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Interactions in droplet and particle system of near unity size ratio

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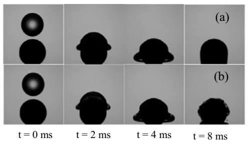
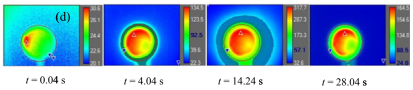
HIGHLIGHTS

- Near unity size ratio droplet-particle interaction studied on hydrophobic surface.
- Deposition to complete spreading observed with increasing Weber numbers.
- A time varying linear, power law and oscillatory regimes noted in lamella thickness.
- Non-isothermal interactions exhibited rebound and lamella breakup outcomes.
- Similar regimes observed with heat transfer except the third due to lamella breakup.

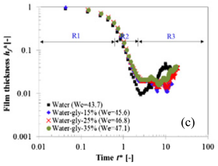
GRAPHICAL ABSTRACT



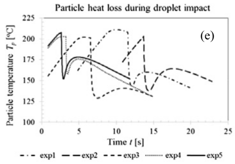
a) Film formation ($T_p = 20^{o}$C) b) film disintegration due to boiling heat transfer ($T_p = 300^{o}$C). [Cond.: water-gly (25%), *We* = 46.8]



Spatial temperature distribution on particle surface (dry state) at different time instants when subjected to a 445 nm blue laser beam.



Three different regimes (R1-R3) of temporal variations in the film thickness at particle apex location.



[Condition: water-gly-mixture (25%), *We* = 46.8]

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ABSTRACT

In this study, we report collision interactions between a single droplet (diameter: 2.48–2.61 mm) and a stationary hydrophobically coated thermally conductive particle (diameter: 3 mm) in the low impact Weber number range of ∼0.9–47.1 Experiments were performed under both cold and hot state with the aid of high speed imaging to capture the interaction dynamics. Two outcomes were observed in the cold state: deposition at low Weber numbers and complete wetting of particle surface through formation of a spreading lamella of thick peripheral rim at higher Weber numbers. The complete wetting behaviour of droplet exhibited three distinct regimes of temporal variations in liquid film thickness at the apex point of particle. In non-dimensional coordinates, these regimes included – a short interval regime of linear reduction in film thickness due to initial droplet deformation, a relatively larger interval of inertia dominated regime of non-linear reduction in the film thickness and a relatively time invariant large interval of gravity draining regime with an oscillatory transition state due to capillary effect. A novel non-invasive laser based particle heating system was deployed for the non-isothermal interaction cases which showed two outcomes – rebound at lower Weber numbers and complete wetting followed by disintegration of the lamella at higher Weber numbers. Variation in particle temperature was insignificant in the rebound regime however significant temperature reduction (∼10–70 °C) occurred due to increased wetted contact and nucleate boiling of secondary droplets at higher Weber numbers. Irrespective of the heat transfer effect at solid-liquid interface, the temporal variations in the film thickness followed the same trend in regime 1 and 2 as noted in the cold interaction cases. The effect of heat transfer was however uniquely characterised by the absence of regime 3 due to nucleate boiling at solid-liquid contact surface which led to rupture of the interface through eruption of vapour bubbles at the end of regime 2.

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Nomenclature

A	area (m^2)
a_1	slope in linear equation in regime R1 (–)
b_1	intercept in linear equation in regime R1 (–)
a_2	prefactor in power law equation in regime R2 (–)
b_2	exponent in power law equation regime R2 (–)
c_1	proportionality constant (s^{-1})
C_p	heat capacity ($J \cdot kg^{-1} \cdot K^{-1}$)
D	distance (m)
f	fraction of input laser power (–)
d	diameter (m)
g	gravitational constant ($m \cdot s^{-2}$)
h	thickness (m)
h^*	non-dimensional film thickness (–)
h_c	heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
k	thermal conductivity ($W \cdot m^{-1} \cdot K^{-1}$)
l	length scale (m)
m	mass (kg)
n	wavenumber (m^{-1})
M_0, M	capillary wave magnitude (m)
p	pressure (Pa)
E_0	rated laser power (W)
Q	heat transfer rate (W)
r	radius (m)
r_a	surface roughness (m)
S	arc distance (m)
T	temperature (K)
V	volume (m^3)
v	velocity ($m.s^{-1}$)
t	time (s)
t^*	non-dimensional time (–)

