [12]). With an emphasis on predicting the mass burning rate, the consequences of varying the initial droplet diameter in combustion scenarios have largely been attributed to soot formation and radiative losses (e.g., [13,14]), yet at a more fundamental level, the reasons behind the effect of droplet size in pure evaporation remain undetermined. Evaporation is often considered the rate-limiting precursor to combustion (e.g., [2]). Thus, the effect of droplet size, coupled with the interrelated parameters of pressure, temperature, and turbulence, remains a topic of considerable interest. Evaporation rates have been shown to increase with the initial droplet diameter in turbulent conditions at room conditions (e.g., [12]), as well as in stagnant environments at high temperature and pressure (e.g., [6]). The experimental evidence presented here seeks to reconcile the effect of elevated temperature and pressure on evaporating heptane and decane fuel droplets with different initial size subjected to a homogeneous and isotropic turbulent flow field with quasi-zero mean velocity. The purpose of this study is to examine the relationship between pure turbulent fluctuations, in the absence of a bulk convective flow, and initial droplet diameter. The additive factors of temperature and pressure serve not only to enhance the applicability of the results but also to modify certain characteristics of the flow field such as the turbulent Reynolds number (e.g., [2]). The resulting disparity in turbulent length scale separation provides insight into the relationship between droplet diameter and small-scale eddy size which has, in the past, not been assigned much importance. The variation

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of the temperature and pressure also results in the modification of certain thermophysical properties of the two-phase system, such as the enthalpy of vaporization, droplet surface temperature, and vapor concentration at the surface, all of which affect the rate of droplet evaporation. Through the implementation of a cross-fiber suspension technique, micro-sized droplets have been successfully generated. Historically, the experimental creation of droplets in this size range has been difficult. In addition, the cross-fiber method, when coupled with sufficiently small fibers, has been largely validated in terms of mitigating fiber conduction effects (e.g., [15]), and the capability exists to suspend nearly spherical droplets which evaporate to completion. Analysis of the entire droplet lifetime is generally not possible using the classical single fiber suspension technique due to the large nodule at the fiber tip. This, consequently, results in the omission of the vaporization process in the final moments of the droplet's vaporization history. The d^2 law, which predicts a completely linear temporal reduction in the droplet surface area, has been shown to deviate significantly from theory in the later stages of evaporation under certain circumstances (e.g., [15]). This effect is witnessed and discussed in the present study, where turbulence intensities exceeding 1.5 m/s are attained, and temperatures and pressures in the 25 – 100°C and 1 – 10 bar range, respectively, are parametrically varied. The range of droplet size distributions, temperatures, pressures, and turbulence levels encountered in actual combustors, combined with the ability to offer validation data to numerical codes, provides the main motivation for this research.

2 Experimental Setup

The present droplet vaporization study is performed in a large 29 L steel spherical chamber (Fig. 1). The vessel is equipped with four pairs of axially-opposed fans for turbulence generation, and four equally spaced quartz windows around the horizontal equator to provide optical accessibility for flow field diagnostics and high-speed imaging. The angular positioning of the fans around the circumference ensures that all fan-driven air flow is directed precisely towards the center of the chamber, thus resulting in a low mean velocity with high fluctuations. Each fan runs off an independent servo amplifier, and fan speed accuracy was checked and set to within 1% of the target RPM. Additional details of the chamber may be found elsewhere [10,16]. At the center of the chamber, an aluminum frame with two intersecting 14 µm SiC fibers is vertically suspended from the top via a single support (Fig. 2).. A fuel droplet was placed at the intersection of the fibers using a capillary tube injection system which is retracted at the instant of droplet generation to avoid influencing the results. This system allowed the generation of droplets ranging between 110 and 730 µm. The chamber was heated using a plate with large heating wires, and the vessel was filled with compressed nitrogen supplied from a commercial cylinder. Fan speed, temperature, and pressure were checked regularly throughout the course of the experiments. Particle image velocimetry (PIV) was performed using a Dantec system to assess the properties of the turbulence at the center of the chamber. Typically, 3000 image pairs provided sufficient convergence of turbulent statistics. The evaporation history of droplets subjected to varying levels of turbulence, temperature, and pressure, was evaluated. The imaging system consists of a high-speed camera with a backlight, while processing of the images to extract d^2 behavior was achieved by utilizing an in-house developed MATLAB code. The evaporation rate, K, was determined by a least-squares fit of the linear portion of the temporal d^2 variation; that is, using $(d/d_0)^2 = K(t/d_0^2)$.

