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An analysis of the droplet support fiber effect on the evaporation process

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ABSTRACT

This paper presents an analysis of the effect of the droplet support fiber on the droplet evaporation process. This effect is evaluated for a droplet evaporating in a hot environment at atmospheric pressure using the experimental results of the present study and those in the literature. Selected published results are acquired using similar test conditions and experimental setups as the present data. The only main difference between these studies is the droplet support fiber diameter which varies between 14 μm and 225 μm. The ambient temperature explored in these studies ranges from room temperature up to 973 K. *n*-Heptane is selected because it is the most common fuel used in these studies. The main findings are that the cross-fiber technique, which uses 14 μm fiber diameters, induces no noticeable heat transfer into the droplet and consequently does not interfere with the evaporation process. In contrast, the classical fiber technique, which uses relatively larger fibers, greatly enhances the droplet evaporation rate as a consequence of increased conduction heat transfer through the fiber. A correlation is proposed to quantify the level of this increase as a function of ambient temperature and the fiber cross-sectional area, d_f^2.

1. Introduction

The vaporization and combustion of single droplets have been the focus of many studies in the last several decades as a simple approach to gain better understanding of the complex spray combustion phenomena. In fact, a single droplet does not represent a complex spray flow, but it does reveal much of the physics about the evaporation and combustion phenomena which may take place in the diluted spray region farther away from the fuel injector. Consequently, studies of single droplets have undeniably helped advance our understanding of the complex spray combustion phenomena.

Two major approaches were employed for studying experimentally individual droplets, which are the free droplet and the suspended droplet techniques. The former consists of a free-floating/falling droplet injected into a stagnant or a flowing environment. In fact, in this configuration, the droplet is not influenced by any unphysical/external parameter/factor, which makes it the most idealistic method for studying the phenomena of evaporation and combustion of droplets. However, compared to the droplet suspension technique where a fiber is used to hold stationary a droplet, studies employing free droplet are relatively seldom. This is mainly due to the difficulties associated with imaging of a free droplet as it drifts out of the camera focus during its lifetime. For experimental droplet combustion studies, ignition is also a major problem although several classical studies have attempted to overcome these issues (e.g., [1–3]). For instance, several studies used piezoelectric generation techniques to create a stream of droplets which, depending on the inter-droplet spacing, could be considered as a cyclic repetition of an individual droplet (e.g., [4–8]). However, this method requires advanced laser-based sizing techniques to avoid the shortcomings associated with digital imaging equipment [4]. Additionally, the free droplet technique is not suitable for studying its evaporation or combustion in a flowing medium, which is a replica of real spray conditions. That is why, for example, most, if not all studies on droplet evaporation and combustion in different environments, which include laminar and turbulent flow, adopted the suspended droplet technique. The simplicity of this technique in terms of, especially, imaging made it the most practical approach for single droplet studies. Despite its practicality and thus the widespread use of droplet fiber suspension technique, the presence of the fiber induces several artificial effects that alter the droplet evaporation and combustion characteristics. It was reported that using a quartz fiber or a fine thermocouple to suspend a droplet conducts heat into (e.g., [9]) or from (e.g., [2]) the droplet much faster than the surrounding gaseous medium. This consequently makes the findings on droplet evaporation and combustion biased, and the degree of the interference of the fiber

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depends on the extent of the heat transfer through the suspending fiber.

There exist a large number of published studies which attempted to quantify the impact of the support fiber on the evaporation process of a droplet. For instance, Yang and Wong [10,11] investigated the impact of the support fiber at a relatively narrow range of ambient temperature (490–750 K) and found that increasing the fiber diameter always shortens the droplet lifetime; that is, increases the evaporation process. They also reported that an intermediate fiber diameter may maximize the heat transfer input from the fiber. For example, Yang and Wong [11] found that a quartz fiber of 150 μm in diameter induced a greater heat transfer rate into the droplet compared to a fiber of 300 μm diameter. However, they reported that a droplet suspended onto the 300 μm fiber was found to evaporate faster due to the reduced liquid volume. They then concluded that using a quartz fiber of 50 μm diameter will not affect the evaporation process of a droplet. The experiments and numerical simulations of Han et al. [12] agree that the rate of heat conduction through the fiber increases and then decreases with increasing the suspending fiber diameter. Shringi et al. [13] numerically studied the effect of the support fiber on the evaporation of a droplet in a flow environment at high temperature and pressure conditions. They discovered that while the heat transfer from the gas phase to the droplet surface is initially very high, it rapidly decreases with time as the droplet surface temperature increases. They then remarked that heat transfer through the fiber remains relatively constant, leading to the fiber supplying a significant portion of the droplet's late stage vaporization energy. They also showed that the droplet suspending fiber can slow down the droplet evaporation process by promoting thermal Marangoni flows near the fiber-droplet contact point, where the circulation of the cooler interior fluid lowers the droplet surface temperature. Recently, Rehman et al. [14] experimentally investigated the effect of heat conduction on the droplet evaporation in a low temperature, forced convection environment. They studied droplets having a diameter ranging between 1565 and 2775 μm in a laminar airflow environment where the temperature was varied between room and 403 K. They varied the suspending fiber diameter and material where glass fibers with diameters ranging between 200 and 800 μm and thermocouples with diameters in the range between 76 and 812 μm were tested. While they found that the suspending fiber technique always increases the vaporization rate, they reported that suspending the droplet on metallic thermocouple wires induces far higher heat transfer by conduction into the droplet and hence results in a higher evaporation rate. Chauveau et al. [15] studied experimentally the evaporation rate of a 800 μm n-decane droplet using the classical suspending technique where quartz fibers with different diameters were tested. They discovered that, when extrapolating the evaporation rate, K, versus the fiber diameter, the theoretical K value that corresponds to a fiber diameter of zero is found identical to the experimentally measured value of the same droplet suspended onto a 14 μm cross-fiber system.

