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Evaporation of multicomponent liquid fuel droplets: Influences of component composition in droplet and vapor concentration in free stream ambience

Santosh Gavhane, Sukumar Pati [1], S.K. Som*

Department of Mechanical Engineering, Indian Institute of Technology Kharagpur, Kharagpur, 721302, India

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ABSTRACT

Theoretical studies have been made to explore the coupling influences of droplet constituent compositions and free stream vapor concentrations on evaporation characteristics, namely, mass depletion rate and droplet temperature of a heptane-dodecane droplet (components with widely varying volatility) and methanol-ethanol droplet (components with close volatility) at lower and higher free stream temperatures. In case of heptane-dodecane droplet, temperature and mass depletion histories are controlled by the heavier component (dodecane). In case of methanol-ethanol droplet, the mass depletion history is controlled by the lighter component (methanol), while the droplet temperature history is controlled by the heavier component (ethanol). The presence of fuel vapors in free stream increases the droplet lifetime, and moreover, the influence is relatively more prominent with the presence of heavier component vapor alone at lower free stream temperature. The composition of component vapors for a fixed value of total vapor concentration in free stream has almost negligible influence on droplet lifetime. It is revealed that the well established empirical relation ($Sh(1+B_m)^{0.7}=2$) for mass evaporation rate of a single component droplet can be used with reasonably fair accuracy in case of multicomponent droplet evaporation with logical modifications of mass transfer number and mass transfer coefficient for multicomponent system.

1. Introduction

Droplet evaporation plays an important role in various fields of technology pertaining to power, medicine, environment and agriculture. Owing to its manifold applications in diverse fields, considerable research efforts have been made by the researchers for past several decades to develop the theory of droplet evaporation. A comprehensive documentation of the classical work on droplet evaporation can be found in Marshall [1], Chigier [2], Clift et al. [3], Law [4], Faeth [5–7], Sirignano [8,9], and Sazhin [10]. Extensive experimental and numerical investigations have been made by Renksizbulut and Yuen [11,12], and Renksizbulut [13] to predict the influence of non-uniform blowing and internal circulation on mass transfer characteristics of a single component evaporating liquid droplet in a surrounding of gas at high temperature, and established fairly accurate heat and mass transfer correlations in this regard. Dash et al. [14] studied numerically the evaporation characteristics of different liquid fuel droplets in a stream of air at elevated temperatures and pressures. They predicted the influence of surface blowing and droplet transience on transport coefficients. Pati et al. [15], in a recent investigation, predicted the evaporation characteristics of water droplet in a quiescent ambience of air with varying vapor concentrations at different pressures and temperatures using three different models, namely, diffusion controlled, kinetic, and empirical.

Evaporation of droplets of complex liquid mixtures is frequently encountered in various engineering applications like combustion, spray drying and other such processes. In appreciation of the importance of multicomponent droplet evaporation on the combustion processes, a host of articles [16–32] has been reported in literature on evaporation characteristics of multicomponent liquid fuel droplets and sprays. Most of the works [16–22] were based on numerical or analytical solution of primarily diffusion controlled

* Corresponding author.
E-mail addresses: sukumarpati@gmail.com, sukumar@mech.nits.ac.in (S. Pati), sksom@mech.iitkgp.ernet.in (S.K. Som).
[1] Present address: Department of Mechanical Engineering, National Institute of Technology Silchar, Silchar, 788010, India.

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Nomenclature

B_m	spalding mass transfer number
C	mass fraction
$\overline{C}$	bulk mass fraction
C_p	specific heat at constant pressure, J/kg K
d	instantaneous droplet diameter, m
D_{ij}	diffusion coefficient of species i into species j in presence of third component, m^2/s
$\mathscr{D}_{ij}$	binary diffusion coefficient of species i into species j, m^2/s
h_{fg}	specific enthalpy of vaporization at droplet surface temperature, J/kg
h_m	mass transfer coefficient, kg/m^2s
k	thermal conductivity, W/m^2K
M	molar weight, kg/kmol
m	mass, kg
$\dot{m}_e$	evaporation rate per unit surface area of the droplet, kg/m^2s
p	pressure, N/m^2
r	radial co-ordinate, m
R	instantaneous droplet radius, m
Re	Reynolds number
Sc	Schmidt number
Sh	Sherwood number
t	time, s
t_l	droplet lifetime, s
T	temperature, K
v	velocity, m/s
v_s	Stefan flow velocity due to evaporation at the interface, m/s
X	mole fraction

Greek symbols

ρ	density, kg/m^3
α	thermal diffusivity, m^2/s

Subscripts

1	lighter fuel component (heptane/methanol)
2	heavier fuel component (dodecane/ethanol)
i	initial
a	air
c	critical
e	evaporation
i	initial
m	mixed
r	radial
ref	reference value
s	droplet surface
∞	free stream

Superscripts

l	liquid phase
v	gas phase
n	nth time plane
n	total number of species used in Eqs. (29)–(31)

model of droplet evaporation and addressed the influences of drop size, constituent composition of the droplet, ambient pressure and temperature, gas phase species diffusivity and variable properties in the liquid phase on the droplet evaporation characteristics. The important features like significance of non-ideality of mixture at high ambient pressure and especially at low ambient temperature conditions, the influence of gravity on droplet vaporization rate were addressed by Ebrahimian and Habchi [23], and Habchi and Ebrahimian [24]. Aggarwal and Mongia [25] reported an important fact that at high pressures, evaporation characteristics of a bi-component fuel can be effectively captured by a single surrogate component fuel owing to the fact that evaporation is more sensitive to droplet heating models than to droplet composition.

A number of works [26–32] have also been reported on the development of different physical models to predict the vaporization rate for multicomponent droplets. The various models were developed based on limiting cases of thermal conduction and species diffusion inside the droplet depending upon the physical situations. Sazhin et al. [28] pointed out the effect of replacing complex multicomponent fuel with relatively few quasi-components having average thermo-physical properties similar to the representative group of actual components. Strotos et al. [29], in their work relating to evaporation characteristics of a bi-component 3D droplet, solved Navier–Stokes equations numerically together with the VOF methodology for tracking the droplet interface.

It is observed that explicit information pertaining to the synergetic link between liquid phase composition of droplet constituents and vapor phase composition of free stream ambience in a perspective of relative volatility characteristics of the constituent droplet components during the process of droplet evaporation is sparse in literature. Moreover, a well established and fairly accurate mass transfer correlation of multicomponent droplet evaporation under a wide range of operating conditions inclusive of droplet and free stream vapor phase compositions is not available till date.

Aim of the present work is to investigate theoretically the coupling influences of droplet constituent composition and free stream vapor concentration on evaporation characteristics of two-component fuel droplets comprising constituents of widely varying volatility and of close volatility. The results obtained from our studies have been used in logical modification of a widely popular empirical correlation of mass transfer from a single component droplet for its use in case of multicomponent droplet evaporation with varying composition of droplet constituents and at different values of concentration and composition of free stream vapor.

2. Theoretical formulation

2.1. Physical statement and assumptions

The physical problem refers to the evaporation of a two-component liquid drop in a quiescent (non-convective) medium of air with or without the presence of fuel vapors at free stream ambience. Free stream temperature, T_∞, is higher than the initial temperature T_i of the drop. The following assumptions have been made for theoretical analysis:

- The droplet maintains a perfectly spherical shape at all times. Instabilities at droplet surface, if any, are neglected. This is reasonable assumption for a small droplet vaporizing in a quiescent medium. Moreover, spherical symmetry exists in both liquid and gas phase without loss of any physical understanding in achieving the objective of the present work as stated in the previous Section.