International Journal of Heat and Mass Transfer 114 (2017) 541–549

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Evaporation characteristics of ethanol droplets containing graphite nanoparticles under infrared radiation

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ARTICLE INFO

Article history:
Received 10 April 2017
Received in revised form 13 June 2017
Accepted 14 June 2017

Keywords:
Droplet evaporation rate
Infrared radiation
Nanofluids
Monte Carlo simulation

ABSTRACT

The evaporation characteristics of liquid ethanol droplets containing graphite nanoparticles under infrared radiation were studied both experimentally and numerically. The experimental results show that the droplet evaporation rate is higher in the presence of a 2 mW infrared radiation field with a fixed wavelength of 2.3 μm than without radiation. The evaporation rate, however, decreases over time. Additionally, with particle addition, the evaporation rate no longer follows the classical D^2-law. The deviation is greater at higher particle concentrations. A model was developed to simulate the instantaneous evaporation rate, considering both effects of particle accumulation on the droplet surface and radiation energy absorption by the nanoparticles. In particular, a stochastic Monte Carlo method coupled with Mie theory and Beer–Lambert law of volumetric absorption was used to calculate the distribution of the absorbed radiation energy within the droplet, which was then used to compute the temperature profiles of the droplet. The modeling results show under infrared radiation, the evaporation rate of the nanofluid droplet increases as a function of particle concentration. This is due to rising droplet surface temperature through radiation absorption by the nanoparticles near the droplet surface. However, at the later stage of evaporation, as the particles start to accumulate on the droplet surface, the effective surface area for evaporation decreases and hence reduces the evaporation rate. These two competing mechanisms combine to control the instantaneous evaporation rate.

1. Introduction

Recently, there is increasing interest in developing high-performance nanofluid-type fuels for high-speed propulsion systems. The idea is to suspend energetic nanomaterials in traditional liquid fuels to increase the fuel's energy density. Previous studies [1–11] on nanofluid fuels with the addition of energetic nanomaterials such as aluminum and boron, as well as nanocatalysts such as cerium oxide, iron oxide, cobalt, and gold, have shown promising performance. Liquid-fueled combustion systems typically spray a cloud of small droplets into a hot combustion chamber. The high-temperature environment inside the combustor causes rapid vaporization of the droplets. The process of droplet evaporation is thus a critical component of spray combustion in practical engines.

In our previous work [12], we measured the burning rate of ethanol droplets containing graphite nanoparticles and found the burning rate can be very much enhanced with even a small amount of particle addition. We then performed Monte Carlo (MC) simulations to compute the distribution of the absorbed radiation energy in the infrared (IR) region (which is emitted from the ethanol flame) by the nanoparticles and found that most of the radiation energy is absorbed by the nanoparticles near the droplet surface. We believe this is the primary reason for the burning rate enhancement phenomenon observed in the experiment. Motivated by this, we decided to investigate the evaporation process of liquid fuels containing nanoparticles under the influence of IR radiation, which can help understand the effect of IR radiation on the burning process of nanofluids fuels.

Despite of a number of studies, the vaporization behavior of nanofluids has not been well understood. A portion of the literature on the subject focused on a sessile droplet placed on a heated surface [13–15]. For sessile droplets, the evaporation behavior is dominated by the pinning effects. For example, when a sessile drop deposited on a solid substrate, the wetted area is limited by a contact line. During the evaporation process, the contact angle of the sessile droplet changes over time depending on the liquid vapor pressure and the ambient conditions. While investigating the evaporation and dry out characteristics of strongly pinned water-based nanofluid droplets, Chon et al. [13] reported that the droplet regression did not follow a constant evaporation rate and attributed this to the variation in latent heat of the vaporization.

