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Behaviour of bubble clusters in a turbulent flotation cell

by

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A thesis submitted for the degree of

Doctor of Philosophy

March, 2013

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Acknowledgments

Above all, this thesis would not have been possible without the help, support and patience of my principal supervisor, Laureate Professor Graeme Jameson, not to mention his advice and unsurpassed knowledge of mineral processing. The good advice, support and friendship of my joint supervisor, Dr. Seher Ata, has been invaluable on both an academic and a personal level, for which I am extremely grateful.

I would like to thank Dr. Peter Ireland and Dr. Peter Yates for their invaluable suggestions on the experimental and theoretical work.

I would like to acknowledge centre officer Mrs Jennifer Limbrick and research assistants Ms Kitty Tang and Mr Bob Jones for their kindness, friendship and support on both official and personal issues.

I am most grateful to my fellow PhD students Alok Gautam, Cagri Emer, Ghislain Bournival, Reza Rahman, and Shina Goel for their kindness and support in the laboratory.

I would like to thank workshop craftsmen John Richards and Lonn Cooper for their precision and high quality work in making the experimental equipment.

Last but not least, I would like to thank my wife Xinyuan Xing for her personal support and great patience at all times.

Abstract

In the flotation process for the separation of valuable minerals from their ores, it is known that the rate of capture of particles decreases as the particle size increases. It has been postulated that the range of particles that can be recovered in conventional machines could be extended by the use of bubble clusters (Ata and Jameson, 2005). However, little is known about the effect of the turbulent shear in the flotation cell, as reflected in the power input or the impeller rotational speed, on the structure of the clusters, or even if clusters can form in existing equipment where the power input is in the range 0.5 to 5 kW/m³.

In this thesis, the behaviour of bubble clusters in turbulent conditions in flotation cells has been studied both experimentally and theoretically. The breakup and re-formation of clusters and the effect of bubble size and impeller speed on the behaviour of clusters has been investigated. The apparatus used was essentially a laboratory flotation cell, agitated by a Rushton turbine. The cell was modified to allow pre-formed clusters to rise out of a fluidized bed and into the path of the rotating impeller. The events were captured using a digital camera, and the images were analysed to give the sizes of the bubbles and clusters.

In the first part of the investigation, a collector was used but no frother. In these conditions, the bubble diameter was effectively controlled by the collector concentration, and it varied considerably. It was found that the sizes of clusters decreases with increasing shear rate at low impeller speeds, and at higher speeds the clusters are broken up into bubbles and particles and then re-form into clusters through collision. At even higher speeds the bubbles themselves are broken up into smaller bubbles that then re-form into small clusters.

In the second part, frother was used at a concentration above the critical coalescence concentration, to control the bubble size, which remained essentially constant at this concentration. The bubbles were too small to be broken by the action of the impeller, so they always remained at the same size. In this case it was found that when the impeller speed was increased, two stages of formation were observed, the fragmentation and equilibrium stages. In the fragmentation stage, at low impeller

speeds, the clusters were loose and filamentous, and as the energy input increases, they rupture and re-form. In the second stage, above a critical impeller speed, dense clusters formed whose size was relatively insensitive to the energy input.

The cluster behaviour was modelled, based on concepts drawn from the related fields of floc breakup and bubble breakup. The clusters were modelled on the assumption that the bubbles were bridged by particles, so the cohesive strength was determined by the capillary force between the bubbles and the particles. Two different theories were investigated for the disruptive force from the turbulent liquid: the shear rate hypothesis of Camp and Stein (1943), and the turbulent fluctuation model arising from Kolmogorov's theory of isotropic turbulence (Kolmogorov, 1941). It was found that neither method is applicable in the fragmentation stage. However, in the equilibrium stage, an equation derived from Camp and Stein's theory was more realistic than that obtained using Kolmogorov's equation.

The results showed that in industrial flotation cells, where the power input is typically in the range 0.5 to 5 kW/m³, clusters that form will be in the equilibrium stage, and their sizes will range from 500 µm to 1 mm.

