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Interaction of a spherical particle with a neutrally buoyant immiscible droplet in salt solution

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HIGHLIGHTS

- Interactions of small particles with a stationary immiscible droplet studied.
- Separation distance, particle trajectory and attachment time quantified.
- Both elastic and inelastic impact interactions noted depending on the particle size.
- Increased surface hydrophobicity enhances particle attachment to droplet interface.
- DEM model provided reasonable agreements to the experimental measurements.

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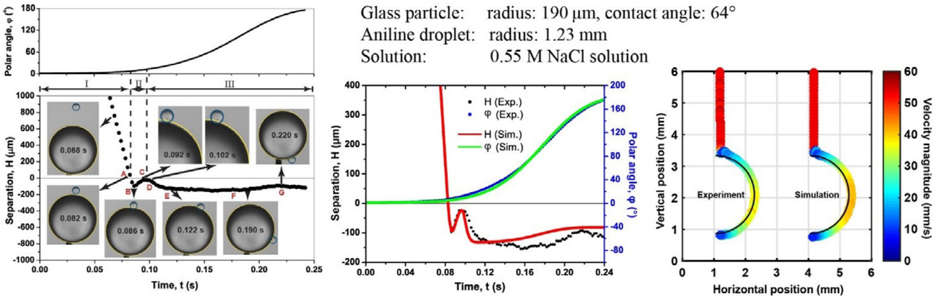
GRAPHICAL ABSTRACT



ABSTRACT

The complex interactions of rigid spherical particles with interface (e.g., gas-liquid or liquid-liquid) underpin important industrial applications such as the separation of minerals using flotation method. The objective of the present work was to investigate this interaction process both experimentally and theoretically involving different size of particles (radius ~ 100–200 μm) with varying surface wettability (contact angle ~ 50–70°) and a stationary neutrally buoyant immiscible oil-water interface (aniline droplet in salt solution) utilizing high speed imaging technique. The results showed that the particle size significantly affects the collision mechanism wherein collision with particle rebound was noted for larger size particles and collision without particle rebound was noted for the smaller size particles. Increasing surface hydrophobicity of the particles was found to be a governing factor that strongly attaches the particle to interface with immersion depth as high as ~50% of particle radius. Collision polar angle was also noted to be a critical parameter that governs the attachment process. When collision polar angle was increased from 15° to 55°, attachment time was noted to increase by ~2.5 times indicating decreasing probability of attachment. A discrete element model (DEM) was also developed to predict the interaction outcomes with suitable modification of the governing forces. To account for the effect of interface deformation, a spatially dependent capillary force profile was utilised incorporating the effect of interface deformation. The contact force model was modified to produce the collision with/without rebound outcomes. Also, the short range hydrodynamic drag force model was modified using suitable correction factors to account for the resistance in the intervening film between the approaching particle and the interface. Experimentally determined parameters such as droplet-particle separation distance, particle trajectory and velocity were compared with the DEM model predictions and reasonably good agreements were obtained.

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Nomenclature

A	Hamaker constant (J)
D_{CC}	centre-to-centre distance (m)
F_B	buoyancy force (N)
F_{cont}	contact force (N)
F_{cap}	capillary force (N)
F_G	gravitational force (N)
F_{mdrag}	modified drag force (N)
F_{sdrag}	standard drag force (N)
F_{vdW}	van der Waals force (N)
F_h	hydrophobic force (N)
f^r	dimensionless correction factor for hydrodynamic force in radial direction (-)
f^t	dimensionless correction factor for hydrodynamic force in tangential direction (-)
g	gravitational acceleration constant (m s^{-2})
H	surface-to-surface separation distance (m)
K	pre-exponential parameter (N/m)
k	spring constant (N/m)
m_p	particle mass (kg)
$\mathbf{n}$	normal unit vector (-)
Re_p	particle Reynolds number (-)
R_d	droplet radius (m)
R_p	particle radius (m)
S	true separation distance (m)
t_{att}	attachment time (s)
U_p	particle velocity (m/s)

Greek symbols

α	half filling angle (°)
η	overlapped distance (m)
θ	contact angle (°)
λ	decay length (m)
μ	liquid viscosity (Pa s)
ρ_l	liquid density (kg/m^3)
ρ_p	particle density (kg/m^3)

