Chemical Engineering Science 161 (2017) 329–340

Contents lists available at ScienceDirect

Chemical Engineering Science

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

Bubble movement in a rotating eddy: The implications for particle-bubble detachment

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HIGHLIGHTS

- Bubble entrainment inside a rotating eddy is observed.
- Bubble coalescence in the centre of the rotating eddy is observed.
- Particle detachment associated with bubble oscillation.
- Particle detachment associated with rapid changes in trajectory of the bubble.

ARTICLE INFO

Article history:
Received 29 August 2016
Received in revised form 12 December 2016
Accepted 15 December 2016
Available online 19 December 2016

Keywords:
Rotating eddy
Bubble entrainment
Bubble-particle detachment

ABSTRACT

Bubbles are an essential part of the froth flotation process for the separation of mineral particles. However, little information is available on the behaviour of bubbles in the turbulent flows in a flotation machine. It has been noted in flotation kinetics studies that the behaviour of bubbles in turbulent eddies is a significant factor in bubble-particle collision, attachment and detachments. In this paper, the performance of single bubbles and groups of bubbles inside a rotating eddy have been studied experimentally. Bubbles were released into a turbulent rotating field in a wall cavity, where a confined eddy was developed by controlling the water flow into the water channel over the open mouth of the wall cavity. To study the behaviour of particles attached to bubbles in the turbulent eddies, particle-bubble aggregates were generated in an external fluidized bed and introduced into the rotating eddy with no frothers added. The process of particle detachment due to centrifugal movement was captured by a high-speed camera. The traditional theory of particle-bubble detachment, which assumes a centrifugal motion of the attached particle on the surface of the bubble, was experimentally verified. However, other modes were also observed. For example, bubbles carrying particles can be brought together in a turbulent vortex, resulting in bubble coalescence and consequent detachment of particles. Inertial detachment modes are also seen, due to rapid changes in the trajectory of the bubble, or because of oscillations of the bubble's surface.

1. Introduction

Bubbles are the silent heroes of froth flotation, where bubbles attach hydrophobic particles and carry them to the froth layer, leaving the hydrophilic particles settling down to the bottom. Bubbles play a vital role in separating particles, based on the differences in the hydrophobicity of particles (Sutherland, 1948). Bubbles interact with particles in three different processes, including: collision between particles and bubbles; particle attachment to the bubble; particle detachment from the bubble (Arbiter, 1962; Klassen and Mokrousov, 1963). The interactions between the particles and bubbles are subject to the influence of the turbulent flow. Once released into the flotation column, bubbles rise from the bottom of the cell to the top of the column. In this process, bubbles collide with particles and are attached to them, which is known as bubble mineralization. As the liquid's flow in the flotation environment is generally within the turbulent regime, the attached particles can get knocked off the bubbles by the perturbations of the surrounding turbulent eddies. It is apparent that the movement of the bubbles in the turbulent flow would be intimately linked to the removal process. Therefore, the movement of the bubbles in the turbulent eddies is a crucial parameter in determining the interactions between particles and bubbles. Jameson (1993) considered the behaviour of individual bubbles in shear fields, and the behaviour of swarms of bubbles in the

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http://dx.doi.org/10.1016/j.ces.2016.12.034

development of the Jameson Cell. However, the information available on the movement of bubbles inside eddies, and their implications for the flotation process, is sparse.

In recent years, effort has been devoted to increasing the understanding of the mechanisms involved in coarse particle flotation because the grinding process needed is highly energy-intensive. If coarse particles can be floated, and minerals need only to be ground to that size, considerable savings in the energy required for this process can be achieved. Nevertheless, particle detachment is the limiting factor in coarse particle flotation as coarse particle-bubble aggregates are vulnerable to turbulent eddies, where coarse particles can easily be knocked off the bubbles. The traditional theory of particle-bubble detachment is based on the hypothesis that the aggregate is trapped inside an eddy and that the particle rotates on the surface of the bubble along with the eddy (Schulze, 1977, 1982). When the centrifugal force acting on the particle is higher than the attaching capillary force, the particle detaches. This theory has only been validated in recently available experimental observations by Wang et al. (2016), where particles were observed to rotate at nearly 200 cycles per second on the surface of bubbles, generating a centrifugal acceleration nearly 20 times that of gravitational acceleration. In another work, particles were observed to transfer between bubbles in a rotating eddy, and bubble clusters were formed in the centre of the eddy by bridging particles in the connecting bubbles.

