

VISUALIZATION OF ANGULAR PARTICLE-BUBBLE SURFACE INTERACTION USING A HIGH SPEED VIDEO CAMERA

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ABSTRACT

Flotation is an important process in mining industries. This process employs the bubble and hydrophobic properties of a particle to separate valuable mining particles from impurities. The most important phenomenon in determining flotation efficiency is the bubble-particle interaction; therefore, understanding this phenomenon is very important. The aim of this research is to study the mechanism of bubble-particle interactions with and without the addition of a collector. The experimental setup consists of a water container, bubble generator, particle feeding system, and an image capturing system. The water container is made from transparent material of a size large enough so that the wall's effects on bubbles and particles can be neglected. Air bubbles are generated by a bubble generator which consists of a small nozzle and programmable syringe pump. A high speed video camera and halogen lamp backlighting system are used as image capturing devices. Observation of the images reveals that bubble-particle interaction follows the stages of bubble-particle collision, particle attached to the bubble, and particle detached from the bubble. The addition of a collector to the liquid affects the bubble-particle interactions.

Keywords: Angular particle; Bubble; Collector; Flotation; Interaction; Mining

1. INTRODUCTION

In mining industries, valuable materials are produced from mined ore following several treatments, namely, crushing, grinding, screening, ball mill, and flotation. Flotation is the most important process in mining industries. This process separates valuable material from others, and it has a long history. It has been applied in mining industries for more than 100 years. For example, flotation is applied in the recovery of the mineral Sphalerite (zinc sulfide, ZnS). Flotation is also used in gold mining in the mineral rich area of Papua, Indonesia.

The flotation process is controlled by three things: engineering, physical aspects, and chemical aspects. The engineering aspect is related to the bubble generator, particle feeding system, and design of the flotation column. The physical aspect is related to hydrophobicity and floatability, bubble-particle interactions, froth drainage, and flotation kinetics. The chemical aspect is related to mineral surface chemistry, reagent chemistry, and mineral-reagent interactions. Those three aspects will determine the effectiveness and efficiency of the flotation.

An important part of the physical aspect is the bubble-particle interaction. In a typical column flotation, particles are fed from the upper part of the column and bubbles are released from the bottom part of the column. When particles move downward and bubbles move upward, they

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meet and interact. It is already known that the bubble-particle interactions follow the stages of bubble-particle collision, particle attached to bubble, and particle detached from bubble.

In several cases, the hydrophobic character of the particles should be modified from hydrophilic into hydrophobic by adding a specific reagent. Several types of reagents with various functions are used in the flotation process. According to their function, reagents are classified as a frother, collector, or depressant. The frother is a reagent class which functions to stabilize the bubble-particle aggregate. The collector's function is to change the hydrophobic character of the particle from hydrophilic into hydrophobic. The depressant reagent functions to prevent mineral impurities from rubbing off on floating bubbles and precipitating.

Various efforts continue to be made to create flotation conditions such that the stages of the bubble-particle interaction can take place properly so that a greater efficiency and effectiveness of flotation can be achieved. Many studies in this field have been done. The collision efficiency of small particles with spherical bubbles was studied by Flint and Howarth (1971) and Anfruns and Kitchener (1977). Their works revealed that the important parameters determining the collision are particle size and gazing diameter.

Schulze (1999) showed the mechanism of attachment of particles to the surface of the bubble and the determining parameters. This was also investigated by Verrelli et al. (2011). Further research in the field of sliding particles on the surface of the bubble has been done by Nguyen and Evans (2004), Koh et al. (2009), Verrelli et al. (2015), Lecrivain et al. (2015), Wang et al. (2015), and others. Research on particles' rebounding from bubble surface has been done by Zhao et al. (2015). Studies on the attachment of particles on the surface of the bubble have been done by Schulze (1999), Parkinson and Ralston (2011), Basařová and Hubička (2014), and others.

Previous studies also explain parameters that affect the flotation process. The effect of bubble size on flotation rate was shown by Ahmed and Jameson (1989), Yoon and Luttrell (1989), and Szatkowski and Freyberge (1998). The effect of gas flow rate on flotation efficiency was shown by Dobby and Finch (1986). Several researchers developed a model to study bubble-particle interactions, for example, the work by Reay and Ratcliff (1975) and Jiang and Holtham (1986).