3 Results and Discussion

Details of the turbulence characterization of the generated flow field inside the spherical chamber have been reported elsewhere [10,16]. However, further tests were performed to ascertain the effect of pressure and temperature on turbulence intensity and integral length scale. It is well-known that the turbulence intensity, defined as the square root of the turbulent kinetic energy, $q^{0.5}$, is a linearly increasing function of the fan speed for similar fan-stirred chambers. Furthermore, the present PIV results indicate that the relationship between fan speed and intensity is relatively independent of temperature, pressure, and the cross-fiber support frame within the central region (~10 mm radius) of the chamber (Fig. 3). Similarly, the integral length scale, L, remains unchanged regardless of the variation in any of the aforementioned parameters, including fan speed. Based on the correlation coefficients extracted from 21 PIV runs, the average integral length scale value is 21.23 mm with a standard deviation of only 1.08 mm. Thus, the effect of temperature and pressure on the turbulent Reynolds number, $Re_{t,L} = q^{0.5}L/v$, is limited to modifying the kinematic viscosity, v, of the gaseous phase.

Previous results (e.g., [12]) have established the droplet size-turbulence relationship on the evaporation rate of heptane and decane droplets at room conditions (Fig. 4). The evaporation rate, K, continuously increases with turbulence at any droplet size. Also, K increases linearly with the initial droplet diameter at any given level of turbulence intensity (fan speed). The variation of droplet size produces little effect on K in a stagnant environment. These relationships hold for all temperatures and pressures tested. The effectiveness of turbulence, defined as the ratio of evaporation rate over the corresponding stagnant value, K/K_0, increases with pressure. This finding is shown in Fig. 5 for heptane; the same trend is noted for decane fuel (not shown). The difference in K/K_0 between the 5 and 10 bar groups is less than that for the 2.5 and 5 bar groups, indicating that increasing pressure beyond 10 bar may yield diminishing improvement to the normalized evaporation rate. It is generally accepted that fuels of lower volatility are affected to a greater extent by turbulence (e.g., [8,9]). The supporting experimental evidence for such claims typically involves large, consistently-sized droplets. However, Fig. 6 indicates that the volatility-turbulence relationship may not persist in the same capacity at high pressure, especially for smaller droplet sizes, where K/K_0 trends for heptane and decane at 10 bar begin to converge. Conversely, the difference between fuels at 1 bar is relatively independent of droplet size. Substantially higher turbulence intensity should be examined on this basis, however generating small droplets at high pressures and fan speed is an experimental challenge. Despite K correlating linearly with d_0 at any turbulence intensity and pressure, plotting the slope of K vs. d_0 against pressure yields no discernable monotonic trend which further illustrates the complexity of the relationships involved. Both heptane and decane adhere to the d^2 law at room temperature and pressure. However, increasing the pressure can promote deviation from linearity at various points during the droplet's lifetime, with or without turbulence. Although it is acknowledged that quasi-steady hydrodynamic theories, from which the d^2 law is derived, are not applicable at reduced pressures exceeding unity (e.g., [5]), these findings allude to the possibility that transient effects set in at pressures well below the critical value. Figure 7 plots the d^2 lifetime of a typical heptane droplet at high pressure and moderate turbulence; two distinct linear sections are clearly visible. Although this type of behavior has been witnessed previously (e.g., [15]), the conditions were vastly different (microgravity experiments, high temperature, and atmospheric pressure). The instantaneous diameter at which deviation from linearity occurs, d_{dev}, is found to be a function of the initial diameter, pressure, and turbulence. In all cases, d_{dev} is a linearly increasing function of d_0. At low pressure, the relationship between d_{dev} and d_0 is relatively independent of the turbulence level (Fig. 8). As pressure increases, turbulence begins to have an effect, and the various intensity data groups begin to separate. Precisely how turbulence affects the d_{dev} vs. d_0 relationship may be fuel-dependent, and further research is required to make firm conclusions.

