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Dynamics of bubble-particle interaction in different flotation processes and applications - a review of recent studies

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Abstract: Flotation process involves aggregation of the particles based on the material/compound type of random mixtures such as ores and seawater. It is primarily used in pretreatment of water desalination and other industrial applications. The process makes use of various fluid mechanics principles as multi-fluids are involved. The multi-fluids in most of the flotation processes are of different phases, such as air and water. Like any other process, the efficiency of flotation is important, and hence most of the studies have been dedicated to understanding how the various parameters are affecting the flotation process. Among various parameters, fluids properties and flow parameters chiefly affect the flotation process. In particular, the bubble-particle interaction of the flotation process has been of interest as it is one of the cost-effective ways to enhance flotation efficiency. In this review, the authors present the latest developments in such parametric studies. This paper could be of interest to research students, academic researchers, and practitioners who want to contribute to (or take from) flotation research.

Keywords: flotation, bubble-particle interaction, bubble dynamics, multiphase flow, fluid interface

1. Introduction

Flotation is a widely used separation method used for wastewater treatment, mineral beneficiation and processing, plastic recycling, and desalination. The essence of the flotation process depends on using the gas bubbles to capture the particles based on their surface hydrophobicity and hydrophilicity. In this technique, components like fine particles, oil droplets, gang minerals etc. are separated from the mixture based on their hydrophobic or hydrophilic properties. The gas bubbles are produced in flotation columns in the size range of 0.5 mm in diameter. The bubbles are then used to adhere the hydrophobic particles selectively and carry them to the surface of the liquid, hence they form a froth zone where it can be separated while the hydrophilic (water-adherent) particles are discharged from the bottom outlet. The efficiency of the flotation process is a function of the probability of collision, attachment, and detachment between bubbles and particles. Froth flotation is an extensively accepted separation method where the separation characteristics depend on narrow particle size range between approximately 10 to 100 μm.

Beyond this particle size range, the separation efficiency of flotation process reduces notably because of difficulty to attachment of weak hydrophobic particles to gas bubbles. Very fine particles may float with smaller size bubbles and fine or mid-sized particles with the bigger size bubbles. Fine particles experience a slow separation rate due to their large surface area and lower mass. This phenomenon is observed due to reduced bubble-particle collision. But in the case of coarse particles there is problem of bubble-particle detachment. The contact angle has a significant effect on the composition of recovery from the flotation process and hence can considerably affect flotation efficiency. On the other hand, several studies have been reported on the flotation cell which has generally simple arrangement and small scale size however can considerably affect the flotation efficiency.

In this paper, d_{32} has been taken as standard to measure or compare bubble sizes against the usual d_{10}. d_{32} is known as Sauter mean bubble diameter, while d_{10} is arithmetic mean diameter. Most of the

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reviewed papers discussing bubble diameter have used Sauter mean bubble diameter as the reference. The Sauter mean bubble diameter is defined as the diameter of a sphere that has the same volume/surface area ratio as a particle of interest. In fluid dynamics, Sauter mean diameter is an average of particle size.

Understanding the different flow regimes and its transition characteristics is necessary to analyze a flotation process. The factors which affect the flow regime depends upon the geometric variables (diameter, length, sparger pore diameter, particle size, and cross-sectional area) of the column, dynamic variables (flow rate of flowing fluids), and physical properties (density, viscosity, and surface tension) of the flowing fluid. Column dimensions and sparger design are an integral part of flotation columns, which provide improved separation performance. The transition of flow regime depends on the column dimension, sparger design, and physical property of the system. The physical properties of the flotation system refer to the features related to bubble, particle, and wetting films. Many industries are facing acute problems due to the complex flow behavior of gas-liquid or gas-liquid-solid in a multiphase system. Besides, most of the industries make use of various fluids essentially non-Newtonian in nature, thus flow regime, and its transition characteristics are required to improve the efficiency of flotation. The bubbles are assumed to be spherical in most of the flotation system analysis, and the bubble dynamics considerably depend on the flow regime. The change in flow regime affects several critical design parameters of flotation.

There has been a lot of study with regard to effect of bubble size and distribution on flotation process. Interfacial area available for the particle adhesion characterizes the separation efficiency of the system, which helps in the design and scale-up of the flotation column. The interfacial area directly affects the flotation rate constant. The interfacial area in the flotation column depends on the bubble size, gas holdup, superficial gas velocity, gas distributor design, properties of phases, and column geometry. Smaller bubbles coalesce to form a larger bubble, the interfacial area for the collision of bubble-particle reduces, which causes a reduction in attachment probability of particle on the bubble; hence flotation efficiency decreases.

Above all, it is very important to understand the bubble-particle collision process as it can considerably affect the flotation efficiency. The relative motion of particles and gas bubbles governs the probability of the bubble-particle attachment, bubble loading, and flotation rate. Countercurrent movement of feed and gas bubbles is the movement of the said things opposite to the direction of the flow of slurry into the flotation to retain more slurry and results in the reduction of the rising velocity of the bubbles, which increases their retention time in the slurry. Hence it decreases the compressed air requirement and increases the specific throughput of the column. In the countercurrent operation, the probability of bubble-particle collision is high because of the sizeable aerated mixture in the column, the long-distance of the transport of the bubble and particle along the column length and low longitudinal slurry mixing.

In this review paper, the authors present various studies that have been reported in the last two decades on the fluid flow issues as observed in different flotation conditions. In addition, the effect of bubble size distribution, superficial gas velocity, surfactant concentrating and three different particle sizes such as coarse (100 μm) and fine (15 μm) on the flotation characteristics have been discussed. The authors also discuss details of additional factors affecting flotation, the applications of flotation and effect of nano scale bubble and particles on bubble size in flotation. A flow chart briefing the topics that are discussed in the present review is given in Fig. 1.

2. Discussion on recent studies of flotation and its applications

Different methods of flotation processes based on the working principles in relevance to the present paper are as follows:

1. Electroflotation: The electroflotation method is used to separate ions or solid particles, dissolved or suspended in the liquid phase, by attaching them on the bubble surface produced on the electrode and which moves upward in the flotation column. In electroflotation method, when liquid waste is exposed between cathode and anode and energy supplied, an electric field is produced between the electrodes which causes the generation of hydrogen and oxygen bubbles on cathode and anode

electrode respectively. The bubble size produced by this method is in the range of 13-80 µm (Ren et al., 2019).

