



# Fuel vaporization: Effect of droplet size and turbulence at elevated temperature and pressure



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## ABSTRACT

This paper presents an extensive experimental study regarding the effect of turbulence and droplet size on the evaporation rate of suspended monocomponent alkane droplets at elevated temperature and pressure conditions of up to 100 °C and 10 bar, respectively. Individual droplets of *n*-heptane and *n*-decane were suspended at the intersection of two crossed micro-fibers in the center of a fan-stirred spherical vessel. The droplet size was varied in the range between 110 and 730 μm. Eight axial fans generated a controlled turbulent flow field with quasi-zero mean velocity and turbulence intensity up to 1.5 m/s. The results reveal a linear relationship between the initial droplet size and its turbulent steady-state evaporation rate, where larger droplets evaporate at a faster rate than their smaller counterparts at all elevated temperature and pressure conditions. The normalized turbulent evaporation rate increases with pressure, whereas elevated temperature produces the opposite effect. The ratio of the Kolmogorov length scale to initial droplet diameter is shown to be of paramount importance for interpreting the effect of turbulence, as the normalized evaporation rate increases dramatically at lower values of this ratio under all test conditions. However, the ability of turbulence to enhance the vaporization rate vanishes when this ratio approaches unity, suggesting that only droplets which are initially larger than the smallest turbulent eddies experience enhanced evaporation. In addition, the widespread belief that turbulence enhances less volatile fuels more than their high volatility counterparts also depends on the ambient pressure and initial droplet size. The ability of turbulence to generate small-scale structures and, subsequently, the interaction of these eddies with the available fuel concentration gradient at the surface of the droplet governs the relationship between fuel type, initial droplet size, and ambient temperature and pressure. A turbulent Reynolds number or a vaporization Damköhler number is used to correlate turbulent droplet evaporation rates at all explored test conditions.

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## 1. Introduction

Spray combustion is a complex two-phase phenomenon which occurs at elevated pressure and temperature in turbulent environments. A persistent belief encountered in fuel vaporization studies is that a single, isolated droplet can adequately predict certain fundamental characteristics of atomized liquid emanating from a spray, as droplets tend to act independently of one another after the rapid primary and secondary breakup of liquid fuel jets (e.g., [1–3]). Although ultimately an idealization, the basic physics of single droplet evaporation apply throughout a range of realistic spray combustion modes. Numerous studies have investigated the effect of pressure and temperature on droplet evaporation (e.g., [4–8, 9] and the references cited therein), whereas investigations

into the effect of droplet size (e.g., [10,11]) and turbulence (e.g., [12–16]) have been less abundant, especially when evaluated simultaneously (e.g., [17–19]). The consequences of varying droplet size in combustion scenarios have largely been attributed to natural convection, soot formation, and heat loss by radiation (e.g., [20–23]), yet the reasons for the effect of droplet size in pure evaporation conditions remains undetermined. The objective of the present study is to continue the experimental evaluation of droplet size-turbulence interactions, established in [19], by modifying the turbulent ambient through elevated pressure and temperature. Because the pressure and temperature are only moderately elevated, the primary focus of this work is to establish fundamental evaporation theory rather than directly address combustion phenomena at realistic diesel or gas turbine conditions. This research applies to other areas of droplet science including spray cooling (e.g., [24,25]), where the behavior of droplets before surface impingement is a factor in overall system performance. Such environments may be turbulent due to vapor production (e.g., [26]) or the presence of

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forced convection if a combination of thermal management techniques is required.

In certain practical situations, evaporation is considered the rate-limiting precursor to combustion (e.g., [2,27]). Thus, the effect of droplet size on the evaporation rate, coupled with the interrelated parameters of ambient pressure, temperature, and turbulence, remains a topic of considerable interest. The competing effects of temperature and pressure alone are complex (and relevant) enough to have warranted serious investigation. Whether increasing the pressure assists or impedes the evaporation rate depends on the temperature range. Low ambient temperature lacks a sufficient gradient to drive heat into the droplet, whereas a high-temperature gaseous phase can take advantage of the lower vaporization enthalpy afforded at higher pressures. In this regard, the temperature range in the present study is decidedly low based on the experimental results of Nomura et al. [5], who found that a heptane droplet's lifetime increases with pressure in the range below 480 K. Similarly, an analytical study by Chin and Lefebvre [28] placed this value slightly higher at 600 K. Numerical models have reproduced similar findings (e.g., [6–8,29]).

