Froth Flotation

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Contributor: Yao Ning

Froth flotation is an important operation for the recovery of valuable minerals in the mining industry. The essence of flotation processes lies in the interactions between particles and bubbles, which can be categorized into three successive sub-processes which are bubble-particle collision, attachment and detachment. These three sub-processes determine the overall performance of flotation processes for treating a particular ore.

flotation   turbulence effects   bubble-particle collision   attachment   detachment

1. Introduction

There are limitations of flotation operation in treating particles of different sizes [1][2]. This size limitation can be varied for different type of ores and flotation works well for particles of base metal ores in the range 20 to 150 μm in diameter [3]. Recovery of fine and coarse particles declines progressively and underlying reasons are different depending particle size [4].

Fine particles with small inertia will more likely follow streamline and therefore have lower chance of colliding with a bubble [5][6]. Though this is not a problem for coarse particle flotation, coarse particles with higher inertia would more likely detach with modest disturbances from surrounding liquid motion [7]. Therefore, studying interactions between particles and bubbles are fundamental to improve flotation performance. It is unavoidable that fine particles are produced in the grinding processes for the beneficiation of minerals [8]. Moreover, it is desirable to treat coarse particles using flotation for the early rejection of gangue as large amount of energy can be saved in the comminution processes [9]. It is highly necessary for studying particle-bubble interactions under the effects of turbulent flows as they are limiting factors in determining flotation performance [10][11].

Studies have been directed towards expanding size limit [12][13] and manipulating particle-bubble capture [14]. Studying particle-bubble interactions in turbulence is key to expand size limit and improve flotation performance. We have done a systematic endeavor to understand the effects of turbulence, especially on particle-bubble collision and particle detachment. Critical literature reviews on separate sub-processes have been presented on particle-bubble collisions [15][16], attachment [17][18][19] and detachment [20]. It is desirable to combine these three sub-processes together and consider the effects of turbulence on the flotation process as a whole. The effects of turbulence on the particle-bubble interactions in general is considered to be a stochastic process [21]. It can be attributed to the dynamic interactions between particles or bubbles with the turbulent eddies in flotation environment. On one side, hydrodynamics in flotation machines need to be characterized [22], and on the other side, how turbulence control sub-processes in flotation machines should be examined [11]. In this way,

hydrodynamics in flotation machines can be optimized to improve flotation performance [22]. Though some classical work in old days have been cited, we aim to collect literature in this century.

# 2. Particle-Bubble Collision, Attachment and Detachment

2.1. Effects of Turbulence on Collision

Due to the limitations of current experimental techniques for studying particle-bubble collisions in turbulent flows, to the best of authors' knowledge, there is no experimental work reported on the collisions between particles and bubbles in turbulent flotation processes. Simplified experiments were designed to study particle-bubble collision efficiency where single bubbles rose in the quiescent slurry [23][24]. Single bubble flotation experiments were designed to study. Particles were considered to stay attached to bubbles upon collision and collision efficiency could be represented by particle collection efficiency. Particle-bubble collision was directly observed using a high-speed camera [25][26][27][28]. Collisions were represented by direct observations of the falling particles around a positioned bubble. It should be mentioned that these experimental studies did not consider the effects of turbulence on particle-bubble collisions.

