Experimental Thermal and Fluid Science 91 (2018) 329–344

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Evaporation of a suspended binary mixture droplet in a heated flowing gas stream

Tuyen T.B. Nguyen[a,b], Subhasish Mitra[a], Mayur J. Sathe[c], Vishnu Pareek[d], J.B. Joshi[e], G.M. Evans[a,*]

[a] Discipline of Chemical Engineering, School of Engineering, University of Newcastle, NSW 2308, Australia
[b] Danang University of Science and Technology – The University of Danang, 54 Nguyen Luong Bang, Danang, Viet Nam
[c] Department of Chemical Engineering, Louisiana State University, USA
[d] Department of Chemical Engineering, Curtin University, Perth, WA 6102, Australia
[e] Homi Bhabha National Institute, Mumbai 400094, India

ARTICLE INFO

Keywords:
Evaporation
Binary mixture
Droplet
Heat and mass transfer
Activity coefficient
Internal circulation

ABSTRACT

Studying vaporization of binary mixture liquid droplets as a model system provides useful information for understanding several engineering applications involving multicomponent systems. The present study investigated vaporization behaviour of both polar and non-polar binary droplet systems in hot convective environment using a mathematical model and experiments. A lumped parameter rapid mixing evaporation model accounting for non-ideal solution behaviour and temperature dependent physical properties was presented. The model predicted temporal variation in droplet diameter and temperature were validated against the experimental data for heptane-decane and water-glycerol mixture. Experiments involving the water-glycerol system involved both size and temperature measurement of millimetre-size droplets at constant gas temperature ~353 K and at free stream gas velocity ~4.3 m/s. In general, model predictions were in good agreement with the experiments however some deviations in the model prediction were noted at the transition stage specifically for the water-glycerol system which was attributed to the liquid phase diffusional resistance not accounted in the present modelling framework. Inclusion of activity coefficient into the model was shown to have insignificant effect on the evaporation rate in both non-polar and polar systems. Internal motions induced by the external shear flow and internal density difference were quantified. Time scales based on heat transfer (convective heat transfer and thermal diffusion) and mass diffusion accounting for the internal motion were estimated. It was shown that the unsteady heating duration of the droplet fall within the two limits set by the heat transfer and mass diffusion time scales.

1. Introduction

Evaporation of liquid droplets plays a significant role in many practical applications such as internal combustion engine, spray drying of milk powder, coating of tablets in pharmaceutical sector, vaporization of feed stream in fluid catalytic cracking unit etc. In most of these applications, atomized droplets (~few tens of microns) are ejected at a high velocity (~30–100 m/s) in hot gas, which then undergo rapid vaporization involving a coupled heat and mass transport process. Further, the droplets vaporized in the industrial applications are usually multicomponent, where the vaporization rate depends on the instantaneous relative volatility of the components during the evaporation lifetime of the droplet. Understanding the evaporation mechanism requires quantifying the key parameters such as transient reduction in the droplet size and increase in droplet temperature, which are critical to control the concerned process performance.

The earliest well-known evaporation experiment is reported by Ranz and Marshall [26,27] for a stationary water droplet evaporating in convective environment in Reynolds number range from 0 to 200 which was later shown to be valid for extended Reynolds number range up to 1000. Later, Downingm [47] and Wong and Lin [40] investigated the evaporation performance of hexane and decane droplets respectively in forced convective environment however these experiments were carried out only at moderate droplet Reynolds numbers (up to 110) and for single component droplets only. On evaporation of the two component hydrocarbon droplets in heated gas medium, Gokalp et al. [14] reported evaporation behaviour of heptane-decane droplets in air at temperature of 372 K and gas velocity of 1.45 m/s while Daif et al. [9]

* Corresponding author.
E-mail address: Geoffrey.Evans@newcastle.edu.au (G.M. Evans).

http://dx.doi.org/10.1016/j.expthermflusci.2017.10.025
Received 29 June 2017; Received in revised form 3 October 2017; Accepted 22 October 2017
Available online 25 October 2017
0894-1777/

Notation

B_M	mass transfer number
C_p	heat capacity, J/kg K
d	droplet, m
D	binary diffusion coefficient of vapour into carrier gas, m^2/s
G	heat transfer correction factor
k	thermal conductivity, W/m K
m	mass, kg
n	the n^{th} time step
$\dot{m}_d$	vaporization rate, kg/s
p	pressure of the system, Pa
$p^*_{v,i}$	vapour pressure of each pure component, Pa
R_0	initial droplet radius, m
R_g	universal gas constant, J/mol K
t	time, s
T	temperature, K
u_b	buoyancy-driven velocity, m/s
u_s	liquid velocity at the droplet surface, m/s
u_∞	droplet-gas relative velocity, m/s
Y	mass fraction
X	mole fraction