Previous studies have found that the effect of turbulence decreases at higher temperature as temperature-dependent effects such as improved mass diffusivity and heat transfer begin to dominate (e.g., [11]). Similarly, results from the present study reveal that the turbulence effectiveness and droplet size relationship is greatest at low temperatures. For decane, the slope of K/K_0 vs. d_0 is over twice as large at 25°C than it is at 100°C for 1000 RPM. This difference increases to four times at 3000 RPM. Increased Kolmogorov length scale, η, at elevated temperature may also play a role, as small ratios of η/d_0 were shown to be beneficial to the vaporization rate of alkane fuels [12].

4 Conclusions

These experimental results represent an initial effort into understanding the complex relationships between fuel droplet vaporization and four fundamental factors: initial droplet diameter, ambient turbulence, pressure, and temperature. Droplets with diameters below 200 µm have been successfully generated and studied. The effectiveness of turbulence increases with pressure at all droplet sizes, while the inverse is true for temperature. Furthermore, conditions under which d^2 behavior deviates from linearity are identified. Future research will combine high pressure and high temperature, seek to develop correlations, and provide explanations regarding the physics responsible for the above findings.

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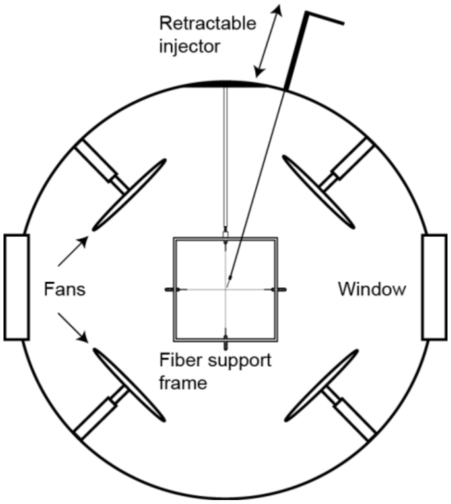

Figure 1. Side cross-sectional view of chamber with frame installed.

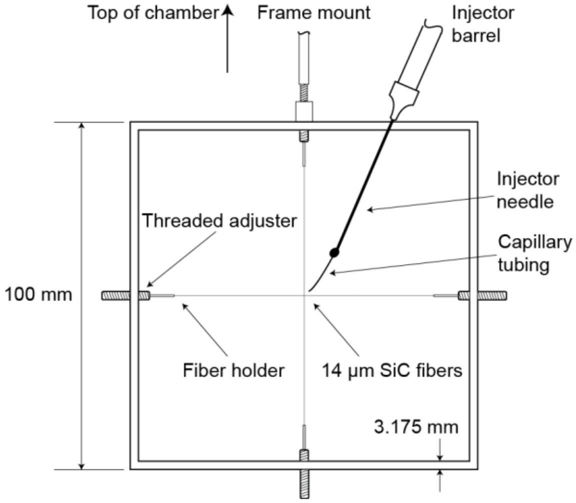

Figure 2. Details of the aluminum cross-fiber support frame and injector.

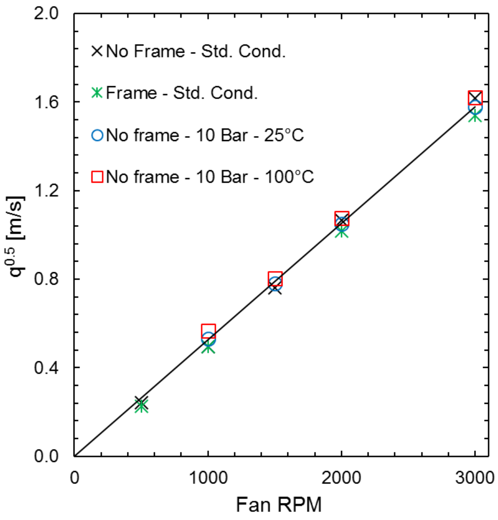

Figure 3. Turbulence intensity vs. fan RPM for various test conditions.

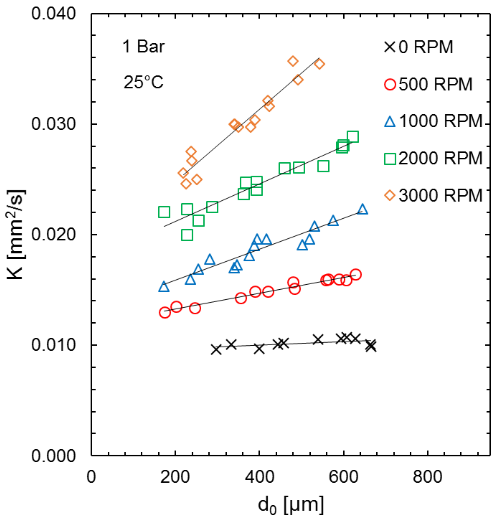

Figure 4. Heptane droplet evaporation rate vs. initial droplet diameter at various turbulence levels.

