Effect of the Initial Diameter on the Vaporization Rate of a Fuel Droplet in a Turbulent Atmosphere: Experimental Data

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1 Introduction

The performance of Spray combustion relies heavily on the liquid fuel breakup mechanism and also the resulting drops vaporization process. This process depends on a variety of parameters which includes the fuel properties and the conditions of the surrounding environment. The influence of each of these parameters on droplet vaporization process has been widely reported in the literature (see for example, [1-9], to cite only a few). However, one of the aspects that has not been studied extensively is the extent of the role of droplet size on the gasification process. This is a practical issue as the droplet's size upon the injection of a spray into a combustion chamber spans over a wide range ([1]). Recent published studies on this specific topic brought important information (e.g., [10-20]). For instance, Khan et al. [13] reported that the vaporization rate increases with the initial diameter of kerosene fuel droplet evaporating in a quiescent hot environment at high pressure. These results corroborate those of Lefebvre and co-workers (e.g., [1, 21-23]) who found that the heating period becomes longer with larger droplets. Bae and Avedisian [14] examined experimentally the influence of the initial diameter on the droplet burning rate in a quiescent atmosphere. Their results indicated that the droplet burning rate was unaffected by the droplet initial diameter for sooting flames, whereas it decreased with larger droplets for droplet sooting flames. These findings were found to be in agreement with previously published results for the case of droplet sooting flame (e.g., [15, 17, 18, 19]). Abou Al-Sood and Birouk [12] performed a numerical simulation to examine the effect of droplet initial diameter on the vaporization rate of a droplet evaporating in turbulent environment at elevated ambient pressure and temperature conditions. They reported that increasing the droplet initial diameter decreases the droplet wet-bulb temperature and increases the vaporization rate and heat-up period. More recently, Awasthi et al. [20] examined numerically the effect of size of methanol droplet combusting in a hot quiescent environment at 1 atm where they observed a substantial change is the gasification rate with droplet size.

The present paper builds upon these published studies and thus reports new experimental data on the effect of initial diameter on the vaporization rate of a hydrocarbon fuel droplet evaporating in a turbulent atmosphere at room conditions. To do so, a 14 μm size cross fiber setup was used to suspend the droplet. Tests were performed in a quiescent and convective flow conditions at atmospheric pressure.

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2 Experimental Setup

A new droplet suspension system was designed and fabricated in house. It allows forming droplets much smaller than previously investigated in our lab. A 14 micron diameter SiC fiber was selected for the cross fiber design. Due to its delicate nature, a 4-inch square aluminum frame with a 1/8 inch thickness was designed to allow the individual fibers to be installed outside of the combustion chamber. The frame was then installed as a unit since installing the fibers individually was found to have a high probability of breaking up. In addition, a spring system was included in the frame to improve the fiber's tolerance when pushed on by the injector during droplet formation and thus giving it some movement before it would break up compared to being secured rigidly on both ends. This system also allowed for a more constant fiber tension throughout the experiment. A schematic diagram of the complete cross fiber setup is shown below in Fig. 1(a). The cross fiber frame system was designed with four turn-buckles which allow the frame to be adjusted from all four supports (mounting brackets). Small nuts were arranged throughout the set-up in order to tighten down the system once all adjustments were made so that the entire fixture and frame become rigid. The 14 micron fibers were adhered into place on the frame using JB Weld and the tension of each fiber can be adjusted using the adjustment screw at each end of the fiber causing the spring to become partially compressed. The position of the frame was adjusted using the turn-buckles to center the cross fibers at the center of the combustion chamber. Each nut is then tightened down making the setup rigid. Droplets can be suspended onto the 14 micron SiC cross fiber using a manual fuel injection system. A micro injection needle was implemented in order to produce a small enough droplet so that it can be transferred onto the fiber. An originally designed, 30 gauge (305 microns), needle provided a large surface tension and consequently could not release a droplet. Therefore, a 50 micron acrylic micro-tubing was used by gluing it into the end of a 30 gage stainless steel needle. The injection system was setup at the top of the chamber pointing downward at about a 25 degrees angle from the vertical centerline of the chamber. This allowed gravity to aid in the transfer of the droplet from the micro-tubing onto the cross fiber. Once a droplet was formed, the injector was immediately pulled up away from the droplet and a sequence of images of the droplet was captured using an imaging system (a high speed camera with a backlight system) until the droplet had completely evaporated. These images were then analyzed using an in-house developed Matlab code to determine the droplet evaporation rate. Detail of the imaging system and image processing is reported elsewhere [24-25].