Several studies examined the effect of the suspending/support fiber on droplet combustion using experimental (e.g., [16,17]) and numerical (e.g., [18]) approaches. It was reported that fibers used for combustion studies can interfere with the droplet burning rate, flame and soot stand-off ratios and flame extinction characteristics. For instance, Mikami et al. [19] used a 14 μm SiC fiber to suspend a droplet in a flame spread experiment and concluded that the effect on the flame shape and heat transfer were much smaller than in the case of a 125 μm quartz fiber. Hicks et al. [17] found experimentally that droplets suspended onto a cross-fiber of 14 μm diameter featured a lower burning rate than the same droplet suspended onto a 110 μm classical quartz fiber with a 360 μm bead. Liu et al. [16] used a 14 μm cross-fiber system for ground-based microgravity tests and compared the results with the same droplet suspended onto a classical 80 μm single fiber. They reported that the droplet suspended onto the cross-fiber exhibited very similar burning characteristics, such as flame and soot stand-off ratios, to free-floating droplets. In contrast, the droplet suspended onto the large fiber tends to distort soot shells near the fiber droplet intersection.

It is important to mention that if the support fiber is to improve the evaporation rate, the effect is most likely to be witnessed towards the end of the droplet lifetime. This is exactly what is observed when using the classical fiber suspending technique where the d^2-law does not hold towards the end of the droplet lifetime; that is, a clear acceleration of the temporal variation of d^2 can be witnessed (e.g., [14]). This, of course, is not the case when using the cross-fiber technique (e.g., [20,21]) where tiny fibers are used. In this case, thed^2-law tends to hold until the complete depletion of the liquid or at least such an acceleration does not manifest (e.g., [20,21]).

This brief discussion of the literature clearly reveals the influence of the suspending technique on the evaporation and combustion processes of a droplet. Thus, the objective of the present paper is to analyze such an impact by quantifying the additional increase in the droplet evaporation rate due to the heat conduction through the suspending fiber. Due to limited published experimental data, only available results in stagnant environment at standard ambient pressure are analyzed where the effect of droplet diameter is also omitted in the present investigation.

2. Experimental setup

The experimental set-up is well documented elsewhere [22,23], and thus, only a brief description is provided here. The experimental test facility consists mainly of a furnace and the droplet support and formation system. The furnace is essentially a short cylinder with an inner diameter of 68 mm and a height of 100 mm, which produces a volume of 360 cm^3. The furnace is capable of attaining a temperature of up to 1200 K, generated by a Joule effect heater placed in a pressure chamber that envelops the furnace. The droplet, which is suspended at the intersection of a cross-fiber system, is formed by injecting the liquid fuel using a piezo-electric injection system. The cross-fiber consists of two quartz fibers each having a diameter of 14 μm and fixed perpendicularly using a metallic frame system. *n*-Heptane (C_7H_{16}) is chosen as the liquid because it is intensively used in the literature and consequently makes possible to perform comparisons with published data. In order to avoid oxidation at high temperatures, nitrogen is selected as the furnace gaseous medium surrounding the suspended droplet. The droplet is initially formed in the lower section of the chamber and then introduced into the furnace by the aid of a motorized displacement system. Once the droplet is exposed to the hot atmosphere in the furnace, the temporal regression of the projected droplet surface area is recorded using a high-speed video camera with a frame rate that can be varied between 150 and 750 fps depending on the test conditions. For each experiment, approximately 700 images are recorded in order to achieve a satisfactory temporal dynamics. In addition, at least five experiments are performed for each test conditions to verify the repeatability of the results as well as to minimize statistical errors. The images are analyzed via post-processing to deduce the droplet instantaneous projected surface area and hence the time variation of its squared equivalent diameter. Note that the involved error in determining the droplet diameter is found around ±3%. For instance, the droplet evaporation rate at T = 973 K is found around 0.296 mm^2/s with a standard deviation of 1.2%. Two series of droplet vaporization experiments are carried out in the present study; one in normal gravity, and another in