Table of contents

Acknowledgements.....	ii
Abstract.....	iii
Table of Contents.....	v
List of Figures.....	viii
List of Tables.....	xii
Nomenclature.....	xiii
Chapter 1 Introduction.....	1
1.1 Background.....	1
1.2 Objectives of the study.....	5
1.3 Outline of the thesis.....	5
Chapter 2 Literature review.....	7
2.1 Introduction.....	7
2.2 Previous studies on bubble clusters.....	7
2.3 The behaviour of droplets in turbulent flow.....	13
2.3.1 The importance of bubble size in flotation.....	13
2.3.2 Measurement of bubble size.....	14
2.3.2.1 Fiber optic probe method.....	14
2.3.2.2 Drift flux analysis.....	14
2.3.2.3 Capillary method.....	16
2.3.2.4 Photographic method.....	17
2.3.3 Bubble breakup in turbulent flow.....	18
2.4 The behavior of flocs in turbulent flow.....	24

2.4.1 Methods for measurement of floc size and shape	24
2.4.1.1 Microscopic methods	25
2.4.1.2 Light scattering	25
2.4.1.3 Photometric dispersion analyzer	26
2.4.1.4 Focused beam reflectance measurement	27
2.4.1.5 Photography and image analysis	27
2.4.2 Floc strength	28
2.4.2.1 Floc strength factor	28
2.4.2.2 Floc strength modeling based on floc size and shear rate	30
2.4.2.3 Ultrasound	44
2.4.2.4 Oscillating multigrid mixer	45
2.4.2.5 Micromechanical floc strength measurement	46
2.4.2.6 Micromanipulation	48
2.5 Particle-bubble detachment in turbulent flow	50
2.6 Summary and conclusions	64
Chapter 3 Experimental	67
3.1 Apparatus	67
3.2 Material	71
3.3 Experimental procedure	72
3.4 Data analysis	73
Chapter 4 Experimental observations of cluster behaviour	76
4.1 Introduction	76
4.2 General observations on cluster formation	76
4.3 Cluster behaviour in turbulent conditions	78
4.3.1 Effect of turbulence on the cluster size	79

4.3.2 Cluster size distributions.....	82
4.3.3 Cluster strength.....	86
4.3.4 Shapes of clusters.....	90
4.4 Breakup and re-formation of bubble clusters.....	92
4.5 The effect of bubble size on the behaviour of bubble clusters.....	99
Chapter 5 New theory for breakup of bubble clusters.....	110
5.1 Introduction.....	110
5.2 Theory.....	110
5.3 Verification of the theory.....	113
5.3.1 Bubble clusters in the fragmentation stage.....	113
5.3.2 Bubble clusters in the equilibrium stage.....	116
5.4 Sensitivity analysis	119
5.5 Conclusions	123
Chapter 6 Conclusions.....	125
6.1 Summary of conclusions.....	125
6.2 Contributions of this work.....	129
6.3 Recommendations for further work.....	130
List of References.....	131
Appendix.....	140

List of Figures

Figure 1.1. The recovery of sulfide mineral particles after 1 minute of flotation in a batch cell (Jowett, 1980).	2
Figure 2.1. Bubble-particle aggregates consisting of several bubbles and particles (Schulze, 1984).	8
Figure 2.2. Photographs of bubbles and bubble clusters in cell 2 and cell 3 of a bank of four continuous cells (Jameson and Allum, 1984).	9
Figure 2.3. Schematic diagram of the apparatus used for the observation of bubble clusters in a flotation cell (Ata and Jameson, 2005).	10
Figure 2.4. The fraction of bubbles involved in clusters, and contact angle of quartz with increasing collector dosage (Ata and Jameson, 2005).	11
Figure 2.5. Steps of the formation of bubble clusters (Ata and Jameson, 2005).	12
Figure 2.6. Schematic diagram of capillary bubble sizing method (Randall et al., 1989).	16
Figure 2.7. Schematic of photographic method for bubble sizing (Hernandez-Aguilar et al., 2004).	17
Figure 2.8. Basic types of globules deformation (Hinze, 1955).	19
Figure 2.9. flow patterns that can cause globule deformations (Hinze, 1955).	20
Figure 2.10. The schematic working mechanism of light scattering instruments (Gregory, 2009).	26
Figure 2.11. the schematic arrangement of the first PDA device (Gregory, 1985).	27
Figure 2.12. Three types of change in floc size as a function of increasing shear rate (Jarvis et al., 2005).	41
Figure 2.13. Schematic procedure of micromechanical floc strength method (Jarvis et al., 2005).	47