3 Results and Discussion

Turbulence characterization was reported elsewhere; see Birouk and co-workers [24-25]. Figure 1a shows that droplet is almost spherical in accordance with the observations reported by Chauveau et al. [26] for cross-fiber technique. Whereas, the droplet suspended on the classical quartz fiber departs noticeably from the sphericity (see Fig. 1b). Nonetheless, Figure 2 shows that both droplets exhibit a quasi-linear temporal variation indicating the applicability of the d^2-law for both droplet suspending techniques. Figure 3 presents the n-heptane droplet vaporization rate as a function of the droplet initial diameter for different turbulence intensity levels (similar trend is observed with n-decane droplet). This figure shows clearly that the increase in the droplet vaporization rate with the droplet diameter is insignificant in a quiescent atmosphere (see also Fig. 2a); whereas it is quite apparent in a turbulent environment (see also Fig. 2b). In Figure 3, we included the data of the classical suspending quartz fiber which correspondent to d_0 greater than 1000 µm assuming that the droplet heat transfer is unaffected by the size of the suspending fiber at room temperature conditions. This figure shows that, for example, when the droplet initial diameter increases from 500 µm to 1000 µm, the vaporization rate increases by only less than 8% in quiescent atmosphere, and as high as 16%, 20% and 20% at 0.31 m/s, 0.93 m/s and 1.24 m/s, respectively. It is evident that the effect of the droplet size prevails in the presence of a convective flow field around the droplet. This experimental finding corroborates the numerical simulation results reported by Abou Al-Sood and Birouk [12] where the same turbulence intensity resulted in a higher vaporization rate when the droplet size was increased from 100 µm to 1500 µm. This could be attributed to the increased heat transfer between the droplet and its surrounding ambient air as a result of reduced droplet steady state (wet-bulb) temperature with increasing droplet size (Abou Al-Sood and Birouk [12]). A reduction in the droplet wet-bulb temperature yields an enhanced temperature gradient at the droplet surface which in turn promotes vapor formation. The fact that the vaporization rate does not vary significantly with droplet size in a quiescent atmosphere may be attributed to the lack of enough vapor diffusion away from the droplet surface (that is vapor accumulation).

To develop a correlation between droplet size, vaporization and ambient conditions, a Damköhler number is adopted. This non-dimensional number is defined as the ratio of the flow characteristic time scale, t_{flow}, over the vaporization characteristic time sacle, t_{vap}, as Dam = t_{flow}/t_{vap}. The vaporization characteristic time scale is defined as (Chauveau et al. [24]) $t_{vap} = r_s/u_r$ where r_s (taken as r_0) and u_r are the droplet instantaneous diameter and vapor blowing radial velocity which is defined as $u_r = (\rho_v/\rho_l)(-dd_s^2/dt)/2r_s$ where ρ_v and ρ_l are the fuel vapor and liquid density. The flow characteristic time scale is defined as $t_{flow} = d_0/\sqrt{q}$. Figure 4 illustrates the variation of Damköhler number (abbreviated as Dam) versus droplet size (i.e., the initial diameter) at typical turbulence intensity. This figure clearly reveals that as the droplet size increases, the Damköhler number reduces which is an indication of a decrease in the flow characteristic time scale; that is a decrease in the vapor residence time in the vicinity of the droplet surface which means an enhanced vapor diffusion and also formation. Figure 5 presents a correlation between n-heptane droplet vaporization rate and Damköhler number for different droplet initial diameter at various turbulence intensities. Similar correlation was also found for n-decane droplet as shown in Figure 6. The two correlations, displayed in Figs. 5 and 6, are comparable as the exponent of Damköhler number is nearly the same and the only difference is in the coefficient of the best fit expression which could be attributed to the strong dependence on the fuel properties.

