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Evaporation of a droplet larger than the Kolmogorov length scale immersed in a relative mean flow

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ABSTRACT

An experimental effort to understand the contribution of turbulence to the evaporation rate of fuel droplets has been performed with particular attention to conditions when the turbulence scale is smaller than the droplet diameter. N-heptane has been chosen as working fluid to give measurable evaporation rates from droplet images over relatively short experiment times. An active turbulence grid wind tunnel is built for the requirements of this experiment. A camera triggered by a pulse generator takes images of the droplets pinned on wires across the tunnel. The results show a small increase in evaporation rate with increasing turbulence intensity, and that mean flow around the droplets has more impact on evaporation than does the turbulence state.

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1. Introduction

Liquid fuels provide a large share (35%) of world energy consumption at present and for the foreseeable future. Furthermore, liquid fuel combustion remains the most important source of energy for all modes of transportation because few alternatives have portable power properties that can compete with those of liquid fuels (e.g., energy/unit mass and energy/unit volume). All practical liquid fuel combustion devices, mobile or stationary, use atomizers to produce sprays of fine droplets.

In order to release their stored chemical energy the fuel droplets must first vaporize before their vapor mixes with the surrounding air into a combustible mixture. The four critical processes in spray combustion are atomization, vaporization, mixing, and chemical reaction. These processes generally take place inside a combustion chamber where the flow is turbulent and mixing rates are high. Often, therefore, the vaporization rate is the main controlling mechanism of the entire combustion process. Turbulence controls the dispersion of the droplets and the rates of mass and heat transfer, and consequently the vaporization rate. On the other hand, droplets can modify the turbulence structure (Elghobashi and Truesdell, 1993; Ferrante and Elghobashi, 2003). Thus, understanding these two-way interactions and the physical details of the vaporization and mixing processes in such a turbulent flow is an essential prerequisite to understanding the chemical reaction process and the eventual control/optimization of the spray combustion energy conversion process. There is a substantial amount of work on the interaction of droplets with turbulence (Faeth, 1987; Han et al., 1986) but what is rarely studied is the situation when the turbulence scale is small relative to the droplet diameter. In this case, the small scale effects are less dispersive but may produce modified transport behavior to the droplet surface. Hence, it is the aim of this current work to examine the effect of turbulence on the evaporation rate of droplets when the smallest turbulent length scale is smaller than the drop diameter. Separating the evaporation effects produced by turbulence from those due to a relative mean flow ($U_{rel} = \overline{U_{air}} - \overline{U_{drop}}$, where the over line represents the average value of the corresponding U velocities) is not a simple task because immersing a free droplet in a turbulent flow, even if the Stokes number is very small usually includes a U_{rel} due to gravitational or inertial effects.

The possibility of experimenting with traveling drops has been considered and some work has been initiated. A set up similar to Bhalwankar and Kamra (2007) has been studied where the droplets are shot upwards in a vertical wind tunnel. However, sizing the drops is a complex process due to their random position in the tunnel leading to out of focus challenges, along with short residence times and difficulties obtaining the real magnification of the image over the entire droplet trajectory.

Noting these complexities of working with traveling drops, our experiments are simplified into pinned drops ($U_{rel} = \overline{U_{air}}$).

The suspended droplet approach permits larger droplets and longer residence times but creates higher mean relative velocity

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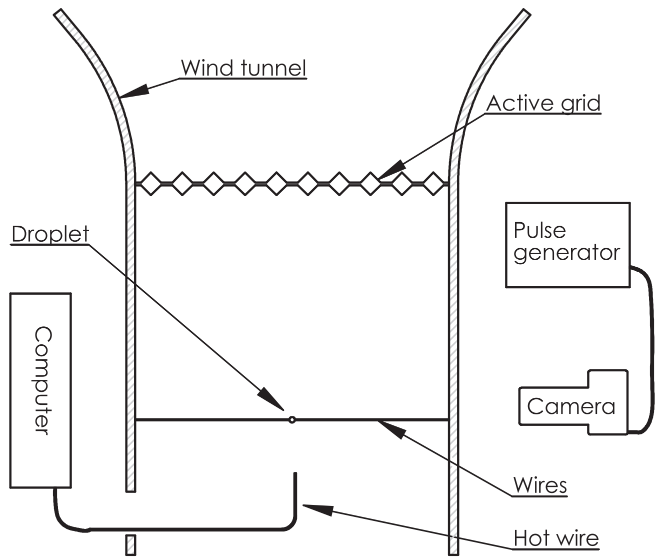

Fig. 1. Sketch of the experimental set up.

conditions and can lead to questions regarding the impact of the droplet supports on the results. Our measurements (and those of others e.g., (Eslamian and Ashgriz, 2007; Zhang, 2003)) with suspended droplets have confirmed that the effects of suspension fibers are small until the droplets reach sizes comparable to the fiber diameter.

