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Collision behaviour of a smaller particle into a larger stationary droplet

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ABSTRACT

The present study investigates the collision behaviour of a smaller particle into a larger stationary droplet – a phenomenon related to many process engineering applications. Experimentally, the collision process was studied using high speed video imaging involving glass ballotini particles (diameter: 1.13 ± 0.02 mm) and a supported stationary water droplet (diameter 3.41 ± 0.01 mm) at different particle impact velocities (Weber number range: 0.2–13.5). A transition from partial to complete penetration was observed with decrease in sinking time and significant shape deformation of the droplet when Weber number was increased. Numerically, a one dimensional transient force balance approach was adopted which included contributions of six major forces during the penetration process, including: gravity, capillary, fluid drag, buoyancy, pressure and added mass. It was found that the capillary force controlled the interaction process. Recognizing the limitation of using the one dimensional model to capture the details of the collision physics especially the movement of three phase contact line (TPCL) on the particle surface, a 3D computational fluid dynamics (CFD) model was developed using the multiphase volume of fluid (VOF) method combined with the dynamic meshing technique. The CFD model was in good agreement with experimental measurements of the sinking time of the particle and overall collision dynamics including shape deformation of the droplet.

1. Introduction

The interaction of particles with a gas–liquid interface is an important element in a number of industrial processes. Of many process industry applications, such as recovery of minerals by film floatation [1,2], fluidized catalytic cracking [3], spray drying [4], fabricating reinforced metal matrix [5] and granulation [6], the optimum interaction of particles with the gas–liquid interface is critical for the process performance. In film flotation, the desired mineral particles of economic interest can be separated from the gangue materials by preferential settling of the particles at the gas–liquid interface. In other applications, such as in the feed vaporization zone of an FCC riser, the feed droplets of gas oil are vaporized with intense interactions with the hot catalyst particles. Among many different possible interaction outcomes, smaller feed droplets may stick to the larger hot catalyst particles and smaller hot catalyst particles may be partially or completely retained inside the droplet until complete vaporization. When particles have higher impact momentum, they may penetrate the feed droplets resulting in a brief contact period and partial vaporization of the liquid phase. Heat and mass transfer events associated with such interactions are often considered critical for the process performance. In some applications, particles are intended to be retained completely inside the droplets during such interactions. For example, in spray drying applications, fine particles separated from the product stream are returned to the drying chamber again to interact with the atomized feed droplets as they serve as seeds for the crystallising products [4]. Another such example is manufacturing of discontinuously reinforced metal matrix composites to meet the need of lightweight applications which requires incorporation of ceramic reinforcements in particle form in the liquid or semi-liquid metallic matrices [5]. In a multi-particle environment (e.g. dense particle bed) such as the wet granulation process, controlled droplet interaction is required to obtain the desired product quality. Depending on the impact velocity of the droplet and the characteristics of the particles (cohesive or free-flowing), such interactions could include: droplet pulling particles as it penetrates the dense bed (*tunnelling*), droplet spreading over the bed surface and penetrating at the same time to form granules (*spreading*), and droplet forming a crater in the bed and penetrating at the same time (*crater formation*) [6].

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In practice, all of the abovementioned particle to gas–liquid interface interactions can be broadly classified into particle interaction with either a planar or curved gas–liquid interface. Due to relatively less studies reported on the interaction of particle with the curved interface, few previous relevant works on the interaction of particle with the planar interface are discussed below as necessary background of the present study.

When a particle impacts on a gas-liquid interface much larger than its own characteristic size, then depending on the physical characteristics of the system it may either be retained at, penetrate through, or rebound off the interface. Such interaction behaviour also depends on the contact angle forming on the particle surface where the gas–liquid interface attaches (three phase contact line) as well as the movement of the gas–liquid interface relative to particle velocity [1,2,7]. When the gravity force acting on the particle in the downward direction is exactly in equilibrium with the upward acting forces, the particle floats at the interface and a static contact angle forms on the particle surface. However, when a particle penetrates the interface, the contact angle dynamically changes with the movement of the three phase contact line (TPCL). When the particle surface is hydrophobic with contact angle greater than 90°, at lower impact velocity the particle oscillates on the interface; whilst at higher impact velocity the particle oscillation increases eventually leading to rebound off the interface [8].

For a hydrophilic particle having the contact angle is less than 90°, when the impact velocity is gradually increased, the inertia of the particle is able to overcome the resistive forces at the interface leading to the formation of a TPCL. Further downward motion of the particle is eventually inhibited by the opposing upward forces acting at the interface and in the bulk liquid which include capillary force, drag force and buoyancy force [2,7–11]. Of all these forces, the capillary force, which depends on the interfacial surface tension, particle size and contact angle, plays a critical role in governing the impact interaction. If the capillary force is sufficiently high then this upward acting force, in combination with buoyancy, may pull the particle off the interface leading to rebound. Conversely, when a particle impacts the interface at a higher velocity the downward inertial force of the particle is greater than the upward restoring forces and results in complete penetration of the interface.

