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Experimental investigation of the effect of droplet size on the vaporization process in ambient turbulence

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ABSTRACT

This paper presents the results of an experimental investigation of the effect of droplet size on the fuel vaporization process in a turbulent atmosphere at standard ambient conditions. Single droplets of n-heptane and n-decane are formed and evaporated at the intersection point of two micro-fibers placed in the center of a fan-stirred spherical vessel which is maintained at room temperature and pressure. The droplet initial diameter varies in the range between 145 and 730 µm. A controlled isotropic and homogeneous turbulent flow field with nearly zero mean velocity and intensity ranging between 0.25 and 1.5 m/s is generated inside the vessel by means of eight axial fans. The results indicate that the droplet normalized squared diameter varies quasi-linearly with time, suggesting the applicability of the d^2 law at all examined conditions. More importantly, the results reveal that the droplet initial diameter becomes a significant contributing factor in determining the evaporation rate in a turbulent environment, as the rate of vaporization is found to increase with both turbulent intensity and droplet size. However, droplet size produces no effect on the vaporization rate in quiescent (no flow) surroundings. The results also emphasize that as the ratio of the Kolmogorov length scale over droplet initial diameter approaches unity, the effect of turbulence becomes negligible, illustrating the importance of the small-scale eddies, and their relation to droplet size, in the transport/transfer of mass. The coupled effect of droplet size and turbulence on the vaporization rate is correlated in terms of either a turbulent Reynolds number or a vaporization Damköhler number.

1. Introduction

The performance of spray combustion relies heavily on liquid fuel breakup and the resulting droplet vaporization process. Therefore, a thorough physical understanding of fuel droplet evaporation and combustion is vital for improving the output and efficiency of power generation systems. Early classic analytical and experimental investigations concerning the vaporization of individual droplets led to the pivotal d^2 law which states, most importantly, that the reduction in droplet cross-sectional area varies linearly with time (e.g., [1,2]). In fact, prior to the introduction of computational analysis, early research involved experimental and theoretical studies on the evaporation and combustion of single isolated fuel droplets, as this scenario was believed to reasonably portray the essential phenomena involved in actual fuel injection and atomization processes (e.g., [3]). Although great progress has been made in developing more powerful and encompassing numerical codes, data obtained from single fuel droplet investigations still play a key role in the success of numerical models for spray combustion (e.g., [4–7]). Despite the wealth and foundation of knowledge on single droplet evaporation and combustion achieved in the last several decades, research on this issue is still ongoing due largely in part to the enormous importance of gas turbine and diesel engines and their performance and emissions characteristics. Evaporation of fuel droplets is principally dominated by the fundamental processes of heat and mass transfer, and the knowledge gained can be applied to various fuels, injector spray patterns, and combustor geometries.

Experimentation on a single fuel droplet is typically performed using either free-falling or fiber-suspending techniques. The former approach, while ideal, experiences significant experimental difficulties, especially concerning ignition and image capture. The latter method, which is much simpler, has therefore been widely implemented. However, a major disadvantage of this technique is its inability to form small, spherical droplets of practical relevance. To overcome this issue, a new droplet suspending technique has been recently developed (e.g., [8–14]). This technique consists of depositing a droplet at the intersection point of two micro-fibers (referred to, hereafter, as the cross-fiber technique), as opposed to the tip of a single, larger fiber. The cross-fiber approach is capable

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Nomenclature

d	diameter [m]
D_{AB}	mass diffusion coefficient of species A into B [m^2/s]
Da_v	vaporization Damköhler number
K	evaporation rate [mm^2/s]
L	turbulent integral length scale [m]
N	fan speed [RPM]
P	pressure [atm]
q	turbulence kinetic energy [m^2/s^2]
$q^{0.5}$	turbulence intensity [m/s]
r	radius [m]
Re	Reynolds number
rms	root mean square average [m/s]
Sc	Schmidt number
T	temperature [K]
t	time [s]
V	velocity [m/s]
ν	kinematic viscosity [m^2/s]
X	mole fraction
η	Kolmogorov length scale [m]
ρ	mass density [kg/m^3]

Subscripts

d	diameter
F	fuel
l	laminar, liquid
r	radial
s	droplet surface
t	turbulent
v	vapor
0	initial, stagnant
∞	ambient value

of forming smaller (in the vicinity of 100 µm) droplets with nearly spherical shapes while retaining the ability to anchor larger droplets as well, resulting in a wide range of initial diameters for testing.