A review article Birouk and Gokalp (2006) provides multiple references of the present state in doplet evaporation within forced turbulent convection. Gokalp et al. (1992) found that the evaporation rate of n-heptane droplets was insensitive to turbulence for a range of Reynolds number between 100 and 450. Further studies (Wu et al., 2001) obtained a correlation of the evaporation rate with the Damköhler number, confirming that the effect of turbulence on the mass transfer rate of droplets decreases with increasing Damköler numbers, and the evaporation rate becomes insensitive to turbulence for a Damköhler number approaching unity. However, as indicated in the review article, Birouk and Gokalp (2006), the mentioned correlations assume the vapor thickness theory developed for laminar flows is also valid for turbulent flows, and this is still to be verified.

In the present work, we studied the evaporation rate of n-heptane droplets affected by changes in turbulence intensity and mean flow up to Reynolds number 700.

2. Experimental setup

Fig. 1 is a schematic of the experimental apparatus. A vertical wind tunnel with downward air flow has been used for all the cases. Since the cross section of the tunnel is square, two crossing nylon fibers have been set in the test chamber of the tunnel creating an orthogonal X. The drops are placed in the X intersection. During the experiment, a camera pointing at the plane of the drop takes sequential images at a fixed time rate of 0.1 frames per second in the still air experiments, and 0.3 frames per second when the air tunnel is flowing. The drops are held by surface tension. Since, as mentioned earlier, the fibers can generate interference with the drop in, for example, not letting it deform as it would in a free state, we use the maximum droplet size that the fibers can hold, and we disregard all images for which the drop is small enough that the fiber interference is significant (i.e., when surface tension keeps the drop still).

Since we are interested in cases where the Kolmogorov length scale is smaller than the drop diameter, we need to start with a fairly large drop (order of 1 mm) so the requirement for large droplets to avoid suspension fiber interference is consistent with the goal of the research anyway.

Eslamian and Ashgriz (2007) gives a useful explanation for the relative merits of using suspended droplets versus free droplets for evaporation studies. In addition, a droplet in high Reynolds number flow experiences the impact of a large eddy during a relatively short time compared to the time it takes for the drop to reach the velocity of the surrounding fluid. This means that even droplets in stationary turbulence experience flow interactions with large eddies that appear fairly steady from the droplet reference frame and interactions with small eddies that are unsteady. Hence, when the timescale of the droplet response is long with respect to the timescale of changes in the eddy field, the droplet is responding always to a mean-like flow component and a fluctuating component, even when the droplet is freely moving. Because of this reaction time, characteristic of droplets in turbulent flows, we expect that results obtained by studying pinned drops are relevant for understanding free drops immersed in flows where the eddy turnover time is smaller than the relaxation time for such drop.

Our results therefore represent cases where there is pure mean flow ($U_{rel} = \overline{U}$), and those where large eddies act as contributions to local mean flow ($U_{rel} = \overline{U} + u \sim \overline{U}$). Even though U_{rel} is time dependent, neglecting unsteady terms and volumetric forces in a force balance, allows for a simple estimation of the relaxation time for a drop:

$$\frac{1}{2}\rho_{air}U_{rel}^2\,Area\,C_D = \rho_{drop}\,Volume\,\frac{dU_{drop}}{dt} \tag{1}$$

where ρ is density, and C_D is the drag coefficient. Assuming a spherical shape to compute area and volume where d is the droplet diameter, and

$$\frac{dU_{drop}}{dt} \sim \frac{U_{rel}}{\tau_{relax}} \tag{2}$$

so that the relaxation time is

$$\tau_{relax} \sim \frac{\rho_{drop}d}{\rho_{air}U_{rel}C_D} \tag{3}$$

The turnover time, defined as the life span of a large eddy, is

$$\tau_{turnover} = \frac{l}{u} \tag{4}$$

and the integral length scale is

$$l \sim \frac{u^3}{\varepsilon} \tag{5}$$

where u is the root mean square of the perturbation velocity u' ($U = \overline{U} + u'$), and ε is the dissipation of turbulent kinetic energy. From the definition of the Kolmogorov length scale η, we obtain

$$\varepsilon = \frac{\nu^3}{\eta^4} \tag{6}$$

so that the turnover time is

$$\tau_{turnover} \sim \frac{u^2}{\varepsilon} \sim \frac{\eta^4 u^2}{\nu^3} \tag{7}$$

where ν is the kinematic viscosity. We can define a Reynolds number based on the drop diameter $Re_d = U_\infty d/\nu \sim U_{rel}d/\nu$, a ratio of densities $\mu = \rho_{drop}/\rho_{air}$, a ratio of length scales $\beta = d/\eta$, a ratio of length scales $\kappa = \lambda/\eta$ (where λ is the Taylor length scale), a Reynolds number based on Taylor scale $Re_\lambda = u\lambda/\nu$, and assume $C_D \sim 1/Re_d$. For the present experiment, $\mu \sim 10^3$. When the active turbulence grid is on, $\beta \sim 10^1$, $\kappa \sim 10^1$, and $Re_\lambda \sim 10^2$. And when the turbulence grid is off, $\beta \sim 10^1$, $\kappa \sim 10^0$, and $Re_\lambda \sim 10^1$ (Table 2).