Most recent studies used computational fluid dynamics (CFD) to study the effect of turbulence on collision efficiency in flotation [29][30][31]. A single bubble was considered either rise at constant velocity or stationary. The Reynolds averaged Navier–Stokes (RANS) model was used to simulate turbulence. Note that this model cannot simulate small turbulent flow structures in the scale of bubbles or particles. To study the effect of turbulence on the collisions between particles, a direct numerical simulation (DNS) model was built in our group [32][33]. Collisions between a group of particles and bubbles were studied in a forced homogeneous isotropic turbulence (HIT) as is shown in **Figure 1**. The turbulence intensity of this background flow was modulated in terms of turbulent energy dissipation rate. Due to most collision models were developed for quiescent liquid, collisions between particles and bubbles in quiescent liquid were simulated and compared to the predictions calculated using widely accept collision models [33]. Results showed collision efficiency as a function of particle diameter and bubble diameter. The collision efficiency between particles and bubbles decreased with increasing bubble diameter and increased with increasing particle diameter, which was in accordance with the general trends of model predictions. In the study of particle-bubble collisions in HIT turbulence, the effects of preferential concentration of particles and bubbles on collision were studied. The collision kernel was found to increase with turbulent dissipation rate as is shown in **Figure 2**. This was due to the increase of increasing radial relative velocity in more turbulent flows. The effects of preferential concentrations on the particle-bubble collision kernel were ineffective compared to the effects of radial relative velocity.
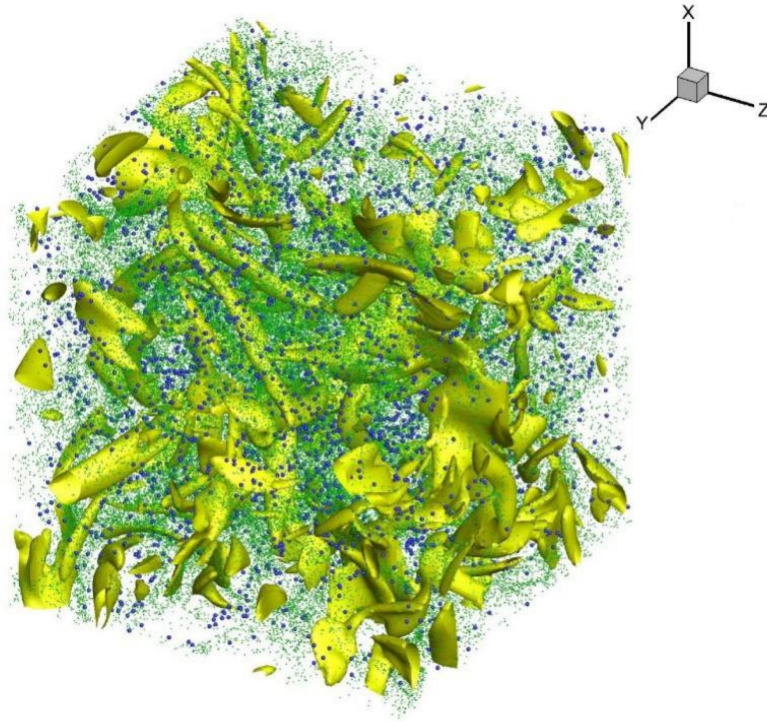
Figure 1. Particles (green dots) and bubbles (blue dots) in a homogeneous isotropic turbulence characterized by 3D vorticity field [33].
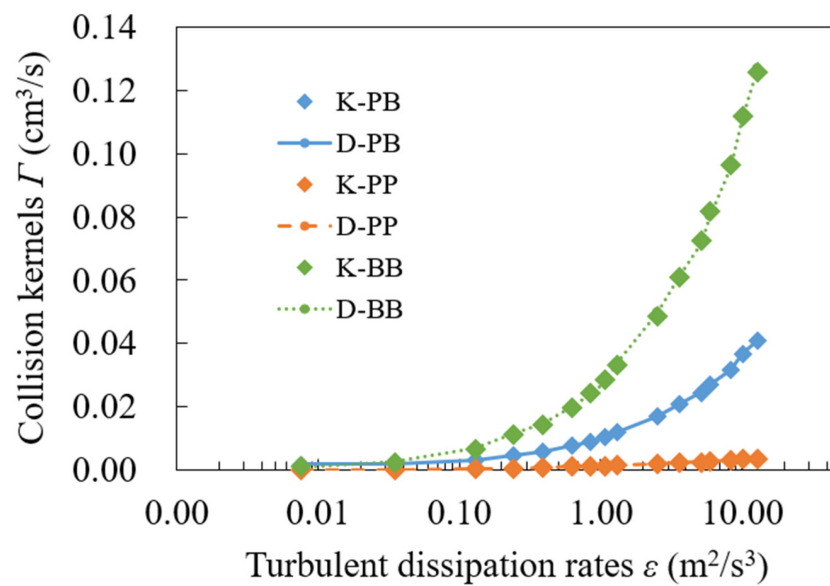
Figure 2. The collision kernels as a function of the turbulent energy dissipation rate [32].

Particles and bubbles were considered to be point particles in the above simulations. This will not hold for higher turbulent flows where bubbles and particles will be larger than small turbulent structures. The model was further improved by replacing point-particle model with particle-resolved simulations [34][35]. The dynamic collision kernels and kinematic collision kernels increased with turbulent dissipation rate. This observation was identical to our previous simulations using point-particle method. It has to be mentioned that these simulations considered

turbulence as homogeneous and isotropic, whereas in real flotation machines, turbulence can be much more complicated. Direct numerical simulations of real flotation machines have not been achieved yet. Moreover, particle-resolved DNS consumes enormous computational cost. Though it can fully represent interactions between turbulent structures and dispersed particles or bubbles, the simulation domain is only dozens of millimetres which is anything but close to real flotation machines.