4 Conclusions

The experimental results presented above revealed that, in a quiescent atmosphere at standard ambient pressure and temperature, neither the droplet suspending fiber technique (fiber size) nor the droplet size showed an effect on the vaporization process. Whereas, the droplet initial diameter has seen to exert an apparent effect on the droplet vaporization rate. Using the collected data, a correlation in terms of Damköhler number was found between the droplet vaporization rate, droplet size and turbulence intensity. Surprisingly, the expression of this correlation is similar for both heptane and decane and the only difference is the dependence coefficient.

References

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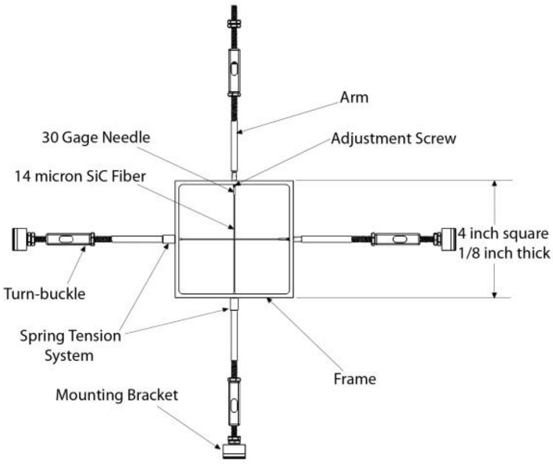
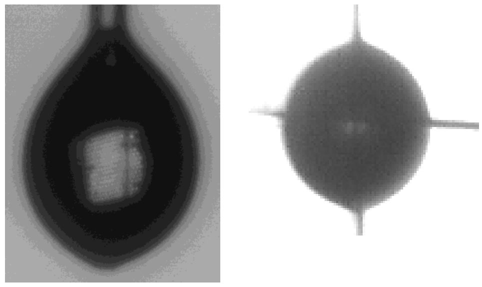
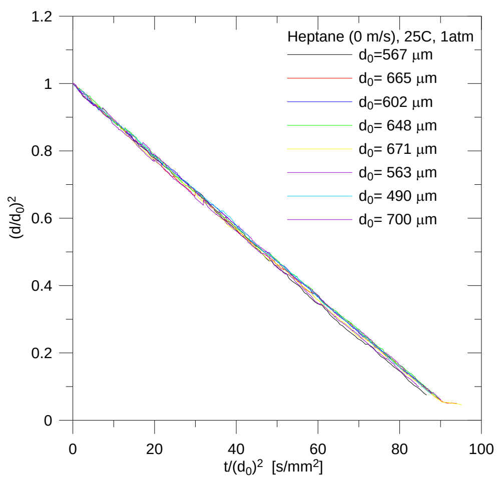


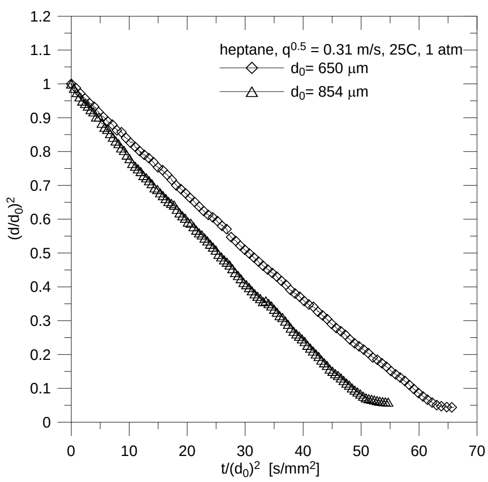
Figure 1. Cross-fiber suspending droplet set-up



