

# **Vaporisation of single and binary component droplets in heated flowing gas stream and on solid sphere**

A thesis submitted for the degree of

**Doctor of Philosophy**

By

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## DECLARATIONS

I hereby certify that the work embodied in the thesis is my own work, conducted under normal supervision.

The thesis contains no material which has been accepted, or is being examined, for the award of any other degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. I give consent to the final version of my thesis being made available worldwide when deposited in the University's Digital Repository, subject to the provisions of the Copyright Act 1968 and any approved embargo.



THI BANG TUYEN NGUYEN

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## SELF-PUBLISHED WORK INCLUDED IN THE THESIS

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Figure 5.21 Experimental relationship between the pinned spreading diameter and contact angle at solid temperatures from 323 - 358 K and glycerol concentrations from 0 – 35 %. Operating conditions:  $d_p = 10$  mm,  $T_a = 296$  K, relative humidity  $RH = \sim 50$  %; ..... 163

Figure 5.22 Reduction in normalised droplet volume with normalised time for three different binary mixtrue droplets compared with pure water droplet, at the same surface temperature at 323 K. Operating conditions:  $d_p = 10$  mm,  $T_a = 296$  K, relative humidity  $RH = \sim 50$  %; ..... 165

## ABSTRACT

Droplet vaporisation is significant to a number of multiphase process engineering applications which include but not limited to Fluid Catalytic Cracking (FCC) process for producing transport fuel; fluid coking for producing fuel gas, distillate and petroleum coke; spray coating of tablets in pharmaceutical industry; drying of seeds in spouted bed in food industry and spray drying of milk in dairy industry. The principal aim of this study was to improve the physical understanding the droplet vaporisation in a multiphase environment due to both convective (homogeneous vaporisation) and conductive heat transfer (heterogeneous vaporisation) with the aid of experimental measurement and numerical modelling. The principal aim was met first by numerically quantifying the feed droplet vaporisation time in a typical multiphase application (FCC riser) including both homogeneous and heterogeneous modes; and then separately investigating these two modes by experimentally quantifying the vaporisation behaviour of a suspended droplet in a hot convective flow and on a heated spherical particle, respectively.

A comprehensive quantitative comparison of the existing models (both homogeneous and heterogeneous) was conducted to predict FCC feed droplet vaporisation time under typical industrial operating conditions. Noting a dearth of suitable physical model that accounts for the conductive heat transfer between feed droplets and catalyst particles, a new vaporisation model based on the particle-droplet collision mechanism was proposed which provided a reasonable agreement with the available heterogeneous models. It was noted that all homogeneous models predicted a larger droplet vaporisation time compared to the heterogeneous models which could be attributed to the large difference in the Nusselt number in these two modes of heat transfer.

Evaporation behaviour of binary mixtures droplet in high Reynolds number ( $\sim 714$ )

environment was next studied experimentally and a numerical model was developed. Transient change in droplet size and temperature were measured for both pure component system (water) and a polar binary system (70 % water and 30 % glycerol) at free stream temperature  $\sim 353$  K and superficial gas velocity  $\sim 4.3$  m/s. Reasonable agreements with the model predictions were obtained for single component system however some deviation was noted for binary system specifically at the transition stage which was attributed to the liquid phase diffusional resistance due to high system viscosity. Transient droplet temperature measurements were performed which showed an unsteady heating stage followed by a thermal equilibrium stage. The unsteady heating stage was shown to be within the two limits of characteristic thermal convection and mass diffusion time scale.

Heterogeneous vaporisation behaviour was examined by the experimental studies of binary mixture droplets evaporating on heated spherical particle. Effect of liquid composition for three different binary system droplets (water-glycerol, water-IPA and water-butanol) and solid surface temperature (range) on the droplet vaporisation rate were studied. It was observed that droplets exhibited pinned mode evaporation (i.e. evaporation with constant wetting area and reducing contact angle) for major duration of its lifetime, at  $\sim 95$  % for pure water and a major time for binary systems. A model was given to determine time varying theoretical contact angle based on droplet evaporation rate incorporating the effect of Marangoni flows which provided good agreement with the experimental data. Furthermore, local temperature measurements of the droplet showed a short initial unsteady heating duration followed by a longer thermal equilibrium stage regardless droplet compositions and solid surface temperature; the actual heating duration was found to be less than 10 % of the droplet lifetime and fell within the range of the calculated thermal diffusion time-scales. Finally, a scaling analysis was carried out to quantify the internal motions within the droplet. It was shown that under the given operating conditions, surface tension driven flow component (thermal Maran-

goni flow) dominates over the convective flow component due to density difference (Rayleigh flows) which justifies inclusion of the additional Marangoni number based correction factor in the evaporation model to correctly predict the vaporisation rate.

This study aimed to shed light on the two different modes of droplet vaporisation process in multiphase system and it is expected that some of the models developed in this study can be incorporated in CFD framework to aid design of the relevant process equipment.