2.2. Effects of Turbulence on Attachment

Particle-bubble attachment is characterised by three elementary steps and they are thinning of intervening liquid film to a critical thickness, rupture of critical film and formation of a stable wetting perimeter with the expansion of three-phase contact [18]. Induction time was defined as the time required for above whole process to occur [36], whereas, Albijanic et al. [17] considered induction time as the time of thinning intervening liquid film to a critical thickness. Though there is disagreement on the definition of induction time, it is widely accepted that particle-bubble attachment occurs only when contact time is longer than the induction time. Major parameters affecting particle-bubble attachment are solution chemistry and surfactants, surface chemistry of minerals, and surface forces [37]. The effects of turbulence on attachment process are overlooked or rarely discussed.

2.3. Effects of Turbulence on Detachment

A comprehensive literature review on the detachment of a particle from the surface of a bubble can be found in [20], where previous studies on the bubble-particle aggregate stability have been critically analysed. The effects of turbulence on the detachment of a particle from the surface of a bubble can be analysed in two perspectives, i.e., force and energy. Schulze [38][39] considered that rotating turbulent eddies interacted with the bubble-particle aggregate in a way that a particle would rotate on the surface of a bubble when the bubble-particle aggregate was trapped in a rotating eddy. The particle would detach when the centrifugal force originated from particle's centrifugal movement is higher than attaching force. Mao and Yoon [40] considered this process from energy perspective and kinetic energy required for detachment to occur was provided by turbulent eddies. There are discrepancies in the sources of turbulent kinetic energy from turbulent structures of different scales [41]. It is noted that exponential distribution function was used in these models to describe particle detachment probability. Researchers seem to accept this without further interrogation and the rationale behind this still remains obscure.

To view the detachment of a freely moving particle-bubble aggregate in a turbulent flow, an experimental apparatus as depicted schematically in **Figure 3** was designed, where the movement of aggregates were confined in a wall cavity. Large eddy simulation (LES) was used to simulate turbulent flow fields and turbulence was shown inhomogeneous inside the cavity [42]. For the first time, the hypothesis of particle's centrifugal movement proposed by Schulze [43] was experimentally observed. By tracking the movement of a particle, the rotational speed could reach as high as 200 cycles per second in the rotating vortex, as is shown in **Figure 4**. A number of different detachment mechanisms were identified, including inertial detachment due to the rapid changes in bubble movement, or because of the oscillations of the bubble's surface [44]. When a bubble was loaded with more than one particle, behaviour of attached particles could become more complicated [44]. It seems impossible to model