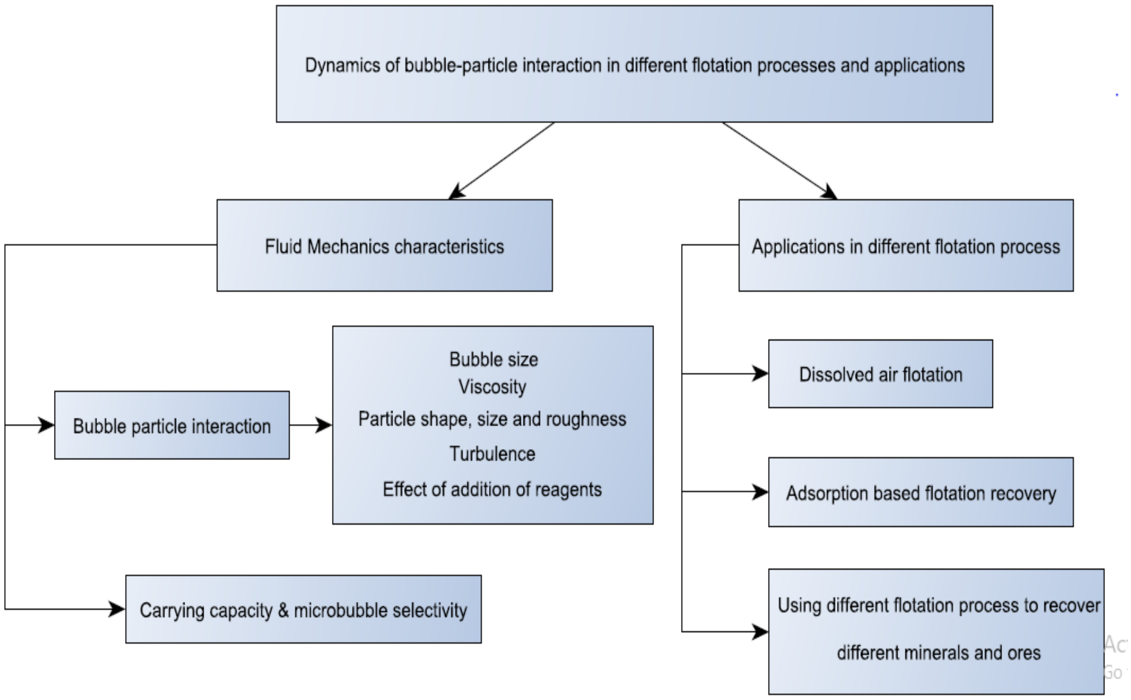

Fig. 1. Flow chart giving the details of topics discussed in the present review

1. Dispersed Air flotation: This method operates by dispersing the gas bubbles into the liquid. The bubble size range is 700-1500 µm. High speed rotating diffuser causes mechanical mixing of liquid and gas, producing bubbles which are transported directly into the flotation column. It is widely used in refinery, petrochemical plants to treat wastewater from oil.
2. Dissolved Air flotation (DAF): In this method, the air is pressurised to dissolve and create a saturated water solution which is passed through a pressure reducing mechanism to generate microbubbles. This microbubbles size falls in the range of 20-100 µm. It is widely used to separate water impurities like droplets, particles in the size range of 10 – 100 µm.
3. Ion flotation: This method uses suitable surfactant to float the oppositely charged ions by introducing charged gas microbubbles in the aqueous solution which leads to the separation of metal ions. The bubbles are charged using surfactants. Also, the pH of the solution has a significant effect on the separation efficiency. Ion flotation method used for groundwater shows that contamination level of 5mg/dm^3 of a heavy metal was reduced to about 0.01mg/ dm^3.
4. Froth flotation: Froth flotation is one of the most widely used operational cycles for mineral extraction. In ore/mineral extraction, froth flotation is a strategy by which economically significant minerals are isolated from impurities and different minerals by accumulating them on the surface of the froth layer. In this method, different minerals are selectively separated by mineral processing. Such minerals containing numerous metals, for example, lead, copper, and zinc can be selectively separated by utilizing froth floatation. This process starts with the step of reducing the mineral ore into minute particles. these fine powdered sized particles are then mixed with water and the so-formed mixture is called Slurry. The collector is added to the slurry which acts as a surfactant chemical. The principle behind adding collector is to enhance the hydrophobic nature of the desired mineral. This slurry gets converted to pulp. The container is then filled with this pulp along with the water. Further, air jets are forced into to produce bubbles. Since the mineral's hydrophobic properties are already enhanced, these desired minerals get repelled by water and thus gets attached to the air bubbles. As low in density, these air bubbles rise up to the surface along with the mineral particles attached to it, forming froth. This mineralised froth is then separated and further collected to be used in the next process of refining and extraction.

In this review, the authors have discussed the fluid dynamics issues in these flotation methods under different conditions as studied and reported by various researchers worldwide. The methods proposed above are discussed in this paper along with their applications (past 2 years).

2.1. Influence of bubble-particle interaction, particle characteristics, hydrophobicity and turbulence on flotation

2.1.1. Bubble-particle interaction

The bubble-particle interaction is a fundamental mechanism affecting the flotation process. The collision of the particles with the bubbles is a necessary step for the bubble-particle attachment. Brabcova et al. (2015) has studied the interaction between a stationary bubble and particles moving along the fluid flow. The particles whose initial starting position was far away from the axis of symmetry of the bubble simply deviate across the bubble following the fluid flow. The particles that are in close proximity to the bubble slide across the bubble surface then withdraw due to the gravitational force and buoyancy force. The gravitational and inertial forces have negligible effect on the particle trajectory due to similar fluid and particle density but surface forces are dominant.

The microhydrodynamic forces are active at short inter separation distances, and these forces push the particle away from the bubble. Hydrodynamics strongly depend on bubble-particle sizes and turbulence of the system (Yoon, 2000; Shahbazi et al., 2010). In contrast, the particles are pushed closer to the bubble by the fluid flow. Thus, due to the opposing effects these forces the sliding particle accelerates as it approaches the centre of the bubble and decelerates after crossing it. The particles that simply deviate across the bubble without sliding are found to follow a vertical trajectory under the influence of gravitational force. The particle trajectory determines the collision efficiency (Brabcova et al., 2015) probability (Yoon, 2000; Shahbazi et al., 2010) by the interceptional mechanism. It is found out by the Kernel functions calculated from Navier-Stokes equation and Stokes flow condition which are integral to find out collision probability which are only valid for fine and coarse particles and not for intermediate particle ranges under relatively quiescent conditions (Yoon, 2000; Shahbazi et al., 2010).

Li et al. (2020) studied the attachment of fine and coarse particles with the bubbles. The study involves the interaction of particles with bubble in three different scenarios. The particle interacts with a stationary bubble in a stationary fluid. The interaction of a stationary bubble with particles flowing in liquid. The particle interaction with a rising air bubble. The bubble-particle attachment occurs when the contact time between the particles exceeds the induction time. The contact time is defined as the sliding time for fine particles and bouncing time for the coarse particles. Bouncing time refers to the time taken by the coarse particles to deform the bubble and bounce off it. During the collision of the rising bubble with the particle some particles bounce off vertically after interaction. This is attributed to the elliptical shape of the rising bubble and adhesion/attachment probability. The stream functions derived from collision probability make it possible to predict the adhesion chances between bubble and particle. However, it was observed during the process that the sliding time of particle on bubble was longer than induction time, in this way particle has longer contact time to rupture the disjoining film between them by thinning it (Yoon, 2000; Shahbazi et al., 2010).

In the other configurations normal sliding and bouncing behavior was observed. The bubble-particle attachment occurs when particle makes 90^{o} with the bubble vertical axis this angle is also referred as polar angle. For polar angle of 90^{o} the contact time exceeds the induction time causing bubble-particle attachment. The bubble-particle attachment at 90^{o} was observed only for the stationary bubble and fluid. For the cases involving stationary bubble in a fluid flow and rising bubble the particles were swept off even before attaining 90^{o}. This was attributed to the fluid velocity in case of stationary bubbles in fluid flow. The elliptical shape of the rising bubbles also strengthens the fluid flow along the sides of the bubbles causing particles to get swept off. The interaction of the stationary fluid with particle in fluid field (Brabcova et al., 2015) leads to no bubble-particle attachment in contrast there was a bubble-particle attachment (Li et al., 2020) for the same case. This inconsistency may be attributed to the use of surfactants or due to the spherical shape of the bubbles and particles.

A study of the bubble-particle frequency and collision efficiency for fine and coarse particles has been reported by Darabi et al., (2019). The overall collision efficiency was found to have strong correlation with the individual collision efficiencies due to inertial, gravitational, interceptional, and turbulence mechanism. The bubble-particle frequencies were about 10% to 12% higher in the turbulent region compared to the quiescent region. The bubble-particle frequencies refer to the probability of bubble and particle existing in the same region leading to bubble-particle collisions, greater the bubble-particle frequency greater will be the bubble-particle collisions. The frequency of the bubble-particle collisions increased on increasing the particle size and impeller speed. The collision efficiencies of large particles were mainly affected by the gravitational, interceptional and inertial mechanisms. This was attributed to the large mass of the coarse particles. The effect of inertial forces on the collision efficiencies of fine particles is neglected. The collision efficiencies of fine particles have strong correlation with turbulence. The excess turbulence leads to the effective transport of fine particles and enhances their collision frequencies. The turbulence effects on the collision efficiency of coarse particles are neglected due to their greater mass.

Xu et al., (2011) suggested a model for estimating the detachment force for the coarse bubbles and particles. The vibrational energy produced by loudspeaker along with the gravity was the detachment force. The amplitude at which the particle detached from the bubble was the critical amplitude. For particles of same size, the detachment force showed a strong correlation with the contact angle. The critical amplitude was found to increase with the medium viscosity irrespective of particle size and contact angle. The model suggested was consistent for low frequency (30-50Hz) and low medium viscosity. At high frequencies (90Hz) and high medium viscosities inconsistencies were observed. This was explained by the dynamic contact angle. At high viscosities and frequencies, the dynamic contact angle was greater thus the increasing the detachment force. At low frequencies and viscosities, the dynamic contact angle was low thus the decreasing the detachment force.