For a curved interface, such as a droplet or meniscus inside a capillary channel, both the Laplace and hydrostatic pressure (resistive) forces need to be included when modelling the gas–liquid interface cavity profile generated by the impacting particle [12]. If these resistive forces are sufficiently strong the impacting particle after collision with the interface will decelerate and eventually the velocity will become zero after reaching a certain distance less than the droplet diameter. This impact velocity is defined as critical particle velocity for interface penetration. Experimentally, it has been found that there exists a critical impact velocity [1,2] beyond which the particle cannot be retained at the gas–liquid interface. For process applications, such as flotation, it is important that the particles desired to be captured at the interface should have an impact velocity below their critical value. Experimentally it has been found that the critical impact velocity increases with an increase in surface hydrophobicity and surface tension of the liquid, and a decrease in particle size and ratio of particle-liquid density [1].

For planar interfaces, based on force and/or energy balances of the system, some previous studies [1,2,8,13,14] investigated such critical conditions for different particle–liquid interface systems. Lee and Kim [8] analysed the critical condition for highly-hydrophobic spherical particle penetration without varying the contact angle and suggested criteria for particle sinking and rebounding at the interface. Engh et al. [13] obtained theoretically the critical conditions for horizontal penetration of a particle without consideration of the effect of the cavity formation caused by the particle impact. Ozawa and Mori [14] studied the critical conditions for a hydrophobic particle with density lower than the liquid. The effect of the cavity formation in their model was taken into consideration only by an empirical factor in the expression of the capillary force model. This simplification increased the inaccuracy in their model since the interface depression has an important effect on the penetration process.

In the static equilibrium case the profile of the interface depression can be obtained by balancing the hydrostatic pressure force and the capillary force acting on the TPCL from the well-known Young–Laplace equation. In the force balance analysis on a submerging particle at a planar gas-liquid interface, Shang et al. [7] utilized the Young-Laplace equation to obtain the relationship between the interface inclination angle and interface depression height for computing the hydrostatic pressure force component. The equation has however been also used to determine depression of a curved interface such as bubble during interaction with particles in a turbulent flow field, a scenario commonly encountered in the mineral flotation processes [12]. In this case the particle diameter is considered to be much smaller than the corresponding bubble diameter, and the interface is assumed to be locally planar [12]. It is apparent that the magnitude of this depression would depend on the impact inertia of the particle. Larger the inertia of impacting particle, greater will be the interface depression. Now, for a significant magnitude of the impacting inertia, larger the size of interface/droplet, bigger will be the depression forming a larger gas cavity inside the droplet/liquid body. Interface depression would not be realizable if the interface/droplet size is smaller or comparable to the size of the impacting particle.

Of the very limited studies available on the interaction of particle with a curved interface, work of Dubrovsky et al. [15] possibly could be considered as a benchmark study in this area. They carried out extensive experiments on droplet-particle collision using particles and droplets of different sizes and physical properties. In the experiments where droplet-particle size ratios were greater than 1, they identified four different interaction regimes namely capture, shooting through, bubble formation and target destruction. All observed data were categorized according to the above four interaction types in a regime map using Reynolds number and Weber number as coordinates. At lower Reynolds number, where the viscous effect was dominant, and particle density was relatively less, capture mode was observed wherein the particle retained inside the droplet. As Reynolds number was gradually increased and particle had higher inertia, three distinct interactions modes were observed – “shooting through” wherein the particle was observed to completely shoot through the droplet forming very small liquid fragments (satellite droplets) trailing behind, “destruction” where the droplet was fragmented into many parts during the collision and “bubble formation” wherein air bubbles were entrained into the droplet during collision. In a broad sense, the other two interactions modes – bubble formation and target destruction can be considered to belong to the shooting through mode as particle completely penetrates the droplet in both cases. In many process engineering applications described before where such droplet–particle interactions involve heat and mass transfer phenomena, in the capture mode, the contact time of such interaction is ideally indefinite allowing sufficient time to reach equilibrium however for shooting through mode and its two sub categories, the contact time is brief and equilibrium possibly never reaches.

On numerical studies in this area, Wu et al. [15] studied the penetration behaviour of ceramic particulates into molten aluminium (Al) droplets during spray atomization and co-injection using a force balance model. Factors that affect the penetration behaviour of ceramic particulates into Al droplets were systematically discussed which included size, morphology, density of ceramic particulate; wetting angle between ceramic and liquid A1; and