Previous studies have provided a good understanding of some bubble-particle interaction phenomena. Nevertheless, some important physical phenomena have not received enough attention. Recent research shows that the stages of bubble-particle interaction can be described in a sub-mechanism, such as collision angle, collision radius, sliding, rolling, induction period, and detachment (Nguyen & Evans, 2004; Xu et al., 2011; Verrelli et al., 2011). The sub-mechanism is a constituent stage of bubble-particle interactions which is likely to be a determinant of the efficiency and effectiveness of particle-bubble interaction. A clear understanding of this mechanism will provide a better insight into the interaction of bubble-particles; therefore, research in this area is very important. Previous research in this field generally used spherical particles made of glass. Research using angular shaped particles from mining is still quite rare, so research in this field is unique and challenging.

This research aims to study bubble-particle interactions and the influence of the reagents in the process, with a focus on the collision angle, collision radius, sliding, rolling, and induction period. The study was conducted by observation of particle-bubble interaction using a high speed video camera and an image processing program. This research used real particles from the mining industry, instead of sphere glass particles as used in previous studies. This research focused only on bubble-particle interaction visualization for idle and moving bubbles.

2. EXPERIMENTAL SETUP

The experimental setup consists of a water pool, bubble generators, particle feeding system, and image capturing system, as shown in Figure 1.

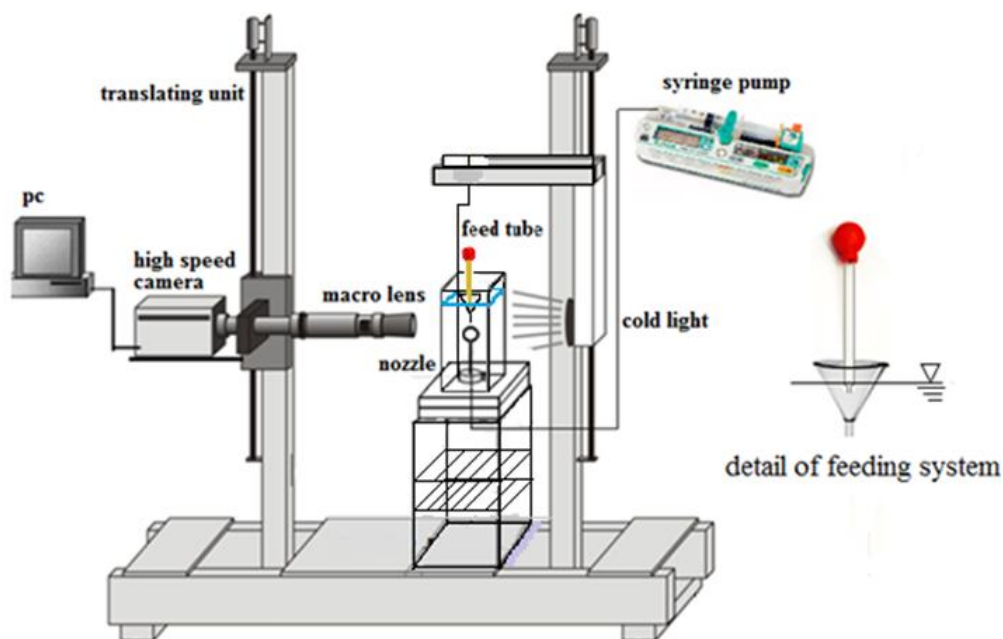


Figure 1 Experimental setup (Basařová and Hubička, 2014)

This setup is similar to the one published in Hubicka's work (Basařová and Hubička, 2014). The water pool is made of acrylic plate of a large enough size so that the effect of the wall on the bubble and the particle can be neglected and filled with water. The bubble generator consists of a nozzle with an inner diameter of 0.3 mm and a syringe pump. The syringe pump is programmed to adjust the air flow through the nozzle. The particle feeding system is designed so that the feeding process does not disturb water surface conditions. It consists of two Burnet pipettes. One Burnet type pipette is cut and functions as channels for releasing particles to the surface of the water. The other pipette is filled with a solution of water and particles.