It has been experimented and demonstrated that only hydrophobic particles adhere to surface of air bubbles (Yoon, 2000; Shahbazi et al., 2010). This selectivity of flotation process determines adhesion probability while collision probability depends on recovery process. However, both adhesion and detachment depend on surface chemistry of bubbles and particles, inertial forces and turbulence. The probability of a particle being collected by an air bubble in the pulp phase of a flotation cell largely depends on bubble-particle collision and their adhesion and detachment probabilities. Hydrodynamics strongly depend on particle-bubble sizes and turbulence of the system.

While hydrodynamics brings about high recoveries, surface forces determine the selectivity of the flotation process. The Derjaguin, Landau, Vervey, and Overbeek (DLVO) theory demonstrated that surface forces in the medium are responsible for rupture of the wetting films during flotation. DLVO theory helps in the quantitative analysis of aggregation of aqueous scatterings (bubbles and particles in this context). The theory also provides the understanding of force between charged surfaces (for example – bubble/particle surfaces) interacting through a liquid medium. However, hydrophobic forces of the particle cause destabilization of the wetting films. Since electrostatic and dispersion forces acting on bubbles and particles are repulsive in nature, hydrophobic force is the only driving force in rupture process. Their magnitudes increase with increasing contact angle. Thus, flotation recovery increased as a result of increasing hydrophobicity of the particles (Yoon, 2000).

On the other hand, bubble rising velocity and trajectory are among the key parameters that influence the hydrodynamic characteristics in a flotation process. The rise velocity of the bare bubble is more than that of the loaded bubble. The results showed that with the increasing bubble size, the deviation from straight vertical path of the target bubbles increases, and it moves in a zigzag path. Moreover, for given bubble size, the rising bare bubble moves in a zigzag path. In contrast, a loaded bubble moves in a direction close to a straight vertical path. This phenomenon happens because a layer of mineral particles attaches themselves to the bubble surface and prevent considerable deformation in the bubble shape during its rise and thereby keeps bubble in its spherical shape. Furthermore, the weight force exerted by the attached particles on the bubble reduces its zigzag motion since this force puts a constraint on the effect of the factors such as variation of dynamic and hydrostatic pressure over the bubble surface. These results will help to better understand the bubble dynamics and how the loaded bubbles will affect the performance of the flotation process (Eskanlou et al., 2019).

Hubicka et al. (2013) derived the following based on a simple geometric interpretation of the grazing trajectory, the bubble–particle collision efficiency is:

$$E_c = \left(\frac{2x_{o,g}}{D_p+D_b}\right)^2 \approx \frac{1}{k^2} \quad (1)$$

where E_c is a bubble–particle collision efficiency, $x_{o,g}$ is the initial position of the particle, D_p and D_b are diameters of bubbles and particles, and k is the deviation of bubble from its trajectory.

The parameter k characterizes the deviation of the bubble from its trajectory. The deviation is primarily due to the liquid flow around the particle. It mainly depends on particle velocity, bubble size, and mobility of the bubble surface. The collision of a small rising bubble with a larger spherical particle settling through a stagnant liquid is used to determine the collision efficiency. A classical review of various models for the calculation of collision efficiency has been reported in (Dai et al., 2000.

This parameter was measured experimentally. On condition that the frame of reference moves together with the particle and its origin is fixed in the particle's centre, the horizontal position of the bubble centre in its initial position (sufficiently distant from the particle) can be defined as x_o and simultaneously the position of the bubble centre at the collision point can be characterized by its horizontal position, x_{col}. Then parameter k is defined as (Basarova et al., 2014):

$$x_{col} = kx_o \quad (2)$$

In this study the authors confirmed the linear relation both experimentally and theoretically. The formula in equation 1 can be used if the parameter k is independent of x_o; hence, $x_{o,g} = (D_p + D_b)/2k$. In mineral flotation, the collision efficiency is relatively low. De et al. (2007) compared all significant theoretical models to the interception mechanism is known to be the predominant one whereas the influence of the gravity mechanism is insignificant. When small bubbles and large particles interact, the situation is completely different and the probability of collision is high. The parameter k characterizes the bubble deviation from its vertical path caused by the flow around the particle. It primarily depends on the particle velocity, bubble size and mobility of bubble surface. It is important to note that the equations 1 and 2 are valid when particle is bigger than bubble.

Experimental observations of the collision of a rising bubble-particle aggregate with the liquid interface has been reported in (Ireland & Jameson, 2014). A small proportion of bubble kinetic energy is converted into surface energy during the collision with hydrophobic (such as teflon) surfaces rather than with hydrophilic surfaces (Krasowska et al. , 2009). This involves addition of surfactants to enhance particle hydrophobicity. After collision it is predicted that the particles will detach from the bubble. The detachment force being provided by the kinetic energy change (of bubble-particle aggregate) at the liquid interface. The results are found to be inconsistent with the hypothesis provided. The particles are still attached to the bubble after collision. They are simply moved around the bubble surface. This behavior is caused due to the dissipation of kinetic energy before collision. The viscosity of the medium and inertial forces dissipate the kinetic energy. The inertial forces push the particles at the bottom into the bubble during collision. This leads to particles being moved around the bubble and being attached to the bubbles. The bubble hydrodynamics are kept constant during the experiment. The bubble-particle aggregate promotes particle retention rather than detachment (Ireland & Jameson, 2014).

2.1.2. Effect of particle characteristics and hydrophobicity on flotation

Gaudin et al. (2007) had demonstrated that fine particles possessed different flotation properties from larger particles, and the rate of flotation was independent for particle diameter up to 4μm and proportional for particles of dia. from 4 to 20 μm. Reay and Ratcliff (1973), did suggested that there existed two flotation regimes that occured one for particles with a diameter greater than 3μm and another for particles with a diameter of less than several microns(Reay & Ratcliff, 1973). For particles with a diameter less than several microns, they become susceptible to Brownian diffusion and enter a second flotation regime. Chipfunhu et al. (2012) studied the flotation behavior of fine quartz particles (0.2-50μm) and defined the criteria for flotation. The contact angle was found to be the key parameter determining the occurrence of flotation. The flotation was found to occur when the contact angle exceeded a critical value known as the critical contact angle. The critical contact angle has an inverse relationship with the particle size. Coarser particles have a smaller critical contact angle compared to the fine particles. With the increase in hydrophobicity of a particle, the more it tends to attach with a bubble, and thus high contact angle between the particle-bubble and significant increase in flotation is observed.

2.1.2.1. Coarse Particle Behavior

De et al. (2007) found that the amount of maximum size of particles that could be raised by a captive bubble is dependent on particle contact angle (Tao, 2005; Miettinen et al.,2010). This process occurs in the absence of turbulence (when the hydrodynamic and acceleration forces are minimum), with gravity and capillary forces being predominant forces. The results indicate that a higher contact angle is required to raise a larger particle size. The size of the particles that can be raised by a bubble decreases with decreasing bubble diameter. Rising velocity is also necessary, and the size of the particle raised by a bubble decreases when the rising velocity increases.

