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Experimental investigation of the effect of natural convection on the evaporation characteristics of small fuel droplets at moderately elevated temperature and pressure

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ABSTRACT

The role of natural convection in droplet evaporation is experimentally investigated for a range of micro-sized alkane fuel droplets at moderately elevated pressure and temperature. This paper assesses the impact of buoyant mass transfer from two perspectives; the resulting variation in steady-state evaporation rate, and the potential relation to non-linear temporal d^2 profiles. The steady-state evaporation rate is found to increase linearly with initial droplet diameter at all tested conditions, where the relative improvement in evaporation rate depends upon the fuel type, pressure, and temperature. In addition to modifying the steady-state evaporation rate, the various environmental conditions also impact the occurrence and timing of d^2 deviation, which manifests as a strong reduction in evaporation rate near the end of a droplet's lifetime. Pressure tends to encourage the appearance of d^2 deviation for both heptane and decane by increasing the proportion of evaporation for which natural convection is responsible. The effect of temperature depends upon the droplet volatility, and the results differ between the two test fuels. Overall, the relative importance of natural convection, as compared to pure molecular diffusion, appears to govern both the expected improvement in, and potential deviation from, steady-state evaporation. Proposed Grashof correlations justify the above hypothesis.

1. Introduction

The phenomenon of natural convection has the potential to significantly modify the rates of heat and mass transfer between evaporating or burning fuel droplets and the surrounding gaseous phase. The dimensionless Grashof number, *Gr*, is a measure of free convective strength and is proportional to the square of pressure, *P*, and the cube of droplet diameter, *d*. The conditions found in a typical combustor both promote and demote natural convection due to the high-pressure environment and small droplet sizes, respectively. Most researchers emphasize the size perspective, and thus natural convection is often neglected as a result. Experiments at microgravity, which are complex yet numerous (see [1,2]), are performed specifically to avoid the effect of buoyancy. However, there is little quantitative experimental evidence to confirm that small fuel droplets, evaporating at elevated pressure and temperature, are unaffected by natural convection. The present study endeavors to provide the data necessary to draw conclusions regarding the role of natural convection in droplet evaporation.

Natural convection can be a dominant force in the determination of single droplet burning rates, K_b, defined as the rate of temporal reduction in d^2. Large, porous fuel-fed spheres were popular in the study of convective processes on burning droplets (e.g., [3–6]). Results indicated that buoyancy effects may persist even in the presence of a moderate freestream velocity, and theoretical/numerical models developed to predict mass burning rates may require proper modification to account for natural convection. The observation that burning rates vary markedly with total pressure, despite classic burning rate theories predicting little pressure dependence, further indicates the importance of free convection [7]. In scenarios where natural convection is influential, droplet size becomes a significant contributing factor in the determination of K_b (e.g., [8,9]). Monaghan et al. [9] compared the mass burning rates for a range of droplet diameters (150–2000 μm) and discovered that K_b increased linearly with initial diameter for heptane. To an extent, this finding invalidated the application of large porous sphere data to realistic spray combustion scenarios, as the mean droplet size of most practical systems is less than 100 μm. Although fuel fed spheres have fallen out of favor with experimentalists, many studies continue to examine droplets with initial diameters on the order of 1000 μm. Interestingly, the burning rates

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Nomenclature

B	mass transfer number
D_{AB}	binary diffusion coefficient
d	diameter
Gr	Grashof number
K	droplet evaporation rate
P	pressure
$q^{0.5}$	turbulence intensity
R^2	coefficient of determination
T	temperature
t	time
X	mole fraction

Greek symbols

β	volumetric thermal expansion coefficient
ρ	mass density
v	kinematic viscosity

Subscripts

avg	average
b	burning
e	evaporation
F	fuel
l	liquid
r	reduced
s	droplet surface, solutal
t	thermal
v	vapor
∞	ambient value
0	initial value
$0g$	value at microgravity

of droplets in the Monaghan et al. study [9] were functions of the initial diameter only, despite the progressive and rapid reduction in Grashof number as the droplet evaporates. The authors assert that a strong natural convective field is established at ignition and persists throughout the droplet lifetime, in agreement with Isoda and Kumagai [10]. It is unclear if this applies to droplet evaporation due to the longer vaporization time scale. Sato et al. [11,12] discovered that natural convection continues to affect K_b into the supercritical pressure regime, although the most significant improvement, as measured by $K_b/K_{b,0g}$, occurs for $P_r < 0.5$. Chauveau et al. [13] reported similar experimental results, where the largest values of $K_b/K_{b,0g}$ for a methanol droplet occurred in the 1–20 bar range. Additional studies have analyzed the natural convection effect on burning droplets by generating positive g-force [14] and numerically comparing forced convection in orientations which aid and oppose buoyant flow [15].