Figure 2.14. A schematic overview of the micromanipulation floc strength technique (Zhang et al., 1999).	49
Figure 2.15. Schematic of the cross section of a cylindrical particle at a liquid-liquid interface (Princen, 1969).	50
Figure 2.16. The value of $c_{23}R^2$ as a function of ϕ_c for $\theta = 180^\circ$ and D larger than 1. (Princen, 1969).	52
Figure 2.17. Schematic of the cross section of a prismatic particle at a liquid-liquid interface (Princen, 1969).	53
Figure 2.18. The curves of $c_{23}s^2$ versus ϕ_c for different values of D (Princen, 1969).	54
Figure 2.19. The relationship between $c_{23}R^2$ and ϕ_c for a narrow range of D and $\theta = 180^\circ$ (Princen, 1969).	55
Figure 2.20. The critical values of $c_{23}R^2$ and the corresponding values of ϕ_c for both spheres and cylinders (Princen, 1969).	56
Figure 2.21. The schematic illustration of a spherical particle attached to a bubble (Schulze, 1977).	56
Figure 2.22. The upper size limit of spherical particles for a fixed solid density and a given value σ at various contact angles (Schulze, 1984).	59
Figure 2.23. The adhesive force as a function of central angle (Nguyen 2003).	62
Figure 3.1. Schematic of equipment for formation and observation of clusters.	68
Figure 3.2. Diagrammatic sketch of the experimental apparatus with dimensions (mm).	69
Figure 3.3. Sketch of the agitated vessel, showing the location of the point at which clusters enter the vessel.	70
Figure 3.4. Sketch of viewing cell used for bubble clusters observation at high impeller speed.	71
Figure 4.1. Some examples of bubble clusters formed in the fluidized bed.	78

Figure 4.2. The mean equivalent diameter of clusters as a function of impeller speed at various DDA concentrations.	79
Figure 4.3. Images of bubble clusters and bubbles formed at DDA concentrations of 5×10^{-5} M and various impeller speeds: (a) 0; (b) 43; (c) 149; (d) 257; (e) 377; (f) 478 rpm.	81
Figure 4.4. Size distribution of bubble clusters at the DDA concentration of (a) 1×10^{-5} M; (b) 5×10^{-5} M; and (c) 9×10^{-5} M at the impeller speeds shown. Note different x-axis scales.	83
Figure 4.5. Cumulative size distribution of bubble clusters formed at DDA concentrations of (a) 1×10^{-5} M; (b) 5×10^{-5} M; and (c) 9×10^{-5} M at different impeller speeds. Note different x-axis scales.	85
Figure 4.6. Cluster equivalent diameter vs. average velocity gradient at DDA concentrations of 1×10^{-5} , 5×10^{-5} and 9×10^{-5} M.	87
Figure 4.7. The dependence of shape factor on different impeller speed at DDA concentrations of 1×10^{-5} , 5×10^{-5} and 9×10^{-5} M.	91
Figure 4.8. Images of bubbles in the absence of particles at impeller speeds of (a) 0 rpm, (b) 1800 rpm at various DDA concentrations.	93
Figure 4.9. Images of bubble clusters formed with particles at impeller speeds of (a) 800 rpm, and (b) 1400 rpm, at the collector concentrations shown.	94
Figure 4.10. The cumulative frequency of clusters at various dodecylamine concentrations at a rotational speed of 1400 rpm, and of bubbles at various impeller speeds at a DDA concentration of 9×10^{-5} M.	95
Figure 4.11. The cluster size and bubble size at impeller speeds of (a) 800, (b) 1400 and (c) 1800 rpm as a function of DDA concentration.	96
Figure 4.12. Mean diameter of bubbles as a function of DDA concentrations at various impeller speeds.	97
Figure 4.13. The cluster size as a function of impeller speed in the absence of frother, at various DDA concentrations.	100
Figure 4.14. The effect of impeller speed on the size of clusters with MIBC at a concentration of 80 ppm at various DDA concentrations as indicated in the legend.	100