Dimensionless numbers

Ca	Capillary number
Fr	Froude number
Gr	Grashof number
Nu	Nusselt number
Oh	Ohnesorge number
Pr	Prandtl number
Ra	Rayleigh number
Re	Reynolds number
St	Stokes number
We	Weber number

Greek letters

α	attenuation coefficient (–)
β	volume expansion coefficient (K^{-1})
Δ	droplet particle size ratio (–)
ε	surface emissivity (–)
L	latent heat of vaporization ($J \cdot kg^{-1}$)
ρ	density ($kg \cdot m^{-3}$)
μ	viscosity ($Pa \cdot s$)
σ	Stefan-Boltzmann constant ($W \cdot m^{-2} \cdot K^{-4}$)
γ	surface tension ($N \cdot m^{-1}$)
θ	contact angle (°)
φ	polar angle (°)
λ	capillary wavelength (m)
τ	characteristic time scale (s)
ω	angular frequency (s^{-1})

Subscript

0	initial state
amb	ambient
avg	average
bl	boundary layer
$conv$	convection
∞	bulk state
d	droplet
f	film
g	gas
int	interface
mfb	minimum film boiling
ref	reference
osc	oscillation
p	particle
rad	radiation
s	static
sup	super
sat	saturation
v	vapour
w	wave

1. Introduction

Occurrence of droplet-particle interactions is ubiquitous in both nature and man-made applications. In nature, for instance atmospheric aerosols often act as cloud condensation nuclei around which cloud droplets are formed. Precipitation leads to interaction of rain drops with the below cloud particulate aerosols due to differential settling velocity which aids in natural scrubbing in the atmosphere. Many engineering applications that frequently encounter such interactions include but not limited to fluid catalytic cracking unit used for producing high calorific value fuels from cracking of atomized heavy gasoil feedstock in contact with high temperature zeolite catalyst particles; cracking of bitumen in fluid coker unit in contact with high temperature coke particles; coating of tablets in spouted bed using solvent sprays in pharmaceutical industries, spray scrubbing of particulate matters from process off-gas streams, etc. (Ge and Fan, 2007; Bakshi et al., 2007; Mitra et al., 2013; Nguyen et al., 2015; Mitra et al., 2016a, 2016b). Besides the importance of the droplet-particle interaction in the aforesaid practical applications, it is also of significant fundamental research interest to understand the complex hydrodynamics coupled with the heat and mass transport process which are essential to gain insights into these interaction mechanisms.

A number of studies on droplet impact on flat surface including the well regarded work of Chandra and Avedisian (1991), Rein (1993), Yarin and Weiss (1995) and Yarin (2006) are available addressing several industrial applications such as spray painting, spray coating, spray cleaning of surfaces, spray cooling, spray forming, metal forming, pesticide spray, shock atomizing and material erosion (Rozhkov et al., 2002). These studies elaborately described different aspects of the droplet impact hydrodynamics such as deposition, spreading, recoiling, splashing/disintegration and rebound. In recent time, Moreira et al. (2010) comprehensively reviewed all the possible interaction outcomes with specific focus on droplet interaction on non-heated, thin liquid film covered wetted and heated surface.

Noticeably such studies on the droplet-particle system are rather limited which unambiguously involve greater complexities in the hydrodynamics due to smaller length and time scales of interactions and different possible variations in size ratio Δ. For a single droplet-particle system, three different interaction modes were described in Mitra et al. (2016b) based on droplet-particle size ratio ($\Delta = d_d/d_p$) i.e. $\Delta < 1$, $\Delta \sim 1$ and $\Delta > 1$. It is worthwhile