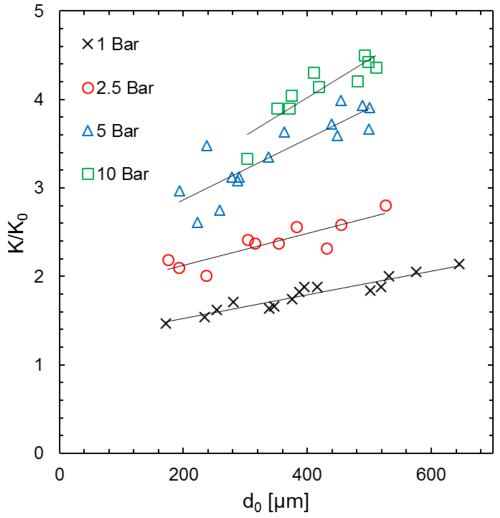

Figure 5. Heptane droplet normalized vaporization rate vs. droplet initial diameter at different ambient pressures and 1000 RPM.

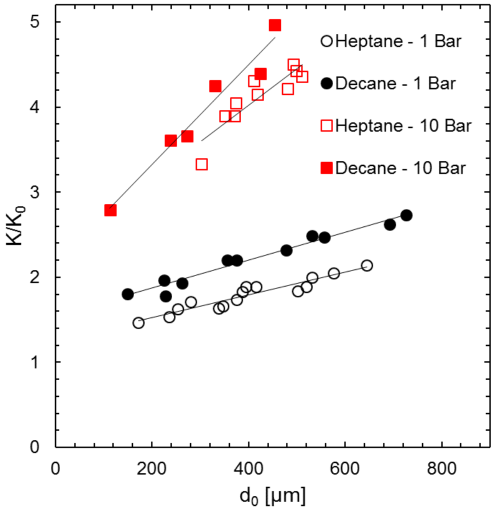

Figure 6. Normalized vaporization rate of heptane and decane vs. droplet initial diameter at two different ambient pressures and 1000 RPM.

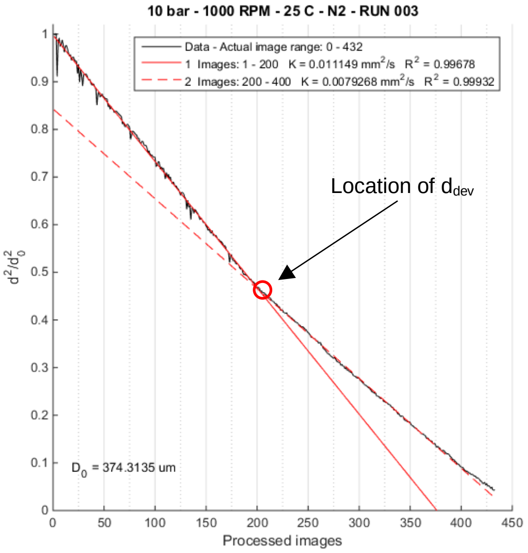

Figure 7. Illustration of the two stages of linearity present in some high-pressure tests – heptane at 10 bar.

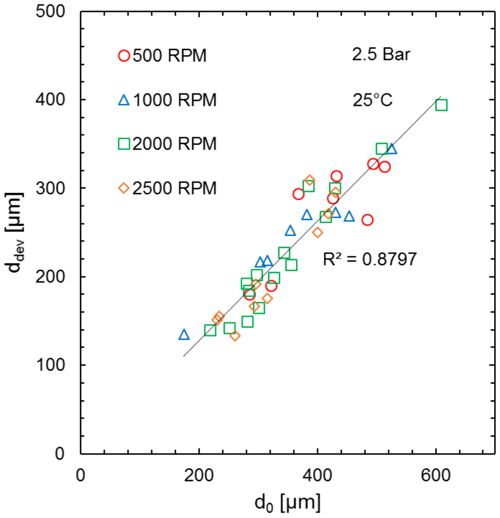

Figure 8. Relationship between the diameter at which linearity breaks up and the initial diameter – heptane at 2.5 bar.