The impact of natural convection is expected to be less for a droplet in pure evaporation. This is due to the absence of flame, as a flame produces large temperature gradients to drive buoyant flow and is itself distorted by the upward flow of hot gas. However, it is generally accepted that the dense constituent droplets in a combusting spray do not burn individually under most circumstances, but rather vaporize to feed an external diffusion flame surrounding the droplet cloud (e.g., [16,17]). Evaporation of droplets may, therefore, be of greater fundamental importance to spray combustion and directly applies to engineering applications such as spray drying and evaporative cooling. Langstroth et al. [18] were one of the first groups to quantitatively examine the effect of natural convection in the evaporation of suspended droplets by varying the size of the containment vessel. They found that larger cylinders allowed unimpeded natural convection boundary layers and thus greater evaporation rates. This requirement of adequate free space surrounding a droplet could have implications for dense sprays, where inter-droplet spacing is minimal. Sato et al. [12] produced convincing experimental evidence of an evaporative natural convection effect for large (1000 μm) heptane droplets by directly comparing tests at normal and microgravity. Although K is consistently higher in normal gravity, it is unclear how elevated temperature affects the balance between natural convection and molecular diffusion. Chauveau et al. [13] measured the evaporation rate of large suspended methanol droplets at room temperature and pressures up to 100 bar. The results indicate significant deviation from theoretical zero-gravity predictions beginning in the moderate pressure range of 5–10 bar. The discrepancy in K continues to expand as the pressure increases. The impact of natural convection at relatively low pressure is also noted by Gogos et al. [19] for numerically simulated droplets in the range of 100–1600 μm. Even the small 100-μm droplet evaporates noticeably faster in normal gravity than microgravity at pressures below the critical point. More recently, Kitano et al. [20] illustrated the importance of including natural convection effects in complex 3D evaporation models when seeking agreement with experimental data at elevated temperature and pressure. Several studies (e.g., [21–23]) have concluded that natural convection is particularly important when predicting the evaporation of multicomponent fuel droplets yet few, if any, examine the differences between small, suspended droplets of monocomponent fuel, even on a qualitative basis. This stands in contrast to sessile droplets, which have been evaluated on a natural convection basis somewhat more thoroughly (e.g., [24–27]).

The determination of K has obvious importance to engineering systems. However, the departure from d^2 law which, by definition, results in a time- and size-varying K, is an aspect of droplet science which has not been seriously investigated. Several studies have shown instances of d^2 deviation (e.g., [28–31]) including Chauveau et al. [32], who postulate that natural convection is instrumental in enforcing d^2 law behavior at low ambient temperature. In the case of Chen et al. [29] and Gan and Qiao [30], the examined droplets were nanofluids, which are a relatively new type of fluid containing nano-sized particles. In both cases, the authors noted d^2 deviation and linked it to the type or concentration of the particles. For these types of studies, it is important to establish a baseline of understanding related to d^2 deviation in pure liquid droplets. Without such knowledge, it is difficult to discern the effects of nanoparticles (in this example) from d^2 deviation induced by, theoretically, natural convection.

The primary objective of the present study is to determine if previous investigations have overlooked the role of natural convection in their assessment of important droplet evaporative mechanisms. To this end, the impact of ambient pressure, temperature, and droplet size on steady-state droplet evaporation rate is explored. Secondary objectives include the analysis of the relationship between natural convection and d^2 law deviation, as well as the validation of classical correlations which account for free convection effects. This necessitates a detailed inspection of individual temporal d^2 plots, while correlations require accurate property estimation (particularly the surface temperature, T_s). To achieve these goals, the present study compares the evaporation