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.06.059
0017-9310/

Nomenclature

Acronyms

IR	infrared
MC	Monte Carlo

Symbols

A	area
c_p	specific heat
d	particle diameter
D	droplet diameter
$\mathbb{D}$	diffusivity
H	enthalpy
$\mathbb{I}$	incident radiation
$K, \mathbb{K}$	evaporation rate
MW	molecular weight
N	number density
P	pressure
Pe	Peclet number
r	radius
R	gas constant
$\mathbb{R}$	normalized radius
$\mathbb{S}$	source term
T	temperature
u	velocity
$\mathbb{V}$	volume
$wt\%$	weight percentage
X	mole fraction
Y	mass concentration

Greek symbols

ϕ	contact angle
σ	effective area ratio
ζ	concentration
ρ	density
λ	thermal conductivity
ϑ	volume fraction
δ	surface particle layer

Subscripts

0	initial
∞	infinity
boil	boiling
e	effective
l	liquid
mix	mixture
p	particle
r	radial
s	surface
sp	single particle
sat	saturation
t	total
u	universal
vap	vapor

For suspended nanofluid droplets, Gan et al. [7] showed that under the natural or weak convection, the nanofluid droplet regression deviates from the classical D^2-law. Furthermore, it was observed that for natural convection, aluminum particle addition to pure ethanol results in an increase in the initial evaporation rate and the evaporation rate continues to drop throughout the entire droplet lifetime. More recent work by Gerken et al. [16] showed that the addition of aluminum nanoparticles to ethanol suppresses vaporization and reduces the initial evaporation rate. Later Wei et al. [17] supported Gerken's conclusions, and they suggested that particle accumulation and aggregation at the gas-liquid interface is the main reason for the reduction of evaporation rate. Wei et al. investigated the effect of the Peclet number (a non-dimensional ratio of particle diffusion time to the droplet lifetime) and the initial particle concentration on the evaporation behavior of nanofluid droplet prior to shell formation. The formation of the nanoparticle shell reduces the mass fraction of the evaporating fluid at the surface and hence reduces the evaporation rate.

Gan et al. [18,19] investigated the effect of radiation on the vaporization behavior of nanofluids. The results indicated that nanofluids vaporize faster in the presence of ultraviolet–visible radiation. Strong radiation absorption by the nanoparticles suspended in the liquid is the governing factor for this enhancement in evaporation rates. Similarly, for the case of combustion of nanofluid fuels where enhancement in droplet burning rate was observed [20], it was hypothesized that absorption of infrared radiation (emitted by major combustion product species CO_2 and H_2O during combustion) by the nanoparticles is the primary mechanism contributing towards burning rate enhancement of liquid fuels with the addition of nanoparticles.

Motivated by the above, the current study focuses on the evaporation characteristics of ethanol droplets containing graphite nanoparticles under the influence of infrared radiation. Graphite was chosen mainly because its reflective index at the nanoscale, which is required for the modeling, have been well documented. Ethanol was selected as the base liquid fuel. Since ethanol is a polar compound, the nanofluid exhibits good suspension quality even without the use of a surfactant, which, otherwise, would complicate the analysis and modeling. The experimental results show that the presence of IR radiation increases the evaporation rate of the nanofluid droplets. Nevertheless, the instantaneous evaporation rate decreases with time. With particle addition, the droplet surface regression deviates from the classical D^2-law, and the deviation becomes greater as the particle concentration increases. A mathematical model was developed to simulate the evaporation process, in which the absorption of the incident radiation was calculated using Monte Carlo (MC) simulations. The modeling results show in the presence of IR radiation, the droplet surface temperature increases, leading to faster evaporation rate. The predicted and measured instantaneous evaporation rates agree reasonably well. It was found two mechanisms - particle accumulation at the droplet surface which tends to suppress evaporation and droplet surface heating due to absorbed radiation by the nanoparticles which tends to enhance evaporation – compete against each other to dominate the change of the evaporation rate.

2. Experimental method

2.1. Nanofluid preparation

The nanofluids were prepared using physical and chemical (where required) dispersion methodologies as discussed in the earlier studies [6,12]. The appropriate amounts of particles were first vigorously stirred with the base fuel, ethanol. This was followed by sonication of the colloidal mixture in an ultrasonic disrupter (Qsonica Q500A) to minimize and delay particle agglomeration.