Figure 4.15. The effect of dodecylamine concentration on bubble size. The impeller speed is zero.	102
Figure 4.16. The bubble size as a function of MIBC concentrations at various DDA concentrations. The impeller speed is zero.	103
Figure 4.17. Effect of impeller speed on the bubble diameter in the presence of MIBC at concentration of 80 ppm.	104
Figure 4.18. Illustrative graph showing the presence of critical impeller speeds at different DDA concentrations.	106
Figure 4.19. The mean diameter of clusters as a function of impeller speeds at various DDA concentrations in the absence of frother. A combination of Figures 4.2 and 4.12.	107
Figure 5.1. The average diameters of bubble clusters in the fragmentation stage versus $r_l e / (R_p S \sin^2(q/2)n)$, from the theory using Camp and Stein's velocity gradient, Equation [5-7].	115
Figure 5.2. The average diameters of bubble clusters in the fragmentation stage versus $\rho_l^{1.5} \varepsilon / (R_p^{1.5} \sigma^{1.5} \sin^3(\theta/2))$, using the Kolmogorov approach, Equation [5-8].	116
Figure 5.3. The relationship between average diameter of clusters in the equilibrium stage and $r_l e / (R_p S \sin^2(q/2)n)$ at high impeller speeds, using Camp and Stein's velocity gradient, Equation [5-7]	117
Figure 5.4. The relationship between average diameter of clusters in the equilibrium stage and $\rho_l^{1.5} \varepsilon / (R_p^{1.5} \sigma^{1.5} \sin^3(\theta/2))$, using the Kolmogorov formulation, Equation [5-8].	118
Figure 5.5. Effect of particle size on the behaviour of clusters ($\theta = 50^\circ$, $\sigma = 0.06$ N/m).	120
Figure 5.6. Effect of contact angle on the behaviour of clusters ($R_p = 100$ μm , $\sigma = 0.06$ N/m).	122
Figure 5.7. Effect of surface tension on the behaviour of clusters ($R_p = 100$ μm , $\theta = 50^\circ$).	122

List of Tables

Table 2.1. The value of the floc strength co-efficient and stable floc size exponent obtained from various researchers.	42
Table 2.2. Floc breakup exponents (Parker et al., 1971).	44
Table 3.1. The number of samples required for various expected errors.	75
Table 3.2 The number of samples counted in the experiments and associated standard deviation and error.	75
Table 4.1. The power consumption, Reynolds number and the energy dissipation rate at the impeller speeds used in the thesis. Impeller diameter $D = 0.05$ m; power number of the Rushton impeller $N_p = 5.5$; volume of tank $V = 0.006$ m ³	86
Table 4.2. Cluster strength factor for different DDA concentrations at various impeller speeds.	88
Table 5.1. The surface tension and contact angle of particles at various DDA concentrations.	113
Table 5.2. Energy dissipation at various impeller speeds.	113