In Rushton turbine cell, it was revealed that a 1.8 mm bubble could only raise a 3.4 mm quartz (coarse) particle, at a constant rising velocity of 20 μm/s, if the particle advancing water contact angle is at least 80^{o}. And from particle recovery, it found that the critical contact angle is smaller for coarse particles, which creates problems in the detachment process. The detachment process controls the maximum floatable particle size for coarse particles. If the particle kinetic energy exceeds the energy required to detach it from the gas-liquid interface, the particle detaches, defining a dynamic limit for flotation (Miettinen et al., 2010). In coarse particle flotation, the attachment force is dominated by the capillary force when particle size is less than 1 mm; the excess force approaches the capillary force with increasing particle size and exceeds the capillary force at about 5 mm. It is very interesting to point out that the excess force increases with decreasing bubble size, which means that smaller bubbles can be used to reduce coarse particle detachment and increase the flotation limit size of the particles which proves from that flotation recovery of coarse particles can be enhanced using smaller rather than larger bubbles (Yoon, 2000). The probability of detachment (P_d) may be described by following:

$$P_d = \frac{1}{1+\frac{Fat}{Fde}} \tag{3}$$

where Fat represents the total attachment force and Fde the total detachment force. Eq. 3 suggests that $P_d = 0.5$ when $F_a = F_d$; $P_d = 0$ when $F_a >> F_d$; and $P_d = 1$ when $F_a << F_d$. From Eq. 4 as suggested by Tao (2005):

$$\frac{F_{at}}{F_{de}} \approx \frac{3(1-\cos\theta d)\gamma}{g(\rho p * \rho w * (1/2 + 3/4 * \cos(\theta d/2)))} * \frac{1+\frac{D_p}{D_b}}{D_p} \tag{4}$$

where D_p is diameter of the particle and D_b is diameter of the bubble.

From Eq. 4 it is proven that F_{at}/F_{de} decreases and Pd increases with the increasing D_p and increasing D_b. Therefore, coarse particles are more likely to detach from air bubbles and use of small bubbles will increase flotation recovery of coarse particles (Yoon, 2000).

2.1.2.2. Fine particle behavior

The critical contact angle for fine particles is found using a single bubble, bubble swarm (flotation column) experiments. For fine particles, the critical water receding contact angle required for flotation is defined by the energy required to rupture the intervening thin liquid film between bubbles and particles. The flotation response of coarse or fine particles was similar either in a column or in a mechanically agitated cell, for a similar bubble size. Flotation of very large particles (of the order of mm) and very fine particles (with a diameter of the order to 6-10 μm) is possible, provided that they have high contact angles with smaller bubbles enhancing the process (Miettinen et al., 2010). Chipfunhu et al., (2012) also suggested that fine particles need to have high contact angle exceeding the critical contact angle to undergo flotation. The author has also proposed that the aggregation of fine particles increases their size and thus reduces their critical contact angle to achieve easy flotation. The treatment of fine particles with the chemical reagents are also found to increase the contact angle and enhance the flotation process.

When strong hydrophobic particles with a contact angle of 110^{o} were presented to the flotation process, then they readily agglomerated and destabilized the froth zone. They plugged to the column and settled down to the pulp zone without reaching the concentrate (froth) stream due to its heavyweight. In contrast, weak hydrophobic particles with contact angle below 20^{o} had minimal impacts on the froth stability as they detached from the bubble surface before reaching the froth zone and settled down (Sobhy and Tao, 2019). The more significant the value of the contact angle, the more hydrophobic the mineral surface will be (Zhou et al., 2020).

2.1.2.3. Particle shape

Verrelli et al., (2014) presented that one of the critical resistances to attachment which is the hydrodynamic resistance arising as fluids flow between the gap between a bubble and approaching particle during a collision. Aspherical particles experience minimal resistance due to their shape and orientation, and hence require less time for an intervening film to thin out, and then attachment occurs. The shape defines how strong collision efficiencies will be. For angular quartz, the collision frequencies were four times greater than spherical glass particles. But entrained particles were eliminated, and detachment was negligible; hence these differences are due to variation in ease of attachment.

2.1.2.4. Particle roughness

Particles with rough surfaces composed of microscale projections might achieve attachment more easily, if bumps or jags protrude through the gap, so that separation is smaller than it might seem. A three-phase contact is expected to occur on one of the projections. Nanoscale features have a less likely effect on ease of breaching/thinning the interjacent liquid; however, it may affect the expansion of the three-phase contact line in dewetting. An astounding feature of surface roughness is that these may more readily harbor small air bubbles (micro or nanobubbles), which promote attachment by hydrophobic forces. By surface roughness effects on flotation, it was concluded that angular particles have much higher attachment efficiencies than spheres because of ease of rupture of wetting films. However, material properties don't interfere/take part in the process (Verrelli et al., 2014).

Particle shape and its hydrophobicity is discussed based on experiments with mono-sized spherical ballotini and ground ballotini in (Koh et al., 2009). These were treated with trimethychlorosilane by methylation of various degrees to achieve varying degrees of hydrophobicity. In the flotation process, film thinning and liquid drainage is critical to formation of stable bubble-particle attachments and is affected by particle shape and surface hydrophobicity. The flotation rate constants are lower in case of 100% methylation than in most fractions for all cases. For spherical ballotini, the maximum flotation rates were observed between 25% and 50% methylation while it was in range between 10% and 25% methylation, maximum rate was recorded for ground ballotini. The reason for low rates in case of 100% methylation is due to destabilization and aggregate of hydrophobic ballotini. With lower methylation degree, the aggregation was less and the ballotini floated more easily.

Taking the case of particle surface properties, in flotation, particles possessing higher elongation and flatness properties were recovered better during flotation, while roundness and relative width had negative effect on the flotation behavior of the particles. The wettability was also reported to decrease with the increase in surface roughness of the particles. Apart from this, the roughness in the case of hydrophobic surfaces considerably affects the bubble-particle attachement (Kosior et al., 2018; Kosior et al., 2013). Zero contact angle was recorded for hydrophilic silica surfaces without methylation for all shapes and sizes. However, hydrophobic silica surfaces with 100% methylation contact angle is 90°.
With very hydrophobic ballotini, froth destabilization and aggregation occurred with particles forming clusters, which were harder to recover from the poor froth layer, resulting in lower flotation rates at 100% methylation. Ground ballotini generally has higher flotation rates than spherical ballotini; the result is consistent with effects resulting from a faster rate of film thinning and rupture at rough surfaces. From contact angle measurements, the ground particles appeared more hydrophobic at low surface coverage (below 35%), but the opposite trend was observed at high surface coverage.

2.1.3. Effect of turbulence and addition of reagent on bubble growth

Tabosa et al., (2016) studied the effects of the cell hydrodynamics on the flotation rate and flotation recovery. For the same speed an impeller with a larger diameter provided better flotation rate compared to a relatively smaller one. This is attributed to the turbulence caused by the increased energy dissipation in an oversized impeller. The turbulence enhances the bubble-particle collision frequency. A contrast to this behaviour is observed on enhancing the impeller tip speed. The energy dissipation is high in this scenario but it does not translate to higher flotation rate irrespective of cell aspect ratio. The proportion of turbulence in the cell affects the flotation performance. The low cell aspect ratio cells have a higher flotation rate due to greater proportion of turbulence in the cell. An excess of turbulence reduces the floatation recovery due to destruction of bubble-particle aggregates. At a low cell aspect ratio and low impeller speed maximum recovery which is 10% greater than usual is obtained. The height of the cell had no effect on the flotation performance. The manufacturing costs can be minimized by reduction of cell height. The turbulence is found to affect the bubble size in a mechanical flotation cell. Amini et al., have used the concept of turbulence kinetic energy to explain this behavior (Amini et al., 2013). The bubble size is found to decrease with the increase in the turbulent kinetic energy in a laboratory flotation cell. The bubble size decrement is observed only up to a certain turbulent kinetic energy. Once the turbulent kinetic energy exceeds this critical value it has no effect on the bubble size. The effect of turbulent kinetic energy on bubble size in the industrial flotation cells are insignificant. The industrial flotation cells operate at high speeds thus their turbulence kinetic energy exceeds the critical value. The critical turbulent kinetic energy is found to be $0.18 m^2/s^2$. The dimensionless parameters like Reynolds number, Froude number, and Weber number are affected by cell hydrodynamics. Shahbazi et al., (2015) has determined the optimum values of the mentioned dimensionless parameters for best flotation performance. For ($Re<73500$ and $Fr<1.61$) due to low turbulence there was a decrease in the flotation rate constant. At high values of dimensionless parameters ($Re>98000$ and $Fr>2.85$) the turbulence was extremely high. This led to a decrease in flotation rate constant. At high Weber number ($We>1854$), there was no recovery due to lack of froth layer generation. The maximum flotation rate constant was observed at $Re = 89800$, $Fr = 2.4$, and $We = 1558$.