The potential to generate small droplets is important as they may, depending on the circumstances, vaporize differently than larger ones. In the rare experimental studies concerning small droplets, the examined droplet diameters have often not been varied systematically (e.g., [15,16]), which makes it difficult to establish meaningful trends. On the other hand, the studies which have examined a wide and continuous range of droplet sizes are often focused on larger (exceeding 1 mm) initial diameters (e.g., [17–20]). It has long been realized that the burning characteristics of droplets will generally exhibit initial size dependency (e.g., [21]), the reasons for which typically revolve around transient sooting behavior in normal and reduced gravity (e.g., [17–20,22–24]), since sooting affects radiative emission and heat and mass transfer. Soot does not apply to droplets in pure evaporation, yet recent studies revealed that small droplets also evaporate differently than larger ones when exposed to turbulence [25] and high temperatures at various pressures [26]. The degree of agreement between numerical models and empirical results may also depend on the droplet size [15,27]. The hydrodynamic evaporation model, which forms the backbone of d^2 theory and is used throughout numerical simulations, has been shown analytically to over-predict droplet evaporation rates compared to more rigorous kinetic models, especially at low pressures, high temperatures, and small droplet sizes (e.g., [27,28]). In combustion, chemical kinetic effects may also begin to dominate as the droplet size decreases (e.g., [29–31]).

From a practical standpoint, mean atomization diameters in a real combustion system may fall below 100 µm (e.g., [29]), well beyond the capabilities of most experiments. The droplet size distribution in a combustor is an important consideration as it affects many parameters, including turbine inlet pattern factor, premixed regime transition, minimum ignition energy, and penetration distance. Flame propagation in a combustor may not even be possible with mean droplet sizes beyond 300-400 µm, depending on the fuel and equivalence ratio [32], which calls into question the practical relevance of drawing conclusions based exclusively on droplet sizes above this limit. Fortunately, the aforementioned cross-fiber technique has the potential to dramatically extend the range of produced droplet diameters to approach increasingly realistic and applicable sizes. In addition, droplet suspending fibers having sufficiently small diameters with low thermal conductivity were found to have negligible conductive effect, leading to consistent and reliable results. For instance, Yang and Wong [33] investigated the heat conduction effect of the support fibers and found that small quartz fibers (<50 µm) have little consequence and thus can be used in evaporation studies. Chauveau et al. [8] found that 14 µm quartz fibers arranged in a cross-fiber pattern induce no conduction heat transfer interference when suspending relatively small droplets, even at elevated temperatures. It is therefore reasonable to assume that the implementation of cross-fibers will not obscure the results of evaporation at room temperature and pressure.

Spray combustion, and certainly its application in, for example, gas turbine and diesel engines, involves small droplets evaporating and burning in a convective, highly turbulent flow (e.g., [34,35]). In most applications, injectors and combustion chambers are specifically designed to increase turbulence, thereby enhancing the premixing of fuel and oxidizer, promoting recirculating flow, and boosting the flame speed (e.g., [29]). However, while numerical studies are capable of approximating small, sub-100 µm droplets (e.g., [8,31,36]) and turbulent flow conditions (e.g., [7,36–38]), experimental investigations are necessary to validate these numerical models. In fact, numerical validation is often a significant motivation when undertaking experimental work (e.g., [10,39]). Experimental difficulties in producing and igniting small droplets, combined with the uncertainty of how empirical findings for large droplets apply to small droplets, have produced a knowledge gap in this particular area (e.g., [30,31]). Furthermore, while turbulence is generally assumed to increase evaporation (e.g., [35,40–46]), experimental data of the effect of turbulence on the vaporization of small (in the range below 1 mm and approaching 100 µm) droplets are scarce, if not completely unavailable. Thus, the goal of this investigation is to bridge the gap between experimental data and numerical studies regarding the vaporization of small droplets (approaching 100 µm) in turbulent environments of varying intensity. The present paper reports the results of an experimental study of the vaporization of n-heptane and n-decane droplets suspended onto a 14 µm cross-fiber system while subjected to varying levels of turbulence at standard pressure and temperature conditions.

2. Experimental setup

The main component of the experimental setup is a large sealed spherical chamber with four pairs of internally mounted co-axial fans. The stainless-steel chamber has a volume of 29 L, and it is capable of withstanding high internal pressure and temperature. The axes of the fans converge to the center of the chamber where the fuel droplet is deposited and subsequently evaporated. The vessel is optically accessible from four equally spaced windows along the horizontal equator, which provide flexible access for particle image velocimetry (PIV) and laser Doppler velocimetry (LDV) measurements, as well as imaging of droplet vaporization or burning. The fans, which are intended to create a nearly isotropic and homogeneous turbulent flow field with approximately zero mean velocity at the center of the chamber, are each driven by a servo-