precisely the series of events that take place in the detachment process, as the particle-bubble detachment in the turbulent field is a stochastic process.
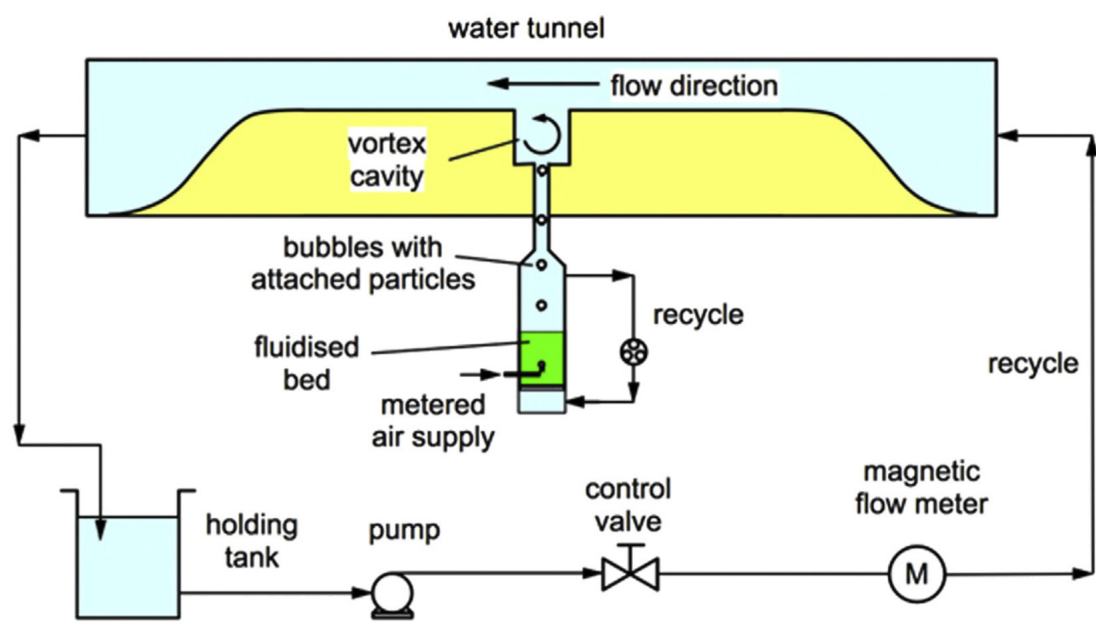
Figure 3. Diagrammatic sketch of the vortex generation apparatus [45].
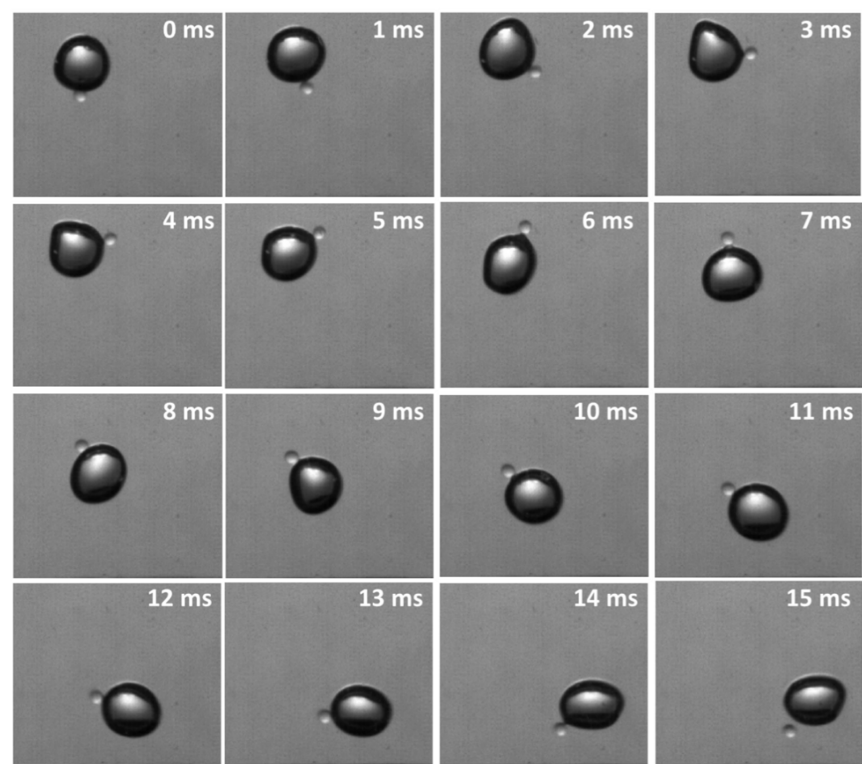
Figure 4. Time series of centrifugal movement of a particle on a bubble surface leading to detachment [46].

3. Conclusions

Herein has reviewed most recent progress in the study of particle-bubble interactions in turbulent flows. The effects of turbulence on particle-bubble collision and detachment have been widely studied. On the contrary, the effects of turbulence on particle-bubble attachment have been overlooked and is not clearly understood at this stage. This is due to the limitations of existing experimental techniques in measuring attachment process and surrounding liquid flows simultaneously. Increasing turbulence is beneficial to particle-bubble collision, but detrimental to stabilizing particle-bubble aggregates. Modulating hydrodynamics in flotation machines is dependent on the particle size, where turbulence is favoured for the flotation of fine particle and depressed for the flotation of coarse particles. Turbulence inside flotation machines should be optimized to improve flotation performance by maximizing particle-bubble collision and attachment and minimizing particle detachment concurrently. Interactions between particles and bubbles in turbulent flows are stochastic in nature and statistical models with empirical factors can be used to represent the effects of turbulence on flotation.

References

1. Gaudin, A.M.; Groh, J.O.; Henderson, H.B. Effect of particle size in flotation. Am. Inst. Min. Eng. Tech. Publ. 1931, 414, 3–23.

2. Trahar, W.J. A rational interpretation of the role of particle size in flotation. Int. J. Miner. Process. 1981, 8, 289–327.

3. Jameson, G.J. Advances in fine and coarse particle flotation. Can. Metall. Q. 2010, 49, 325–330.

4. Miettinen, T.; Ralston, J.; Fornasiero, D. The limits of fine particle flotation. Miner. Eng. 2010, 23, 420–437.

5. Jameson, G.; Nguyen, A.; Ata, S. Froth Flotation: A Century of Innovation; Fuerstenau, M.C., Jameson, G.J., Yoon, R.-H., Eds.; SME: Denver, CO, USA, 2007; pp. 329–351.