The bubble size distribution is usually represented by the Sauter mean diameter. The gas hold-up represents the bubble size and the bubble rise velocity. On increasing the gas hold-up and reducing the bubble size enhances the bubble-particle collisions thus increasing the flotation efficiency. Vazirizadeh et al. (2016) have investigated the effect of the particle size on gas hold-up and bubble size distribution. The addition of hydrophobic talc particles leads to the bridging effect causing coalescence induced break up. Coalescence induced break up refers to the breaking up of large bubbles into smaller bubbles due to particle interaction. Coalescence leads to formation of smaller bubbles having high bubble rise velocity which reduces the gas hold-up. The talc particles can also stick to the bubble surface in numerous layers. These phenomena increase the mass of the bubble and is referred as bubble loading. These loaded bubbles have a low bubble rise velocity thus increasing gas hold-up. The gas hold-up depends on the contrasting factors of bubble coalescence and loading. There will be reduction in the gas holdup on increasing the bubble size only when the bubble loading is less compared to coalescence. The effects of viscosity and density on the two phase (air-water) mixture was examined by. The analysis is done for the temperatures from 4^oC to 40^oC. In this range the variation of temperature dependent fluid properties like surface tension or contained enthalpy are negligible compared to the viscosity. The viscosity was found to decrease on increasing the temperature, and a reduction in bubble size is observed (Zhang, 2014). The use of low-density gas mixture is used to create the effects at higher altitudes. This is essential to determine the effect of density on the bubble size. On increasing the density, the bubble size decreases. The effect of density on the bubble size is not as significant as expected. The viscosity is found to have a more profound effect on bubble size. The viscosity comes into picture during the industrial processes. The high operating temperatures may cause viscosity variations affecting the bubble size and flotation (Zhang et al., 2014). Turbulence can also influence the pulp froth interface, destabilize the lower regions of the froth leading to an effect on the overall performance of flotation. Pulp froth interface will, in turn, impact froth stability and flotation performance by increasing water recovery (Mesa et al., 2019).

Zhu et al., (2018) experimented on down comer experimental apparatus using Methyl isobutyl carbinol (MIBC) and air bubbles (Zhu et al., 2018), and it was seen that the d_{32} values of air bubbles decreased with the increase of MIBC concentration. As seen in the Critical Coalescence Concentration (CCC), above which the d_{32} was almost constant at about 0.645 mm, indicates that MIBC concentration tends to produce a bubble of similar size. At the lower addition of MIBC, adsorption at the bubble surface is lower; hence, the shape and size of the bubble can easily be changed by external conditions. Bubbles discharged from the downcomer coalesce and rise up in the riser, where the turbulence is much lower and less influenced, thus concentration and hydrostatic pressure play important roles in coalescence. The d_{32} of every MIBC concentration showed an approximately linear correlation with the height revealing different slopes. Higher concentration resulted in a smaller slope, which represents a smaller variation on bubble size. Here the bubble size distribution is deemed to be mainly influenced by pressure and coalescence. Hence, the bubble coalescence degree is analyzed by subtracting the pressure impact from bubble size distribution in the column. Furthermore, the difference between the bubble group line and the single bubble line decreased with the increase of the MIBC concentration, which clearly shows size change during the rising process of the bubble group in the riser. Cases, where the concentrations are lower than CCC95, were caused by bubble coalescence during the rising process. CCC95 is the concentration giving 95% reduction in Sauter mean bubble diameter (d_{32}) in comparison to water only to prevent coalescence completely. Cases where a difference of lines between d_{32} and MIBC concentration was tiny, the concentration was larger than CCC95, which indicates that MIBC effectively prevented bubble coalescence during the rising process of the bubbles in the riser. Overall, bubble coalescence in the flotation system is reduced with the addition of frother and does not happen when the frother concentration is above CCC. During the bubble rising process in the riser, bubble size increased with the sampling height, and more bubble coalescence happened at lower MIBC concentrations and higher sampling heights.

2.2. Carrying capacity and micro-bubble selectivity

Martinez-Gomez et al. (2013) experimented on micro bubbles for studying the factors involved with them. They found that different bubble size distribution is generated with different air superficial velocities along with increasing the bubble size/Sauter mean bubble diameter. The authors have also discussed the carrying capacity and micro-bubble selectivity.

2.2.1. Carrying capacity

The air superficial velocity improves the carrying capacity by increasing the number of micro bubbles and the bubble surface area occupied by the particles. It was also observed that the micro bubbles have a low carrying capacity for fine particles, as these particles easily cover the entire bubble surface at low solids content. Conversely, the carrying capacity is higher for coarse particles because a few large particles may have a larger mass than many fine particles, even if the entire bubble surface area is not occupied. Hence, it implies that maximal carrying capacities are a function of particle size and air superficial velocity. The carrying capacity decreases after increasing when particles are much larger than bubble size. And larger carrying capacities are obtained for higher air superficial velocities when a high number of micro bubbles are detected.

2.2.2. The selectivity of micro bubbles

As mentioned, micro bubbles are more selective towards finer particles and slightly selective to coarse particles of each distribution. In cases, where the particles are attached to the bubble, the fine particles can cover the entire bubble surface, producing aggregate with a density lower than that of the water, allowing flotation. However, if coarse particles are used instead, the aggregate density exceeds the water density, preventing flotation.

In contrast, other cases show that when the micro-bubbles are attached to particles, fine and medium particles float readily, and coarse particles float when five micro-bubbles are attached to a particle, which shows that several micro-bubbles can float very coarse particles.

2.3. Flotation - additional factors and applications

2.3.1. Additional factors

2.3.1.1. Nanobubbles and micro-nanobubbles

The nano-bubbles are mostly smaller than 1 μm and can be characterized by having high attachment ability and low probability of detachment due to its small size and low ascending velocity. They attach to the hydrophobic surface and act as secondary collectors for the particles and rapidly attach to the air bubbles (Nazari et al., 2019). These are obtained using several methods such as solvent exchange, hydrodynamic cavitation (Ebrahimi et al., 2020), ultrasonic and temperature variation (Nazari et al., 2019; Zhou et al., 2020). Nano-bubbles have great impacts on flotation efficiency (Nazari et al., 2019), froth flotation (Sobhy and Tao, 2019), gas holdup during flotation (Ebrahimi et al., 2020), and considerable reduction in chemical reagents consumption during flotation (frother and collector dosage) (Ebrahimi et al., 2020).

Micro nanobubbles are tiny bubbles with sizes ranging from 100 nm to submicron, formed in considerable amounts by hydrodynamic cavitation and due to their extraordinary properties such as long lifetime, high gas solubility, high surface stiffness, and incredibly large micro contact angle (Zhou et al., 2020).

A regular bubble for diameter 500 μm would quickly rise from the surface of the slurry and readily collapse. But the nano-bubbles due to Brownian motion will stay suspended. Moreover, due to the presence of an electric repulsion double layer between its surfaces, they do not coalesce and grow. The electric charge shows a relation of strong hydrogen bonding at the gas/liquid interface (Sobhy and Tao, 2019).

Small bubbles coated with hydrophobic particles produced a stable froth because the bubbles coated with particles were more stable than those that were not coated. The maximum froth stability was attained at 70^{o} contact angle when particles with moderate hydrophobicity were present, which can produce stable planes across the foam film, which increased the toughness of the froth structure (Sobhy and Tao, 2019).

2.3.1.2. Electric field

Under the presence of the external electric field, the shape of the bubble changes, and its different shapes affect the contact time and the area between the bubbles and the hydrophobic part in contact. When the electric field was applied, the size of the bubbles reduced during the air flotation process, which was beneficial for the absorption and separation of the bubbles and the hydrophobic particles. Under the influence of the external electric field, the viscosity (proportional to the amount of dissolved gas) reduces, which reduces the size of nanobubbles. Thus, the external electric field can enhance the efficiency of air flotation for separation of hydrophobic particles (Wu et al., 2019).

2.3.1.3. Ultrasonic pretreatment of minerals

Ultrasonic pretreatment cause changes to the surface physiochemical properties of the target (ilmenite) mineral. A slight increase in the collector concentration after ultrasonic pretreatment showed a significant increase in the flotation recovery, but this was not the case in raw target (ilmenite) mineral even at higher concentrations. Thus, pretreatment reduces reagent consumption (Shu et al., 2019).