Nomenclature

a	capillary length, m., Equation [2-98].
A	the projected area of cluster, m^2 .
A_f	the cross section area of a floc, m^2 , Equation [2-44].
A_n	the net sectional area at the plane of rupture of a floc, m^2 , Equation [2-49].
A^*	a coefficient reflecting the packing of the solids in the floc, Equation [2-75].
$\bar{b}_m$	machine acceleration, $m \cdot s^{-2}$, Equation [1-1].
Bo	the Bond number, Equation [2-107].
c	a numerical constant.
C	a constant, Equation [2-17]. floc strength co-efficient, Equation [2-30].
C_1, C_2, C_3, C_4	constants.
$d(1), d(2)$	stable average floc sizes before and after breakage, m, Equation [2-29].
d	the diameter of a floc, m, Equation [2-30].
d_b	the diameter of a bubble, m., Equation [1-2].
d_c	the diameter of a column, m., Equation [2-4]. the diameter of a cluster, m., Equation [5-3].
d_{max}	the maximum stable diameter, m., Equation [2-19].
d_o	the diameter of primary particles in a floc, m., Equation [2-75].
d_p	the diameter of a particle, m., Equation [1-1]
D	the diameter of impeller, m, Equation [2-32], fractal dimension Equation [2-75].
e	the porosity of the floc, (-) Equation [2-52].
E_k	dynamic energy, J., Equation [2-20].
E_s	surface energy, J., Equation [2-21].
f	characteristic frequency of turbulence, Equation [2-28].
f_d	the dynamic force per unit area of a floc, Equation [2-57].
g	acceleration of gravity, $m \cdot s^{-2}$.
g_{floc}	a floc geometry constant, Equation [2-46].
h	vertical distance from centre of a particle to a fluid interface, m., Figure 2.21.
G	the average velocity gradient, s^{-1} . Equation [2-30].
j	the time of ultrasonication, s., Equation [2-81].

J_g	superficial gas velocity, $m \cdot s^{-1}$. Equation [2-9].
k	the number of bonds that are broken in a floc, Equation [2-68]. a proportionality constant, Equation [2-81].
k_f	the turbulent friction factor, 9-0, Equation [2-35].
k, k^*, K, K^*	constants, Equation [2-62] – [2.65].
K_p	a constant, Equation [2-51].
l	distance between two points in a turbulent flow, m., Equation [2-46].
L	capillary length, m., Equation [2-112].
m	a parameter, Equation [2-4], Equation [2-5].
n	the order of the surface harmonic, Equation [2-26], the number of samples to be measured, Equation [3-2].
N	the impeller speed, rps., Equation [2-32].
N_c	the number of contacts broken in a cluster, 9-0, Equation [5-7].
N_{Vi}	a viscosity group, Equation [2-16].
P	the perimeter of a cluster, m.
P_0	the impeller power number, 9-0, Equation [2-32].
Q, q	fitting coefficients, (-), Equation [2-71].
r	the radius of a bubble, m., Equation [2-26]. a coefficient, (-), Equation [2-77].
r_o	radius of three-phase line, m, Figure 2.21.
R	the radius of a cylinder, m., Equation [2-83].
R_B	the radius of a bubble, m., Equation [2-96].
R_c	the radius of a cluster, m., Equation [5-2].
R_p	the radius of a particle, m., Equation [2-91].
Re	Reynolds number, (-) Equation [2-4].
Re_b	bubble Reynolds number, Equation [2-1]
S	maximum velocity gradient in a continuous flow, Equation [2-10]. the cross sectional area of the floc, m^2 ., Equation [2-33].
S_b	bubble surface area flux, $m^2 \cdot s^{-1}$.
T	the tenacity of particle attachment, $N \cdot m \cdot s^{-2}$., Equation [2-110].
u_p	the particle velocity, $m \cdot s^{-1}$., Equation [2-33].
u	the fluid velocity in the region of the particle, $m \cdot s^{-1}$., Equation [2-33].
u_{rel}	the relative velocity between fluid and particle, $m \cdot s^{-1}$., Equation [2-33].
$\overline{u^2}$	mean-square turbulent velocity fluctuation, $m^2 \cdot s^{-2}$., Equation [2-11].
U_{bs}	the velocity of the gas relative to the liquid, $m \cdot s^{-1}$., Equation [2-1].

U_t	terminal velocity of a bubble, $\text{m}\cdot\text{s}^{-1}$, Equation [2-7].
v_K	the Kolmogorov velocity scale, $\text{m}\cdot\text{s}^{-1}$, Equation [2-69].
V_t	the velocity of particle, $\text{m}\cdot\text{s}^{-1}$, Equation [2-100].
V	the volume of stirred vessel, m^3 , Equation [2-32], particle volume, m^3 , Equation [2-33], floc volume, m^3 , Equation [2-52].
We	Weber number, (-), Equation [2-10].
z_o	the depth of meniscus for a particle floating on an interface, m., Equation [2-83].