Dimensionless numbers

$Sh = Kd_d/D_v$ Sherwood number
$Nu = hd_d/k_G$ Nusselt number
$Pe_h = Re_L.Pr$ Peclet number for heat transfer
$Pe_m = Re_L.Sc$ Peclet number for mass transfer
$Pr = \mu_G C_{pG}/k_G$ Prandtl number of gas phase
$Sc = \mu_G/\rho_G D_v$Sc Schmidt number
$Ra = (\beta_T \rho_L^2 g C_{p,L} R_0^3 \Delta T)/(\mu_L k_L)$ Rayleigh number
$Re_{d0} = \rho_\infty u_\infty d_0/\overline{\mu}_G$ Droplet Reynolds number based on gas phase properties
$Re_L = \rho_L u_s d_0/\mu_L$ Droplet Reynolds number based on liquid phase properties

Greek letters

α	thermal diffusivity, m^2/s
β	vaporization parameter
β_T	thermal expansion coefficient, K^{-1}
ε	mass fraction ratio
γ	activity coefficient
L_V	latent heat of vaporization, J/kg
μ	dynamic viscosity, N s/m^2
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
τ_d	relaxation time, s

Subscripts

d	droplet
G	gas
L	liquid
V	vapour
0	initial
s	droplet surface
i	species
∞	free stream

examined both temporal evolution of droplet diameter and temperature for heptane-decane droplets in hot gas flow at velocity of up to 3.1 m/s (droplet Reynolds number ~ 215). Evaporation of droplet in higher gas temperature (up to ~1000 K) was performed by Ghassemi et al. [12], Hallett and Beauchamp-Kiss [15], Han et al. [16] and Zhang et al. [44]; however, these measurements were obtained at stagnant air condition. Table 1 summarizes the published experimental work on binary mixture droplet evaporation at zero to moderate droplet Reynolds number.

Although the available studies report measurement of change in droplet size with time but what lacks in majority of these studies is the measurement of droplet temperature which is rather inadequately reported in the literature and indeed is critical to validate any numerical modelling work in this area. Experiments for binary mixture droplets were done mostly for the non-polar hydrocarbon mixtures and studies on the polar component mixtures are relatively less. Also, effect of solution non-ideality due to polarity on evaporation behaviour has not been paid

Table 1
A comparative summary of experimental studies on multicomponent droplet evaporation.

No	Authors	Material	Air temperature	Initial diameter	Reynolds number/air velocities	Droplet temperature available
1.	Ranz and Marshall [27]	Pure water	298	1.1	0–200	No
2.	Downingm [47]	Hexane	437	1.78	110	No
3.	Wong and Lin [40]	Decane	1000	2.0	17	Yes (thermocouple)
4.	Nomura et al. [52]	Heptane	741	0.8	0	No
5.	Gokalp et al. [14]	Heptane-decane	372	1.56	~105	No
6.	Daif et al. [9]	Heptane-decane	348	1.38	~215	Yes* (infrared camera
7.	Yang and Wong [55]	Heptane, hexadecane	490 750	0.70 1.0	5–17	Yes (thermocouple)
8.	Ghassemi et al. [12]	Heptane-hexadecane	~873	1.28	0	No
9.	Chauveau et al. [45]	Heptane	473, 973	0.5	0	No
10.	Hallett and Beauchamp-Kiss [15]	Ethanol Ethanol & fuel oil	up to 1023	~1.4–1.8	0	No
11.	Woo et al. [41]	Water	358	~1.0–1.5	~80	No
12.	Davies et al. [10]	Water-glycerol	298	0.042	Air velocity 0.4 m/s	No
13.	Javed et al. [49]	Kerosene	1073	~1.0	0	No
14.	Han et al. [17]	Dodecane–hexadecane	1046	1.23	0	Yes (thermocouple)
15.	Han et al. [16]	Ethanol–diesel	Up to 723	0.7–1.3	0	Yes (thermocouple)
16.	Zhang et al. [44]	Biodiesel-butanol	1073	[–]	0	Yes (thermocouple)
17.	Volkov et al. [38]	Water	Up to ~773	2.0–4.0	Air velocity 0–3.5 m/s	Yes (PLIF)
18.	Present study	Water Water/glycerol	353	2.61	708 714	Yes*

* Initial cooling stage observed.