2.3.1.4. Inclined plates

The installation of incline plates is capable of effectively reducing the contamination of fine slime particles in the clean coal; however, the installation leads to the loss of low ash coal particles. This reduction happened because the arrangement of the inclined plates in the flotation column enhanced the drainage behavior of the froth layer and reduced the water entrainment capacity of the fine slime particles. Thus, under proper aeration flow, the flotation efficiency index of the IFC (Inclined plated flotation column) was prominently higher than that of the FC(flotation column) (Ni et al., 2019).

2.3.1.5. Solution irradiated with ultrasonic waves

Micro-nanobubbles are produced by hydrodynamic cavitation process which are more stable than nanobubbles and have a long lifetime. Also, the addition of ultrasonic emission factor may have a positive effect on the floatation performance. Applying ultrasonic irradiation on micro nanobubbles causes instability, which leads to an increase in volume and collapsing; this collapse leads to releasing of energy which cleans the surface of the particles. The gas dissolved in the solution produces tiny bubbles that improve the floatation performance. The results showed that, simultaneous use of these two factors, improved the yield of coarse, medium and fine particles by more than 10%, 10%, and 30% respectively. Furthermore, there was a reduction of 90% in the collector dosage consumption, while the frother dosage reduced to about a quarter (Ebrahimi et al., 2020).

2.3.2. Applications

2.3.2.1. Flotation process for Chinese sub bituminous coal

The sample was considered because in China, their utilization is severely limited, and they have vast reserves, so, intense research activities are going on in order to develop effective processes for upgrading these low-rank coals in order to meet the ever-increasing demand for energy.

So, to improve its flotation recovery, the effects of nanobubbles on the fine coal flotation column and its associated mechanisms were investigated, which were influenced by different operating parameters such as frother dosage, collector dosage, feed flow rate, airflow rate and wash water flow rate. Nanobubbles not only increased the clean coal recovery by 7% for the same clean coal ash content but also reduced frother dosage (controls the bubble size and its quantity and froth stability) by one and a half. A similar reduction was seen in the collector dosage in the presence of nanobubbles, also higher collector dosage resulted in a more significant recovery and higher clean coal ash. At a given feed flow rate, the recovery was always higher in the presence of nanobubbles, and the difference was 20 - 30% at all feed rates except at the low feed rate of 0.1 liters per minute. The improvement in the recovery by nanobubbles was almost 40% at its lowest air flow rate and approximately 12% at its highest air flow rate, the range being 0.6-2.2 L/min. It was also found that wash water addition may be necessary for the presence of nanobubbles as they tend to increase the froth stability and they also increase the clean coal recovery by 20 to 25% at a given wash water flow rate (Ma et al., 2019).

2.3.2.2. Cassiterite Ore Behavior in electro flotation system

The results showed that with the additional sodium oleate and increased concentration of Na_2SO_4 (contributes to the agglomeration of fine cassiterite particles), the zeta potential of cassiterite decreased in the electro flotation system. Zeta potential is the charge that develops at the interface between a liquid medium and a solid surface. With an increase in the size or velocity of the bubbles, the collision probability and recovery of cassiterite decrease because when the bubble size becomes larger, the velocity of the bubble increases, which results in a short idle time in the flotation area. Therefore, the calculation of the flotation rate constant flotation rate and collision probability indicates that the cassiterite particle (<10 μm) recovery is best when the size of the bubbles is approximately 20 μm. Also, by decreasing the bubble size, the flotation recovery of fine particles might also enhance (Ren et al., 2019).

2.3.2.3. Effect of nanobubbles on muscovite (gangue) minerals

Heterogeneous nucleation of nanobubbles can be induced by a temperature rise on the chemically modified surface of muscovite minerals. Dodecyl amine (DDA) was used as a synthetic surface modifier and as a flotation collector. Pine oil acted as a frother with HCL, and NaOH used as pH adjustments. The contact angle of the muscovite surface is around 10^o implying that muscovite is naturally hydrophilic; therefore, to enhance the surface hydrophobicity of Muscovite, DDA was used, which provided muscovite substrates with variable hydrophobicity. The results indicate that the nanobubbles do selective nucleation on variable hydrophobic surfaces. So, selective nucleation of nanobubbles on a more hydrophobic surface will contribute to higher separation efficiency, which will help in achieving the separation of hydrophobized target minerals and hydrophilic gangue minerals. Therefore, the research concludes that temperature rise imposed during pulp conditioning may improve the floatation performance of the mineral (Zhou et al., 2020).

2.3.2.4. Effect of nanobubbles on kaolinite (gangue) particles

Kaolinite is a fine gangue mineral which commonly found in a wide range of industrial ores such as potash, bauxite, and phosphate ores, which is a non-swelling structured clay mineral. It has a clay particle mode: edge-to-edge (E-E), and these E-E associations form a three-dimensional network, which leads to an increase in viscosity. Nanobubble water enhances the entrainment of kaolinite particles, also, there was an increase in pulp viscosity during flotation when compared to tap water. Nanobubbles might stabilize and induce the E-E contacts of kaolinite particles, which would lead to the formation of a porous three-dimensional structure. These Structures with abundant interstitial voids with reduced settling velocity may have an increased chance of being recovered by entrainment (Lei et al., 2020).

2.3.2.5. Nickel removal from wastewater by ion flotation

Water scarcity, the most significant issues at hand, various steps have been taken by numerous researchers to curb this issue as many industries due to increased development were compelled to produce a large quantity of wastewater containing high concentrations of suspended heavy metals ions. Reusing wastewater leads them to adopt various flotation methods to remove these ions from the solution effectively. Ion flotation differs from froth flotation in terms of additional processing involved; however, bubble dynamics, presence of surfactants, and, turbulence do considerably affect the flotation efficiency. The ion flotation method uses rising bubbles to remove soluble complex ions and surfactants. OGC (oscillating grid cell) was found to be active and efficient for the process since it was able to produce relatively homogeneous and isotropic turbulence when compared to OBC (oscillating baffled cell). The results showed that the bubble size, when reduced, lead to increased removal of nickel ions since their residence time in the solution was increased, thus leading to more collision with the nickel ions. Also, when a higher SDS/Ni (II) ratio was used, there was more interaction between the SDS ions and Nickel ions, which lessened the interaction between the rising bubbles, thus less removal rate of nickel ions. Besides, homogenous and isotropic turbulence was found to be more suitable for the ion process compared to inhomogeneous and anisotropic turbulence. Hence the Ion flotation method is better for nickel ion removal due to its high removal rate and high-water recovery during the process (Hoseinian et al., 2019).

2.3.2.6. Effects of nanobubbles on coarse quartz floatation

Quartz, which is the second most abundant mineral in earth's crust, is a gangue mineral which is practically found in every flotation process. Coarse quartz flotation has a long standing problem of high milling cost and low mineral recovery. So the use of nanobubbles on coarse quartz particles was investigated. Coarse particles were used as it minimizes the loss of valuable minerals. During the experiment, when the Nanobubbles were pumped into the flotation cell, it attached itself to the hydrophobic surface and enhanced the flotation recovery. With the presence of nanobubbles, the coarse flotation recovery increased by 21 % and an increase in the flotation rate constant up to 36% (Nazari et al., 2019).

2.3.2.7. Effects of nanobubbles on coal flotation

Froth stability plays an essential role in determining the coal product quality and its recovery in the froth flotation, which depends on the column height in the froth zone. It is not only dependent on froth stabilizer concentration and type but also the particle characteristics and its associated nanobubble and chemicals. Coal flotation tests demonstrated that utilization of nanobubbles altogether improved the coal flotation performance, which can occur at any rate in part ascribed to improved foam stability (Sobhy and Tao, 2019).

