International Journal of Heat and Fluid Flow 42 (2013) 224–235

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Fluid Flow

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

Evaporation phenomenon past a rotating hydrocarbon droplet of ternary components

J. Dgheim *, M. Abdallah, N. Nasr

Laboratory of Applied Physics (LPA), Group of Mechanical, Thermal & Renewable Energies (GMTER), Lebanese University, Lebanon

ARTICLE INFO

Article history:
Received 1 December 2012
Received in revised form 25 March 2013
Accepted 5 April 2013
Available online 29 April 2013

Keywords:
Rotating sphere
Transfer numbers
Correlation
Droplet evaporation
Multi-component hydrocarbons

ABSTRACT

A numerical study of heat and mass transfer from an evaporating fuel droplet rotating around its vertical axis was performed in forced convection only on the side opposite to the flow. The flow was assumed to be laminar, and the droplet was assumed to maintain its spherical shape during its lifetime. Based on the abovementioned assumption, the conservation equations in a general curvilinear coordinate were solved numerically. The behavior of rotating droplet evaporation in the forced convection flow can be investigated by analyzing the effects of the rotation of the droplet on the evaporation process of multi-component hydrocarbons droplet. The droplet is simulated to behave as a hard sphere. The transfer equations are discretized using an implicit finite difference method. Thomas algorithm is used to solve the system of algebraic equations. Moreover, dimensionless parameters of heat and mass transfer phenomena around a rotating hydrocarbon droplet were determined. The thickness of the boundary layer is unknown for this model and therefore, it was determined in function of time. Additionally, the study concerns "Dgheim dimensionless number" which is the ratio of the rotation forces over the viscosity forces. Dgheim dimensionless number is correlated to Nusselt and Sherwood numbers for multi-component hydrocarbon droplets in evaporation by taking into account the effect of heat and mass Spalding, Prandtl and Schmidt numbers respectively. Also, correlations for Nusselt and Sherwood numbers in terms of Reynolds, Prandtl and Schmidt numbers are proposed. These correlations consider the rotation phenomenon and advance the variation of the thermophysical and transport properties in the vapor phase of multi-component blends.

1. Introduction

Fuel droplet evaporation models have been investigated by many authors for several years. However, droplets are usually produced in sprays form, where they often burn in groups rather than individually. However, its applicability to technical sprays is strongly limited (Peiyong, 2010; Merouane and Bounif, 2010) and the evaporation of a single droplet is often studied. The evaporation and the combustion of liquid droplets are in general complex when interactions occur between various physical mechanisms. As a result, it is difficult to isolate and study individual physical processes, particularly in the presence of complicating factors such as spray combustion. Hence, it is advantageous to study liquid droplet evaporation configured as simple as possible so that physics of interest may be observed with minimized interference from other side effects.

In practice, fuel is typically multi-component. Hence, it is interesting to study and understand its evaporation characteristics and mechanisms. Multi-component fuel is used in motor combustion and chemical products. Nevertheless, despite the wide application of this phenomenon, heterogeneous liquid evaporation with fuel–air mixture and with rotation's droplet is not yet fully understood. The prediction of real aviation fuel consisting of several hundreds of pure components is still problematic. This is due to the gas-phase phenomenon which depends on the components that have been vaporized, while the liquid-phase phenomena depend on the components remaining in the liquid.

In reality, the simplest multi-component fuel is binary or ternary and miscible. Concurrently, studying binary and ternary miscible fuel is useful because they exhibit phenomena that do not appear in pure fuels, but rather are characteristic of multi-component blends. Two phenomena are usually important with multi-component blends that are influences of volatility differences and liquid-phase species diffusion on evaporation and combustion. Because of the many practical applications and the scientific interests they generate, the subject has been studied extensively, specially the heat and mass transfer characterizations by isolated droplet evaporation phenomena, which applies for a droplet of one and two components (Strotos et al., 2011; Dgheim et al., 2002).

* Corresponding author. Fax: +961 1 68 15 53.
E-mail address: jdgheim@ul.edu.lb (J. Dgheim).