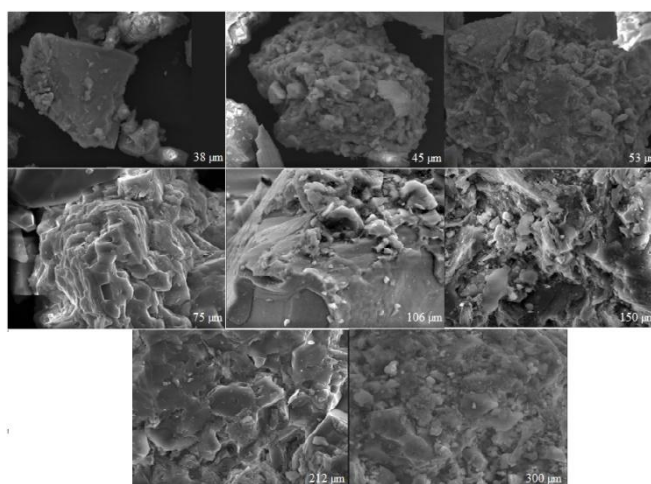


Figure 2 Particle geometry (5000×)

A high speed video camera and lighting system are used as the image capturing system. A micro-lens is used to boost the ability of the camera. Images of bubble-particle interaction are processed by image processing software (Vitcam, MotionXtra HG-SE). This study uses particles derived from a gold mining company. The typical particle sizes are 38 μm , 45 μm , 53 μm , 75 μm , 106 μm , 150 μm , 212 μm , and 300 μm . Particles visualized by scanning electron microscopy (SEM) can be seen in Figure 2, which shows that the particle geometry is angular oblate.

The dynamics of particles moving down when approaching the bubble, crashing, attached, and separated from the bubble were recorded using a high speed video camera at 500 fps. The results will be analyzed using an image processing program (Image J, Wayne Rasband), so trajectories of particles and bubble-particle interaction can be known.

3. RESULTS AND DISCUSSION

In this research, particle terminal velocity for particles with the size of 38 μm is 5.544 mm/s, 45 μm is 6.207 mm/s, 53 μm is 6.98 mm/s, 75 μm is 12.557 mm/s, 106 μm is 22.731 mm/s, 150 μm is 23.478 mm/s, 212 μm is 32.244 mm/s, and 300 μm is 44.196 mm/s. However, bubble diameter is 1.7–1.8 mm.

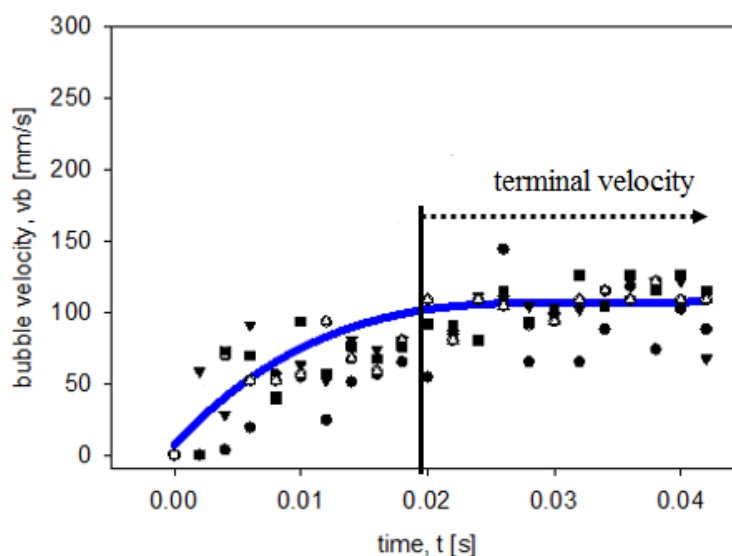


Figure 3 Bubble terminal velocity

Figure 3 shows bubble velocity versus time. This figure depicts the terminal velocity of a bubble that is 100 mm/s with a bubble size that is 1.7 mm in diameter.