Greek letters

α	a constant (-), Equation [2-51]. central angle, equal to ϕ_c , Figure 2.15.
β	a constant, (-), Equation [2-34].
γ	the stable floc size exponent, (-), Equation [2-30]. surface tension, $\text{N}\cdot\text{m}^{-1}$, Equation [2-82].
δ	a constant (-), Equation [2-40]. binding strength, $\text{N}\cdot\text{m}$, Equation [2-81].
$\Delta\rho$	density difference between particle and liquid, $\text{kg}\cdot\text{m}^{-3}$, Equation [1-1].
$\varepsilon, \varepsilon_o$	energy dissipation rate, $\text{N}\cdot\text{m}\cdot\text{s}^{-1}\cdot\text{kg}^{-1}$ or $\text{W}\cdot\text{kg}^{-1}$, Equations [1-2], [2-58].
ε_g	fractional gas holdup (-), Equation [2-9].
ε_L	fractional liquid holdup (-). Equation [2-2].
η	Kolmogorov microscale, m., Equation [2-12].
θ	contact angle, degrees, Equation [1-1].
λ	the length scale of the eddy, m., Equation [2-34].
μ, μ_L	viscosity of fluid, $\text{N}\cdot\text{s}\cdot\text{m}^{-2}$, Equations [2-39], [2-1].
μ_d	viscosity of disperse phase, $\text{N}\cdot\text{s}\cdot\text{m}^{-2}$, Equation [2-16].
ν	kinematic viscosity, $\text{m}^2\cdot\text{s}^{-1}$, Equation [2-14].
ν_c	kinematic viscosity of continuous phase, $\text{m}^2\cdot\text{s}^{-1}$, Equation [2-13].
ν_d	kinematic viscosity of disperse phase, $\text{m}^2\cdot\text{s}^{-1}$, Equation [2-13].
ρ	density of fluid, $\text{kg}\cdot\text{m}^{-3}$, Equation [2-33].
ρ_L	density of fluid, $\text{kg}\cdot\text{m}^{-3}$, Equation [1-3].
ρ_{Fl}	density of fluid, $\text{kg}\cdot\text{m}^{-3}$, Equation [2-92].

r_1, r_2, r_3	density of phases, $\text{kg}\cdot\text{m}^{-3}$., Equation [2-83].
r_d	density of disperse phase, $\text{kg}\cdot\text{m}^{-3}$, Equation [2-16].
r_e	floc effective density, $\text{kg}\cdot\text{m}^{-3}$, Equation [2-51].
r_f	density of floc, $\text{kg}\cdot\text{m}^{-3}$, Equation [2-51].
r_g	density of gas, $\text{kg}\cdot\text{m}^{-3}$., Equation [2-23].
r_0	density of primary particle in a floc, $\text{kg}\cdot\text{m}^{-3}$., Equation [2-52].
r_p	density of particle, $\text{kg}\cdot\text{m}^{-3}$., Equation [1-1].
r_{susp}	density of suspension, $\text{kg}\cdot\text{m}^{-3}$., Equation [2-1].
r_w	density of water, $\text{kg}\cdot\text{m}^{-3}$., Equation [2-51].
S	surface tension, $\text{N}\cdot\text{m}^{-1}$, Equation [1-1]. binding strength per unit area of a floc, $\text{N}\cdot\text{m}^{-2}$., Equation [2-49]. standard deviation, mm., Equation [3-1].
S_y	tensile strength of a floc, $\text{N}\cdot\text{m}^{-2}$., Equation [2-44].
t	disrupting stress at the surface of a globule, $\text{N}\cdot\text{m}^{-2}$., Equation [2-15].
τ_y	the shear strength of the surface layer, $\text{N}\cdot\text{m}^{-2}$., Equation [2-36].
f	power of ultrasonic field per unit volume of floc, $\text{W}\cdot\text{m}^{-3}$., Equation [2-81], energy per bond during rupture process, J., Equation [2-68].
ϕ_c	central angle, degrees, Figure 2.15.
W	shear rate, s^{-1} ., Equation [2-24]. $180^\circ - \phi_c$, Figure 2.21.