Omelka et al. (2009, 2010) studied bubble-particle detachment in a turbulent flow by passing pulp through grids. In these tests, the turbulent energy dissipation rate was around 50–100 m^2/s^3 and the bubbles oscillated and broke in a turbulent flow of high intensity. The movements of the particles on the surfaces of the bubbles were not tracked as a number of particles in the size range of 100–150 μm were attached to a single bubble's surface. The only detachment mechanism detected was the release of particles due to bubble breakup. Goel and Jameson (2012) studied particle detachment as a function of the energy dissipation rate in a stirred tank. Particles were attached to the bubbles in a fluidized bed, and then the newly formed particle-bubble aggregates were released into the stirred tank. It was found that particle detachment increased with the energy dissipation rate. Nevertheless, it is necessary to point out that turbulent flows affect the interactions between the particles and bubbles in different ways. A high energy input supplies sufficient kinetic energy for the particles and bubbles to collide, and subsequently attach. However, a high energy input can generate a great range of eddies of different scales and intensities, which may detach particles from bubbles. Ahmed and Jameson (1989) conducted experiments in a flotation cell with variable impeller speeds, and showed that the flotation rate constant reached a characteristic maximum as the particle size increased, after which detachment began to come into effect. It appears that the energy input should be modulated to reach a compromise in order to achieve an optimized flotation performance. The mechanisms behind this rationale remain a puzzle if the role of a bubble's movements under the influence of turbulent eddies is not recognized.

There is a complete lack of experimental data about the effect of a bubble's movements in a rotating eddy in the flotation process. It is elementary to start with the interactions between the bubbles and the eddies which are based on their relative sizes and velocities, and the differences in their densities (Hetsroni, 1989). When a bubble approaches an eddy in a turbulent flow, the asymmetric distribution of the pressure field around the bubble's surface pushes it towards the centre of the eddy (Chahine, 1995). In the process of reaching the centre, the bubble follows a decreasing ambient pressure gradient, and finally reaches an equilibrium state. A particle with a density higher than that of the fluid phase tends to migrate to, and concentrate on, the edges of the eddy (Crowe et al., 1995). The interactions between the particulate phase (particles, bubbles or droplets) and the continuous phase are generally studied from two perspectives: the influence of the particulate phase on the turbulence properties; and the performance (distribution and movement, etc.) of the particulate phase in the turbulent flow field. The extent of the interactions between the particles and the eddies depends on the ratio of the particle relaxation time to the time available for the particle-eddy interaction. This can be reflected in a dimensionless number, the Stokes number, which is a ratio of the particle relaxation time to the time scale of the eddy. Following the definition given by Balkovsky et al. (2001), the Stokes relaxation time of a particle is:

$$\tau_p = \frac{a^2}{3\beta\upsilon} \tag{1}$$

where a is the radius of the particle, v is the water viscosity, and the density ratio, β is:

$$\beta = \frac{3\rho_f}{2\rho_p + \rho_f} \tag{2}$$

where ρ_f is the density of the fluid and ρ_p is the density of the particle. The response of the particles depends on the flow structure, as reflected in the density ratio β (Toschi and Bodenschatz, 2009). Air bubbles in water ($\beta > 1$) preferentially concentrate in regions of high rotatational velocity, and heavy particles in water ($\beta < 1$) are expelled from the rotating regions.

The strength of the response of a particle to the flow structures depends quantitatively on the actual value of the Stokes number. The characteristic time of the eddy is:

$$\tau_e = \frac{L}{U} \tag{3}$$

where L is the length scale of the eddy and U is a representative flow velocity. Thus, the Stokes number is:

$$St = \frac{a^2 U}{3\beta\upsilon L} \tag{4}$$

A schematic view of the interactions between an eddy, and particles of different Stokes numbers is shown in Fig. 1. Particles with different inertia respond to a vortex differently. A particle for which $St >> 1$ is unaffected by the eddy rotation, whilst a particle

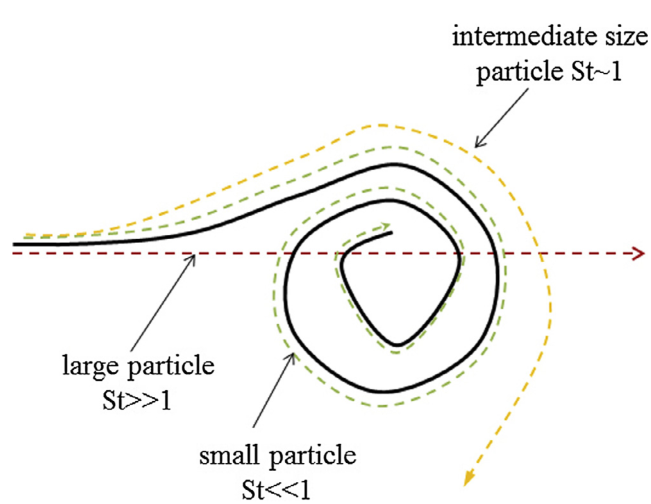

Fig. 1. Schematic view of the effects of the Stokes number on the particle dispersion in the eddy. A particle with a large Stokes value is almost insensitive to the presence of the eddy (the green, yellow and red lines correspond to increasing Stokes values, respectively). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)