2.3.2.8. Role of micro-nanobubbles in reagent desorption and separation of highly hydrophobized minerals (diaspore)

Diaspore is an aluminum oxide hydroxide mineral, which is a major component of bauxite (aluminum ore). Role of micro-nanobubbles in desorbing NaOL from diaspora surface was investigated. Compared with ordinary water cleaning, micro nanobubble water cleaning shows higher NaOL (flotation reagent) removal efficiency from the diaspore surfaces, therefore, reducing the residual concentration of NaOL on the particles, which were more significant when the amount of pre-adsorbed NaOL was relatively small. Results confirm that the hydrophobicity of diaspore surfaces has a maximum value when a single layer of NaOL fully covers the mineral surface. However, when excessive NaOL was used, it resulted in multi-layer adsorption, which did not accord to the further improvement of the hydrophobicity of the diaspore surfaces. Besides, reagent desorption, which was enhanced by the micro nanobubbles cleaning, decreased the hydrophobicity of diaspore particles significantly. This decrease in hydrophobicity, caused the associated flocs/particles to break up and selectively reorganize themselves under stirring conditions. This phenomenon probably contributes to the separation of different hydrophobized minerals since gangue entrapment in the particles acts as a significant limiting factor towards high selective flotation (Zhou et al., 2020).

2.3.2.9. Flotation capacity of ilmenite surface pretreated using ultrasonic waves

The flotation mechanism on the surface of the ilmenite (black iron-titanium oxide ore) and the changes associated with the surface composition of ilmenite before and after the ultrasonic pretreatment was investigated. To verify, various mechanisms such as flotation tests, X-Ray photoelectron spectroscopy, Fourier transform infrared spectroscopy (FTIR), Zeta potential measurement, and microcalorimetry were conducted (Shu et al., 2019) and following were observed.

i) flotation recovery test: for ultrasonically treated mineral, maximum recovery was found to be approximately 2.1 times when compared to raw target(ilmenite) mineral in the pH range of 4-6.

ii) zeta potential measurement: It shows that when pH is less than the isoelectric point (the pH at which the molecule is electrically neutral), the anionic collectors are physisorbed on the positively charged target (ilmenite) surfaces. However, if pH is higher than the isoelectric point, then chemisorption occurs in which anionic collectors are collected on the negatively charged target (ilmenite) surfaces. This observation led to a shift of isoelectric point from pH 6.2 to pH 4.2.

iii) microcalorimetry: the heat released is measured and compared for the adsorption activity of NaOL before and after the ultrasonic treatment. After the ultrasonic treatment in the pH range of 4-5, the ferrous ions are oxidized to ferric ions on the ilmenite surface, which then actively interact with oleate ions to form ferric oleate which causes the floatation of ilmenite particles.

iv) FTIR: the chemisorption of the oleate ions occurs to a significant extent in an ultrasonically treated ilmenite then that on raw ilmenite.

v) X-ray photoelectron spectroscopy: the relative content of Fe3+ ions had significantly increased by 1.7 times after ultrasonic pretreatment.

Also, the ultrasonic pretreatment leads to the oxidation of Fe^{2+} to Fe^{3+}. The latter reacts strongly with NaOL and forms a stable layer of NaOL on the surface of target (ilmenite) mineral; this ultimately increases the flotation capacity of mineral (ilmenite). Thus, the ultrasonic pretreatment done as a surface modification on ilmenite improved its selective flotation from gangue minerals.

2.3.2.10. Effect of nanoscale bubble and particle on bubble size distribution

Javor et al. (2015) suggested two things: One is that the bubble size observed in mechanical flotation cells depends on the balance between bubble coalescence and breakup rates in the cell. Another one is that coalescence occurs in three steps, e.g. drainage, thinning and rupture of the liquid film, when the contact time between bubbles is sufficient. Cilek et al., presented that the structure and stability of a froth phase are critical in determining its ability to transport the hydrophobic mineral particles into the concentrate launder (Cilek and Karaca, 2015). However, frothers, along with other physical and chemical factors of the flotation, affect bubble size distribution and hence, it results in prevention of bubble coalescence.

The presence of the surface-active molecules changes the dynamic properties of the interface due to turbulence caused by its molecular behavior at interfaces. This change in properties along with chemical structure of surface-active molecules and surface tension influences the bubble size and overall performance of frothers (Jávor et al., 2015). However, bubble coalescence in the froth can be decreased by using Nano materials. These materials provide significant enhancement in frother concentration, air flow rate, which increases bubble size (Cilek and Karaca, 2015).

The observations by Javor et al., (2015) also conclude that highly surface-active agents decrease bubble size at its lower concentration than the weak agents because in the presence of weakly surface-active reagents, the molecule exchange occurs rapidly at the air/liquid interface due to the quick diffusion controlled adsorption/desorption. However, the adsorption/desorption of highly surface-active molecules occurs with a long characteristic time caused by the molecule reorientation which sharply diminishes the bubble size. In addition, it was also investigated that the changes in bubble size in the froth zone of a flotation column and bubble growth rate are sensitive to degree of hydrophobicity of particles present in the froth zone (Cilek and Karaca, 2015). The effect of Nano materials on Sauter mean bubble size is a function of frother concentration. It increases the bubble size but no remarkable effects of nano materials on bubble size were observed in absence of frother.

2.3.2.11. Dispersed air flotation used in desalination

Use of the dispersed air flotation for the pre-treatment of the seawater (Altaher et al., 2012) involves the mass transfer of oxygen from bubbles to seawater. Oxygen deficit is the difference between the saturation concentration of oxygen in seawater and the concentration of oxygen in seawater. Oxygen deficit promotes the mass transfer of oxygen. The mass transfer coefficient was found to increase on increasing the air flow rate. This is due to increase in the number of bubbles. The bubbles provide surface for mass transfer. The mass transfer is more effective by the smaller bubble compared to larger bubble. This is due to their large surface area to volume ratio. The effect of temperature is examined within a range of 24^{o}C to 38^{o}C. A greater increase in the mass transfer coefficient has been observed between temperatures of 24^{o}C to 30 ^{o}C compared to the temperature range of 30 ^{o}C to 38 ^{o}C degrees. This is due to the effect of decreasing oxygen deficit. The mass transfer coefficient increases on increasing the temperature. This is attributed to the increase in surface area to volume ratio. At high temperatures the medium viscosity decreases. This enhances the mass transfer of oxygen to seawater (Ireland and Jameson, 2014).

2.3.2.12. Adsorption based flotation recovery for minerals

Some of the recent studies report the enhancement in flotation recovery by improving the adsorption characteristics using reagents. Zhao et al., (2020) carried out an experimental study to study the floatation characteristics of the hemimorphite in the presence of salicyl hydroxamic acid (SHA). Hemimorphite is a zinc oxide mineral. The studies also include the effect of Pb (II) ions on the floatability and SHA adsorption on the hemimorphite surface. The studies have confirmed that the presence of the Pb ions enhances the adsorption (both physical and chemical) of SHA on the hemimorphite surface, provided they are within the optimum pH range, this characteristic is attributed to the ability of the Pb ions to react with the O present in the hemimorphite surfaces and make complexes of zinc oxygen, lead, and silicon (Zn-O-Pb, Si-O-Pb). The formation of these complexes on the hemimorphite surfaces improves their reactivity towards SHA, thus leading to better adsorption of SHA. The floatability of hemimorphite coated with Pb (II) was found to be higher when SHA is used as the collector. Thus, the hemimorphite surface treated with the Pb ions is found to have better floatation characteristics compared to the untreated hemimorphite surfaces, this is due to the greater adsorption of SHA in the case of the former as compared to later. A new method for the floatation recovery of hemimorphite has been proposed using the SHA as the collector. The cuprite leaching process involving micro-flotation, adsorption tests, XPS analysis & spectrometry has been reported by Zhang et al., (2020). This process is used to extract copper and is conducted at room temperature in a mechanically agitated flotation machine. The pure azurite samples are added to water, HCl, and NaOH solution are added too with stirring to adjust the pH of the solution to 8.5. Then Na_2S with the desired concentration is added to react for 5 min. followed by the addition of collector and frother. After the flotation test, the concentrate and tailing products are collected by filtration, drying, and weighed to calculate flotation recovery. The results of the micro-flotation of azurite indicate that the flotation recovery of azurite was very low at low Na_2S concentrations but rapidly increased with increasing Na_2S concentration from $2*10^{-4}$ to $2*10^{-3}$ mol/L in presence of NaIX collector at $5*10^{-4}$ mol/L. At higher concentrations, the recovery dramatically declined. From this experiment, it is concluded that Na_2S concentration is crucial to determine the quantity of flotation recovery. The same trend was observed when using copper oxide with various concentrations. The low flotation recovery of azurite and copper oxide at low concentrations can be attributed to insufficient sulfidization which led to unstable adsorption of the collector on the mineral surface. However, an excessive Na_2S concentration was unfavorable for the given mineral flotation owing to the inhibiting effect of negatively charged sulfide ion species on collector adsorption on the mineral surface. Thus, an appropriate Na_2S concentration should be selected similar to sulfidization flotation of other nonferrous metal oxide minerals. The authors have also studied the effect of concentration of certain chemicals added on flotation recovery enhancement, bond breakage, and binding energy between elements in the alternative copper sources to extract copper.