0142-727X/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatfluidflow.2013.04.001

Nomenclature

B	Spalding transfer number
Cp	specific heat, J kg^{-1} K^{-1}
D	diffusion coefficient, m^2 s^{-1}
DG	Dgheim number
f	spinning frequency, s^{-1}
L	latent heat, J kg^{-1}
M	molar mass, kg kmol^{-1}
Nu	Nusselt number
P	pressure, atm
Pr	Prandtl number
Pe	Peclet number
r	sphere radius, m
Re	Reynolds number
Sh	Sherwood number
Sc	Schmidt number
T	temperature, K
t	time, s
u	velocity component in x direction, m s^{-1}
v	velocity component in y direction, m s^{-1}
w	velocity component in z direction, m s^{-1}
Y	mass fraction

Greek letters

Δ	difference
η	$\frac{r}{r_s}$
λ	thermal conductivity, W m^{-1} K^{-1}
μ	dynamic viscosity, kg m^{-1} s^{-1}
V	kinematic viscosity, m^2 s^{-1}
ρ	density, kg m^{-3}
θ	polar angle, °
ω	spinning velocity, rd s^{-1}

Subscripts

a	air
crit	critical
ebn	boiling
f	fuel
g	gas
L	liquid
M	mass
s	surface
sat	saturated
T	thermal
∞	ambient medium
0	initial
i	number of components

Superscripts

$*$	dimensionless values
–	mean

Regarding the background for multi-component droplet evaporation and combustion, it can be renowned that the study uses significant technical interest because most practical liquid fuels are blends of many chemical products. Each product is characterized by its own physical–chemical properties, such as volatility, diffusivity, and thermal conductivity. Hence, the cases of ternary components, fuel droplet evaporation are not much developed compared to those concerning the mono-component and bi-component liquid droplet (Mattila et al., 1997; Maqua et al., 2008). This is due to their formulation difficulty.

Aharon and Shaw (1998) studied experimentally the combustion of heptane/hexadecane mixture droplets in a reduced gravity environment. They found that the liquid species diffusion coefficient varies significantly. This phenomenon is attributed to the variations in the droplet temperature.

Navier–Stokes equations have been solved by Deplanque and Sirignano (1993) using a difference finite method. The same technique of the abovementioned authors has been used by Bouaziz et al. (2001) who studied the influence of two components hydrocarbon droplet evaporation on physical parameters such as liquid surface temperature, surface mass fraction, Prandtl and Schmidt non-dimensional numbers.

A theoretical investigation on the evaporation of bi-component liquid fuel droplet in high-temperature quiescent gaseous surroundings which was done from the numerical solution of conservation equations of heat, mass and momentum transports in the carrier and droplet phases was studied by Bhattacharya et al. (1996). Liquid fuel droplets containing components of widely varying volatilities, namely, n-hexane, n-hexadecane and components of closely spaced volatilities such as n-hexane and benzene, have been used for the studies.

The role of liquid mixing in evaporation of complex multi-component mixtures is modeled by Abdel-Qader and Hallett (2005) using continuous thermodynamics method. Their calculations show that internal mixing generally has a small influence on droplet behavior for a mixture with a large number of components than it does to a binary mixture. They gave some guidance as when a well-mixed droplet model may or may not be a good approximation for practical work.

Sazhin et al. (2010) considered heat and mass transfer correlations of fuel droplets analyzing the convective and the radiative heating modes of nonevaporating droplets. He reported the classical models of the droplets evaporation phenomena and developed Nusselt and Sherwood semi-empirical correlations. Furthermore, Sazhin (2006) noted that modeling transient droplet heating using steady-state correlations (for the convective heat transfer coefficient) can be misleading, and that at the initial stage of heating stationary droplets, the well known steady-state result $Nu = 2$ leads to under prediction of the rate of heating; while at the final stage the same result leads to over prediction. They declared that the models describing the effects of multi-component droplets are still rather complicated, which limits their wide application in CFD codes.

The rotating sphere is an essential phenomenon in systems such as internal combustion engines where the droplet is injected into the combustion chamber in a rotational motion. Therefore, this phenomenon remains vital pertaining to evaporation and combustion studies.

Numerical studies concerning rotating droplet in evaporation phenomenon have been considered little compared to those for an isolated stagnant droplet in forced and natural convections. For example, Kreith et al. (1963) have proposed, in boundary layer laminar regime, an empirical correlation for a rotating sphere in an infinite medium. They considered uniform thickness in the vicinity of a rotating sphere.

Saikrishnan and Roy (2003) studied the influence of temperature dependency, viscosity and Prandtl number on the steady laminar forced convection flow over a rotating sphere using boundary layer equations solved by finite difference scheme.

Poon et al. (2010) simulated three different flow regimes for a stationary sphere, from steady axi-symmetric, and steady to