(a) (b)

Figure 2. An image of a suspended droplet using (a) a classical fiber, and (b) a cross fiber setup





(a) (b)

Figure 2. Time histories of the normalized diameter of heptane droplet in (a) a quiescent and (b) a turbulent atmosphere

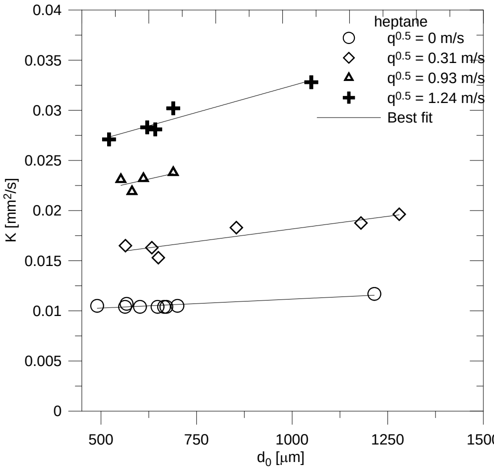


Figure 3. Variation of the vaporization rate of heptane droplet as a function of the initial diameter

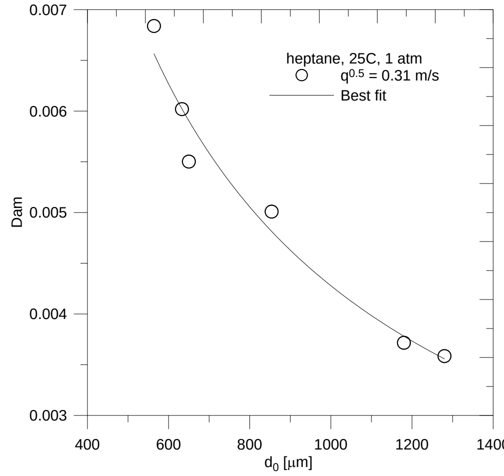


Figure 4. Damköhler number evolution as a function of the droplet size (i.e., initial diameter)

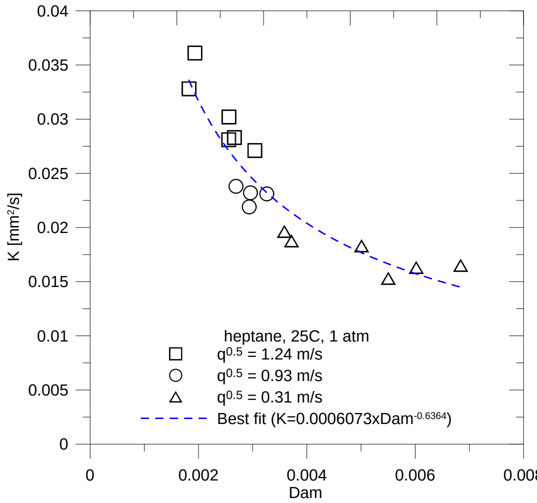


Figure 5. Variation of the vaporization rate of heptane droplet as a function of Damköhler number

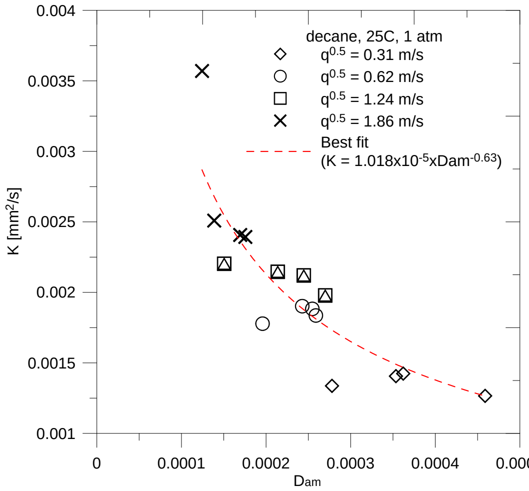


Figure 6. Variation of the vaporization rate of decane droplet as a function of Damköhler number