6. Ralston, J.; Dukhin, S. The interaction between particles and bubbles. Colloids Surf. A Physicochem. Eng. Asp. 1999, 151, 3–14.

7. Goel, S.; Jameson, G.J. Detachment of particles from bubbles in an agitated vessel. Miner. Eng. 2012, 36–38, 324–330.

8. Wang, G.; Bai, X.; Wu, C.; Li, W.; Liu, K.; Kiani, A. Recent advances in the beneficiation of ultrafine coal particles. Fuel Process. Technol. 2018, 178, 104–125.

9. Franks, G.V.; Forbes, E.; Oshitani, J.; Batterham, R.J. Economic, water and energy evaluation of early rejection of gangue from copper ores using a dry sand fluidised bed separator. Int. J. Miner. Process. 2015, 137, 43–51.

10. Li, D.; Wang, H.; Yang, L.; Yan, X.; Wang, L.; Zhang, H. Intensification effects of stirred fluid on liquid–solid, gas–liquid and gas–solid interactions in flotation: A review. Chem. Eng. Process.

Process Intensif. 2020, 152, 107943.

11. Schubert, H. On the turbulence-controlled microprocesses in flotation machines. Int. J. Miner. Process. 1999, 56, 257–276.

12. Kowalczuk, P.B.; Sahbaz, O.; Drzymala, J. Maximum size of floating particles in different flotation cells. Miner. Eng. 2011, 24, 766–771.

13. Sahbaz, O.; Ercetin, U.; Oteyaka, B. Determination of turbulence and upper size limit in jameson flotation cell by the use of computational fluid dynamic modelling. Physicochem. Probl. Miner. Process. 2012, 48, 533–544.

14. Ralston, J. Controlled flotation processes: Prediction and manipulation of bubble-particle capture. J. South. Afr. Inst. Min. Metall. 1999, 99, 27–34.

15. Dai, Z.; Fornasiero, D.; Ralston, J. Particle–bubble collision models—A review. Adv. Colloid Interface Sci. 2000, 85, 231–256.

16. Nguyen-Van, A. The collision between fine particles and single air bubbles in flotation. J. Colloid Interface Sci. 1994, 162, 123–128.

17. Albijanic, B.; Ozdemir, O.; Nguyen, A.V.; Bradshaw, D. A review of induction and attachment times of wetting thin films between air bubbles and particles and its relevance in the separation of particles by flotation. Adv. Colloid Interface Sci. 2010, 159, 1–21.

18. Nguyen, A.V.; Ralston, J.; Schulze, H.J. On modelling of bubble–particle attachment probability in flotation. Int. J. Miner. Process. 1998, 53, 225–249.

19. Nguyen, A.V.; Schulze, H.J.; Ralston, J. Elementary steps in particle—Bubble attachment. Int. J. Miner. Process. 1997, 51, 183–195.

20. Wang, G.; Nguyen, A.V.; Mitra, S.; Joshi, J.B.; Jameson, G.J.; Evans, G.M. A review of the mechanisms and models of bubble-particle detachment in froth flotation. Sep. Purif. Technol. 2016, 170, 155–172.

21. Nguyen, A.V.; An-Vo, D.-A.; Tran-Cong, T.; Evans, G.M. A review of stochastic description of the turbulence effect on bubble-particle interactions in flotation. Int. J. Miner. Process. 2016, 156, 75–86.

22. Schubert, H. On the optimization of hydrodynamics in fine particle flotation. Miner. Eng. 2008, 21, 930–936.

23. Dai, Z.; Dukhin, S.; Fornasiero, D.; Ralston, J. The inertial hydrodynamic interaction of particles and rising bubbles with mobile surfaces. J. Colloid Interface Sci. 1998, 197, 275–292.

24. Nutt, C.; Kemp, M.; Weston, J. Rate of Flotation in a Hallimond Tube. Nature 1963, 197, 40–42.

25. Brabcová, Z.; Karapantsios, T.; Kostoglou, M.; Basařová, P.; Matis, K. Bubble–particle collision interaction in flotation systems. Colloids Surf. A Physicochem. Eng. Asp. 2015, 473, 95–103.