## NOMENCLATURE

### Notation

$A_{wet}$	wetted area, $m^2$
$C_p$	heat capacity, $J/kgK$
$C_{p,m}$	heat capacity of the vapour/air mixture, $J/kgK$
$col_{freq}$	collision frequency, $1/(m^3s)$
$d$	droplet, $m$
$d_p$	diameter of the particle, $m$
$d_w$	wetted diameter, $m$
$d_{equiv}$	equivalent spherical diameter of the droplet, $m$
$d_{max}$	maximum spread diameter, $m$
$D_v$	binary diffusion coefficient of vapour into carrier gas, $m^2/s$
$D_L$	self-diffusion coefficient of the liquid phase, $m^2/s$
$e_{film}$	vapour film thickness, $m$
$k$	thermal conductivity, $W/mK$
$h_L$	height of the liquid cap(excluding solid portion), $m$
$h_{col}$	heat transfer coefficient based on droplet-particle collision, $W/m^2K$
$h_{eff}$	effective heat transfer coefficient used in model of Nayak et al. (2005), $W/m^2K$
$h_{heat}$	heat transfer coefficient in the heating up stage, $W/m^2K$
$h_{vap}$	heat transfer coefficient in the vaporization stage
$L_V$	latent heat of vaporization, $J/kg$
$\dot{m}_d$	vaporization rate, $kg/s$
$n_d$	number of droplet, $1/m^3$
$n_p$	number of particle, $1/m^3$
$r_c$	half of the chord length cap
$Q_{col}$	heat transferred by each collision, $J$
$Q_{total}$	total heat transferred by collisions, $W/m^3$
$R_0$	initial droplet radius, $m$
$\bar{T}$	average temperature used for characteristic thermal diffusion time estimation, $K$

$T_{S,L}$	solid-liquid interface temperature, $K$
$T_S$	bulk solid temperature, $K$
$T_L$	temperature of the liquid, $K$
$T_a$	ambient temperature, $K$
$v_{slip}$	droplet-gas slip velocity, $m/s$
$v_{slip\_dp}$	droplet-particle slip velocity, $m/s$
$v_{slip\_pg}$	particle-gas slip velocity, $m/s$
$V_{cap,L}$	volume of the liquid cap (after subtracting the solid portion), $m^3$
$V_{cap,P}$	volume of the wetted spherical particle cap, $m^3$
$V$	volume of entire spherical cap including liquid and solid portion, $m^3$

### Dimensionless numbers

$B_M$	mass transfer number
$B_T$	heat transfer number
$B'_T$	modified heat transfer number used in the AS model
$Ma$	Marangoni number
$Ra$	Rayleigh number
$RH$	ambient relative humidity, %
$Y_s$	mass fraction at the droplet surface
$Y_G$	mass fraction far away from droplet surface
$\chi_s$	mole fraction at droplet surface
$G$	heat transfer correction factor
$Sh = Kd_d / D_v$	Sherwood number based on Ranz and Marshall (1952) where $K$ is mass transfer coefficient
$Nu = hd_d / k_G$	Nusselt number based on Ranz and Marshall (1952) where $h$ is heat transfer coefficient
$Sh^*$	Modified Sherwood number
$Nu^*$	Modified Nusselt number
$Nu_{eff}$	Effective Nusselt number used in model of Nayak et al. (2005)
$Nu_{heat}$	Nusselt number used in heating up stage

$Nu_{vap}$	Nusselt number used in vaporization stage
$Le = k_G / \rho_G D_v C_{pG}$	Lewis number
$Pr = \mu_G C_{pG} / k_G$	Prandtl number of
$Sc = \mu_G / \rho_G D_v$	Schmidt number
$Re_d = \rho_G v_{slip} d_d / \mu_G$	Reynolds number of gas phase
$Re_L = \rho_L v_{slip} d_d / \mu_L$	Reynolds number of liquid phase
$We = \rho_L v_{slip}^2 d_d / \sigma_L$	Weber number

### Greek letters

$\alpha$	polar angle
$\beta$	vaporization parameter
$\beta_T$	thermal expansion coefficient, $K^{-1}$
$\varepsilon$	holdup (chapter 3) mass fraction ratio (chapter 4)
$\gamma$	activity coefficient
$\varepsilon$	voidage used in the model of Buchanan (1994)
$\infty$	carrier gas phase, far from the droplet surface
$\phi_N$	phenomenological factor used in model of Nayak et al. (2005)
$\phi$	correction factor used in model of Abramzon and Sirignano (1989)
$\theta$	droplet-particle contact angle, <i>deg</i>
$\mu$	viscosity, $Ns/m^2$
$\rho$	density, $kg/m^3$
$\sigma$	surface tension, $N/m^2$
$\tau_{cont}$	contact droplet-particle time, <i>s</i>
$\tau_d$	relaxation time, <i>s</i>
$\kappa$	change in surface tension with respect to temperature
$\Lambda$	change in surface tension with respect to mole fraction

## Subscripts

$d$	Droplet
$G$	gas
$L$	liquid
$V$	vapour
$P$	solid particle
$s$	surface
$m$	mixture vapour/air except “ $m$ ” used in Table 2.2
$Re_m$	“modified” Reynolds number using free-stream density (Table 2.2)
$f$	film conditions (vapour film at the droplet interface – Table 2.2)
$\infty$	free-stream density (Table 2.2)