The effect that droplet size has on determining the overall evaporation rate is less clear. As stated in a thorough review by Givler and Abraham [30], the initial droplet size,  $d_0$ , has not been considered a significant contributing factor in determining the evaporation rate or differentiating between quasi-steady and non-steady behavior, especially in microgravity conditions. Indeed, it is possible to speculate that some of the inconsistencies reported regarding the relationship between temperature, pressure, and vaporization rate may be due to the failure to discern and account for the impact of droplet size. Recent studies have paid more attention to the effect of  $d_0$ . For instance, a numerical study by Zhu et al. [8] found that droplets differing in initial diameter by an order of magnitude (50  $\mu\text{m}$  and 500  $\mu\text{m}$ ) have qualitatively similar evaporation, although the larger droplet attains a supercritical state simply due to the longer time available to absorb heat. At the moderate pressures and temperatures examined in the present study ( $P_r < 0.47$ ,  $T_r < 0.65$ ), this is not considered a factor. Khan et al. [10] presented experimental evidence of a strong initial size effect on the steady-state evaporation rate,  $K$ , of kerosene droplets where  $K$  increases with  $d_0$ , especially as the ambient temperature rises (in the range of 673–1073 K). Although the pressure in Khan et al. [10] remains below  $P_c$  for the presented results, the ambient temperature is greater than  $T_c$ . Xu et al. [31] reported a similar conclusion by showing experimentally that larger decane droplets attain greater steady-state evaporation rates in a hot ambience (633–773 K). Thus, there appears to be little available information on the effect of droplet size on evaporation at low to moderate ambient temperature and pressure. This is particularly true of turbulent studies.

Once considered unimportant in the determination of droplet evaporation rate (although universally accepted as critical for mixing) due to the separation between energetic scales and typical droplet sizes, turbulence has seen something of a renaissance in active study due to recently developed specialized experimental rigs and numerical codes. Of fundamental interest are studies pertaining to homogeneous and isotropic turbulence with quasi-zero mean flow, as this represents the effect of pure turbulent fluctuations in the absence of bulk convection. This type of turbulence may apply to small droplets which are immediately accelerated by the mean flow such that the relative velocity between droplet and freestream is negligible (e.g., [32]). The droplet then experiences only the effect of the turbulent fluctuations. However, a significant number of experimental studies (e.g., [12,14,33,34]) and the majority of numerical codes (e.g., [35–37]) feature a prominent freestream component, where  $U_{\text{rms}} < U_m$ . Although some studies have inferred the effect of pure turbulence by comparing their

## Nomenclature

$B$	mass transfer number
$C$	molar concentration, constant
$d$	diameter
$D_{AB}$	mass diffusion coefficient of species $A$ into $B$
$Da_v$	vaporization Damköhler number
$h_{fg}$	enthalpy of vaporization
$K$	evaporation rate
$L$	turbulent integral length scale
$N$	fan speed
$\dot{n}''$	diffusive molar flux
$P$	pressure
$q$	turbulence kinetic energy
$q^{0.5}$	turbulence intensity
$R$	universal gas constant
$r$	radius
$Re$	Reynolds number
$Sc$	Schmidt number
$T$	temperature
$t$	time
$U$	horizontal velocity, characteristic velocity
$V$	vertical velocity
$\nu$	kinematic viscosity
$X$	mole fraction
$\eta$	turbulent Kolmogorov length scale
$\rho$	mass density

## Subscripts

$b$	normal boiling point
$c$	critical value
$d$	diameter
$F$	fuel
$i$	interface
$l$	laminar, liquid
$m$	mean
$r$	radial, reduced
rms	root mean square average
$s$	droplet surface
sat	saturation
$t$	turbulent
$v$	vapor
0	initial, stagnant, standard
$\infty$	ambient value

results to laminar flow, the applicability of such approaches is unclear. In particular, strong convective flow introduces boundary layer effects (this fact has been used to develop comprehensive film thickness theories (e.g., [38])) which would not be present in zero mean flow scenarios. An experimental study by Marti et al. [39] concluded that increasing the turbulence intensity of flows with a strong mean component displayed little effect on the evaporation rate of a large suspended heptane droplet. Similarly, Gökalp et al. [33] concluded that varying the turbulence intensity did not affect the evaporation rate of a heptane droplet in the presence of a mean flow, although more recent evidence (including the results presented below) related to heptane in zero mean flow turbulence strongly suggest otherwise. Therefore, it is possible that the mean component masks the physics of the small-scale turbulent structures and their interaction at the surface of the droplet.

Experimental studies on the effect of zero mean flow turbulence on droplet vaporization have yielded important findings. For example, a series of investigations undertaken by Birouk and collaborators (e.g., [13,15,16,40,41]) revealed that low volatility fuels are affected to a greater extent by turbulent structures, the

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