3. Conclusions

The bubble particle interaction is fundamental for flotation to occur. The collision of the particle with the bubble depends on the particle size and trajectory. The particles that are close to the bubbles are easily intercepted by the bubble. This is due to the effect of microhydrodynamic force and fluid flow. Hence it is important to ensure proximity between the particles and bubbles by analyzing the fluid flow. The collision efficiencies of particles with bubbles depend on the particle size. The fine particle collision is mainly dictated by turbulence. This is due to their low mass. The inertial and gravitational mechanisms are insignificant in a fine particle collision. The coarse particles have a higher mass and inertia. The inertial, gravitational, and interceptional mechanisms play a key role in a coarse particle collision. In a real scenario, one can expect a mixture of coarse and fine particles. Hence achieving the control over particle collision is relatively difficult. Hence it as an open problem that yet needs to be addressed not only at the lab scale but also in the field. The turbulence effects are neglected due to the large mass of particles. The attachment of the particle with the bubble depends on the shape of the bubble and fluid flow. The particles may not attach to the bubbles after fulfilling the necessary criteria. This is due to irregular bubble shape and high-velocity fluid flow. The detachment force quantifies the stability of the bubble particle aggregate. The detachment force has a strong positive correlation with the dynamic contact angle and medium viscosity. The high stability bubble particle aggregate has high detachment forces. The collision of the bubble particle aggregate with the liquid interface is conducted without varying the bubble hydrodynamics. This methodology should be extended to the pre-treatment of saline water. The results obtained should be analysed. The effect of varying bubble hydrodynamics on the interaction between the bubble particle aggregate and the liquid interface is yet to be studied. The effect of viscosity is studied only in two-phase systems. Some of these studies do not involve a particle. The addition of particles into such systems may yield different results and is yet to be conducted.

The detachment process controls the maximum floatable particle size for coarse particles. If the particle kinetic energy exceeds the energy required to detach it from the gas-liquid interface, the particle detaches from the bubble, defining a kinetic limit for flotation. For fine particles, the critical water receding contact angle required for flotation is defined by the energy required to rupture the intervening thin liquid film between particle and bubble. The flotation response of coarse and fine particles was similar either in a flotation column or in a mechanically agitated cell, for a similar bubble size. Flotation of very large and very fine particles is possible, provided that they have high contact angles with smaller bubbles enhancing the process.

The low flotation rate of hydrophobic fine particles (<20 μm) is mainly due to their low collision efficiency, with bubbles. These values can be increased by decreasing the bubble size and by aggregating the fine particles to an optimum size for flotation. A decrease in the bubble size not only increases the bubble–particle collision efficiency but also increases the bubble–particle attachment efficiency and the number of generated bubbles. These factors also increase the flotation rate of fine particles but might cause higher water recovery, which increases the entrainment of gangue minerals. For fine particles, the main collision mechanism is interception, whereas submicron particles are also affected by Brownian motion, and larger particles by inertia. In practice, fine particle flotation can be improved by allowing long residence times and working at high collector coverages (large contact angles). New approaches are required, which could include very high energy zones for bubble–particle contact or completely novel ways of introducing particles directly to the water–vapour interface. On the other hand, it is experimentally and theoretically clear that the flotation rate increases with increasing particle size. Thus, many techniques have been developed which try to increase particle size and mass and decrease surface energy but have the same feature that fine particles are induced to form flocs or aggregates. The low flotation recovery of fine particles is mainly caused by the low probability of bubble–particle collision. The use of small bubbles increases the probability of collision and adhesion and reduces the probability of detachment. Larger bubbles are needed to provide sufficient levitation of coarse particle–bubble aggregate. Increased surface hydrophobicity promotes the recovery of coarse mineral particles by reducing the probability of detachment.

The flotation performance of a mechanical flotation cell is unaffected by the height of the flotation cell. This can be used to reduce manufacturing costs. Very high turbulence destroys the bubble-particle aggregate and reduces the flotation rate. The bubble size reduces on increasing the turbulence kinetic energy. This behavior is observed only up to a critical value of turbulence kinetic energy. This critical value is found to be $0.18 m^2/s^2$. The bubble size is unaffected by the turbulence kinetic energy exceeding the critical value. In the industrial process, the operating speed is high enough to produce turbulence kinetic energy exceeding the critical value. The dimensionless parameters (Reynolds, Froude, and Weber number) are the functions of the cell hydrodynamics. The maximum cell performance was observed at Re=89800, Fr=2.4, and We= 1558. The gas hold-up is affected by the contrasting factors of coalescence and bubble loading. The coalescence decreases the gas hold-up, whereas the bubble loading increases it. The gas hold-up is found to decrease with increasing bubble size only when the bubble loading is dominated by coalescence, in a two-phase system on increasing the temperature the medium viscosity and the bubble size decrease. The bubble size was found to decrease on increasing the density. On comparison, the viscosity is found to have a greater effect on bubble size than density. In the dispersed air flotation on increasing the airflow rate, the mass transfer coefficient of oxygen increases exponentially. The mass transfer of oxygen is found to increase on increasing temperature. This is due to the higher surface area to volume ratio in bubbles. The interaction of a bubble-particle aggregate with a liquid interface results in particles being moved around the bubble surface. The bubble-particle aggregate is found to promote particle retention. This is due to the dissipative effects of inertial and viscous forces in the initial stages of collision.

In the flotation of fine and coarse particles, the main problems are the attachment of fine particles and detachment of coarse particles due to differences in contact angles during collision and detachment, respectively. The detachment problem in coarse particles is because particle kinetic energy is greater than the energy required to detach coarse particles from the gas-liquid interface. So small bubbles if cluster with a particle can raise it. For fine particles, due to the dominance of the Brownian movement, the collision probability is very low and, hence in flotation recovery, fine particles are separated out. However, these problems can be rectified by using large and small bubbles for the flotation of fine and coarse particles, respectively. Microbubble selectivity towards is also a new solution for problems to fine and coarse particle flotation. As fine particles float more readily when microbubbles are introduced; however, five microbubbles are required to raise one coarse particle. Thus, microbubble introduction is essential for fine and coarse particle flotation.

The flotation process is widely used for the separation of fine coal particles and associated minerals. However, the process has a low flotation recovery and efficiency for ultrafine (<150 μm) coal particles due to its narrow range of particle size. Due to this, a large amount of ultrafine coal waste is dumped in a significant amount in tailing slurry dams. These slurry dams have always been associated with protracted pollution and loss of valuable minerals. This loss of ultrafine coal particles cannot be accepted at this point in time when it is difficult to sustain the ever-increasing demand for energy. This loss can be reduced by wide-scale use of nanobubbles as it enhances the process efficiency and also reduces the consumption of chemical reagents. Since nanobubbles have a long-range of attractive forces which are measured between hydrophobic surfaces, these have a selective adsorption property for different hydrophobic particles. This selective adsorption has contributed to the significant enhancement of particle attachment and flotation recovery. Its wide range effect on flotation of various minerals like muscovite, kaolinite, quartz, coal pyrite, phosphate, and scheelite makes it one of the most prominent resources in the flotation process. Not only nanobubbles but various applications like an electric current, ultrasonic waves have contributed to a great extent towards the enhancement of the flotation process. On the other hand, the adsorption using reagents can enhance the flotation recovery of minerals. Therefore, it is better to upgrade the ongoing traditional process with such useful resources because they not only enhance the process but also reduces the cost of flotation.

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