1. Introduction

Insightful understanding of a number of industrial applications such as oil recovery, printing, deinking, emulsion stability and mineral flotation requires knowledge of complex phase interactions mechanisms. For instance, in mineral flotation, a well-known multiphase complex physico-chemical process, oil droplets or bubbles are utilised as carriers in liquid medium for recovery of valuable mineral particles (Polat et al., 2003). Three distinct sub-processes could be noted here which involve particle collision with the immiscible interfaces (oil droplets, air bubbles), particle attachment to interface followed by rupture of the intervening thin liquid film and finally detachment of particles from interface (Nguyen and Schulze, 2004). The effectiveness of the flotation recovery of the valuable mineral particles critically relies on the ability of air bubbles/oil droplets to capture the hydrophobic particles from the suspension. The collision process is controlled by the hydrodynamic effects involving motions of bubbles and particles and fluid medium. The attachment and detachment processes are essentially governed by the combined hydrodynamics, DLVO forces like van der Waals and electrical double layers and non-DLVO force like the hydrophobic interaction force (Tabor et al., 2014) which is in particular is difficult to quantify and model mathematically.

A number of factors such as particle size and shape, density, surface roughness and hydrophobicity, air/water interface curvature, surface mobility, and liquid medium conditions (surfactant type, concentration, salinity and fluid flow field) affect the particle attachment phase leading to formation of particle-bubble aggregates. In addition to the physicochemical phenomena in flotation, surface chemistry involving flotation reagents also controls the overall process response to a significant extent. Taking advantage of the state-of-the-art surface force apparatus (SFA) (Manica et al., 2007; Pushkarova and Horn, 2008), atomic force microscope (AFM) (Chan et al., 2011; Dagastine and White, 2002; Ducker et al., 1994; Mulvaney et al., 1996; Snyder et al., 1997; Webber et al., 2008) and bubble/droplet probe technique (Shi et al., 2015; Tabor et al., 2011, 2012; Xie et al., 2015), it has been possible in recent time to quantify the surface forces between solid-solid, deformable fluid-fluid interfaces, and solid-fluid interface. However, during attachment of a particle to the interface (bubbles or droplets), measurements of the interaction forces associated with local dynamic surface deformation is still an intractable issue (Tabor et al., 2014).

From the macroscale experimental point of view to understand the bubble-particle interactions, high-speed imaging technique has been favoured in recent years by many researchers recording the motion of freely depositing particle around a stationary or rising bubble to visualise the interaction processes directly. Wang et al. (2003a) investigated the effects of particle (glass ballotini) hydrophobicity on the attachment outcome and measured the sliding velocity of particles on an air bubble/glass sphere in order to account for the effect of surface mobility of the collecting sphere. They noted that higher the surface mobility, faster is the sliding velocity (Wang et al., 2003b). Nguyen and Evans (Nguyen and Evans, 2004b) studied the particle-bubble sliding interaction using high speed imaging and recorded the rupture of the intervening liquid film followed by a jump-in behaviour between a hydrophobic particle and a stationary bubble which was a proof of the attachment process. The jump-in phenomenon and induction time duration was later verified by Verrelli et al. (2011) using high-speed videography.

To supplement the high speed visualisation of bubble-particle interactions and recognising the difficulty in measuring the interaction forces experimentally, in recent years, discrete element method (DEM) based modelling has emerged as a promising computational approach for simulating the particle-bubble interaction problems in froth flotation (Gao et al., 2014, 2015; Maxwell et al., 2012; Moreno-Atanasio, 2013; Moreno-Atanasio et al., 2016; Wierink, 2012). Maxwell et al. (2012) provided a DEM model to analyse the influence of various system parameters, such as particle size distribution, hydrophobic force (expressed as a power law), on the bubble capture efficiency in the absence of particle–fluid interactions. Moreno-Atanasio (2013) extended the work by Maxwell et al. (2012) and adopted the same approach to investigate the effects of different hydrophobic force laws (i.e. power law decay in the form of $1/H$ and $1/H^2$, and single exponential law decay in the form of $-H/\lambda$, where H is the separation distance and λ is the decay length) on the particle-bubble interaction. Gao et al. (2014) evaluated the effect of hydrophobic force using the single exponential law in their DEM model and demonstrated influence of decay length parameter on the particle-bubble interactions using a sensitivity analysis.

In a subsequent work, Gao et al. (2015) utilised DEM model to simulate the interaction between particles and a stationary bubble in a quiescent liquid with particular emphasis on its ability to describe the motion of the particle sliding over the bubble surface