26. Li, S.; Schwarz, M.P.; Yang, W.; Feng, Y.; Witt, P.; Sun, C. Experimental observations of bubble–particle collisional interaction relevant to froth flotation, and calculation of the associated forces. Miner. Eng. 2020, 151, 106335.

27. Verrelli, D.I.; Bruckard, W.J.; Koh, P.T.L.; Schwarz, M.P.; Follink, B. Particle shape effects in flotation. Part 1: Microscale experimental observations. Miner. Eng. 2014, 58, 80–89.

28. Verrelli, D.I.; Koh, P.T.L.; Nguyen, A.V. Particle–bubble interaction and attachment in flotation. Chem. Eng. Sci. 2011, 66, 5910–5921.

29. Islam, M.T.; Nguyen, A.V. Effect of microturbulence on bubble-particle collision during the bubble rise in a flotation cell. Miner. Eng. 2020, 155, 106418.

30. Li, S.; Schwarz, M.P.; Feng, Y.; Witt, P.; Sun, C. A CFD study of particle–bubble collision efficiency in froth flotation. Miner. Eng. 2019, 141, 105855.

31. Li, S.; Schwarz, M.P.; Feng, Y.; Witt, P.; Sun, C. Numerical investigations into the effect of turbulence on collision efficiency in flotation. Miner. Eng. 2021, 163, 106744.

32. Chen, S.; Chen, X.; Wan, D.; Yi, X.; Sun, X.; Ji, L.; Wang, G. A lattice Boltzmann study of the collisions in a particle-bubble system under turbulent flows. Powder Technol. 2020, 361, 759–768.

33. Wan, D.; Yi, X.; Wang, L.-P.; Sun, X.; Chen, S.; Wang, G. Study of collisions between particles and unloaded bubbles with point-particle model embedded in the direct numerical simulation of turbulent flows. Miner. Eng. 2020, 146, 106137.

34. Chen, S.; Chen, X.; Wan, D.; Sun, X.; Ji, L.; Wu, K.; Yang, F.; Wang, G. Particle-resolved direct numerical simulation of collisions of bidisperse inertial particles in a homogeneous isotropic turbulence. Powder Technol. 2020, 376, 72–79.

35. Wang, G.; Wan, D.; Peng, C.; Liu, K.; Wang, L.-P. LBM study of aggregation of monosized spherical particles in homogeneous isotropic turbulence. Chem. Eng. Sci. 2019, 201, 201–211.

36. Yoon, R.-H.; Yordan, J.L. Induction time measurements for the quartz—Amine flotation system. J. Colloid Interface Sci. 1991, 141, 374–383.

37. Xing, Y.; Gui, X.; Pan, L.; Pinchasik, B.-E.; Cao, Y.; Liu, J.; Kappl, M.; Butt, H.-J. Recent experimental advances for understanding bubble-particle attachment in flotation. Adv. Colloid Interface Sci. 2017, 246, 105–132.

38. Schulze, H. Hydrodynamics of bubble-mineral particle collisions. Miner. Procesing Extr. Metall. Rev. 1989, 5, 43–76.

39. Schulze, H.J. New theoretical and experimental investigations on stability of bubble/particle aggregates in flotation: A theory on the upper particle size of floatability. Int. J. Miner. Process. 1977, 4, 241–259.

40. Mao, L.; Yoon, R.-H. Predicting flotation rates using a rate equation derived from first principles. Int. J. Miner. Process. 1997, 51, 171–181.

41. Wang, G.; Zhou, S.; Joshi, J.B.; Jameson, G.J.; Evans, G.M. An energy model on particle detachment in the turbulent field. Miner. Eng. 2014, 69, 165–169.

42. Wang, G.; Evans, G.M.; Jameson, G.J. Bubble-particle detachment in a turbulent vortex II— Computational methods. Miner. Eng. 2017, 102, 58–67.

43. Schulze, H.J. Physicochemical elementary processes in flotation. In Developments in Mineral Processing; Elsevier Science Publishers: Amsterdam, The Netherlands, 1983; p. 348.

44. Wang, G.; Evans, G.M.; Jameson, G.J. Bubble movement in a rotating eddy: The implications for particle-bubble detachment. Chem. Eng. Sci. 2017, 161 (Suppl. C), 329–340.

45. Wang, G.; Evans, G.M.; Jameson, G.J. Experiments on the detachment of particles from bubbles in a turbulent vortex. Powder Technol. 2016, 302, 196–206.

46. Wang, G.; Evans, G.M.; Jameson, G.J. Bubble–particle detachment in a turbulent vortex I: Experimental. Miner. Eng. 2016, 92, 196–207.