Figure 4 shows a typical bubble-particle interaction. Images in this figure were captured by high speed video camera at speed 500 fps. Particle size is 150 μm and air flow rate is 15 ml/h., which provides a maximum bubble radius of 0.77 mm before being detached from the nozzle tip. Figure 4a shows a particle moving downward and approaching a stationary bubble. A few moments later, the particle strikes the bubble as shown in the final image in Figure 4b. Shortly after the collision, the particle will be attached to or detached from the bubble. If the particle is attached to the bubble, then it will slide, following the curvature of the surface of the bubble, and stop at the bottom of the bubble, as shown in final image of Figure 4e. In this situation, the bubble and particle form bubble-particle aggregates. Interaction of the bubble-particle typically consists of a collision, sticking, sliding, and aggregate formation. Bubble-particle interaction, as mention above, requires 30 frames which is equivalent to about 60 ms.

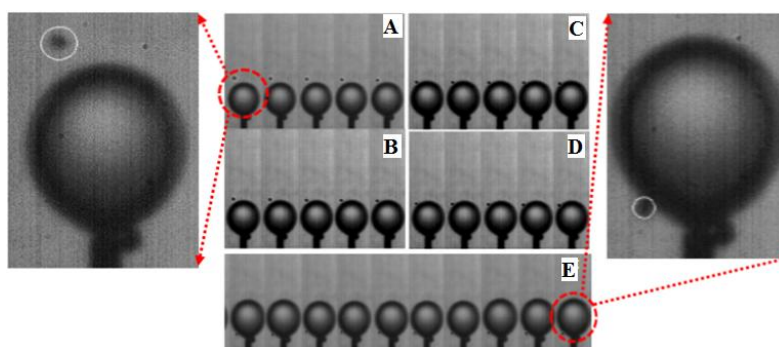


Figure 4 Bubble-particle interaction; particle size is 150 μm at 500 fps

Bubble movement accelerates the particle so that the particle slides faster. Figure 5 shows the effect of bubble motion on interaction. This image shows the interaction of the bubble-particle just prior to leaving the nozzle tip and when the bubble rises due to buoyancy force. This process is indicated by 13 frames, equivalent to 26 ms, which is faster than the process that occurs on the stationary bubble.

Particle size affects bubble-particle interaction. Large particles often fail to form a stable bubble-particle aggregate. Large particles detach when they encounter sliding, and at the same time, fail to form stable aggregate bubble-particles.

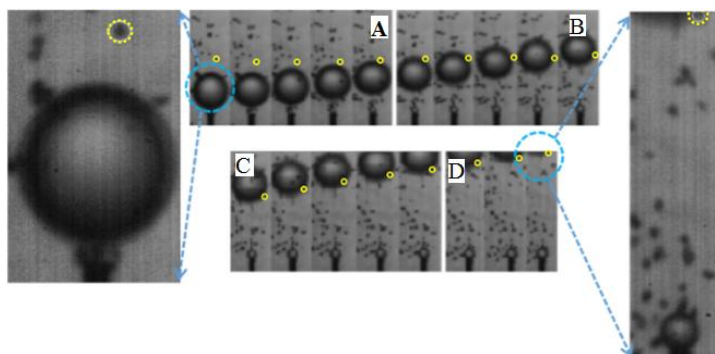


Figure 5 Bubble-particle interaction; bubble just detached from nozzle tip

Reagent influences are evident in this experiment. Collector reagent added to potable water changes the bubble-particle interaction process. The collector changes the hydrophobicity properties of the particles. In general, the complete processes of bubble-particle interaction in the water with the addition of the collector consist of some process and collision, sticking, sliding, and formation of a stable bubble-particle. In contrast, the bubble-particle interaction in potable water without the collector is incomplete, even though some particles bounce when they collide with the surface of the bubble. However, to come to the conclusion of reagent effect on the bubble particle interaction process, further research is needed to obtain sufficient data.

Figures 6 and 7 show the trajectories of particles when interacting with the bubble. Coordinates (0.0) show the location of the central axis of the nozzle tip. Particles move down closer to the bubble due to gravitational force. The initial position of the particle is shown in the first image at the top right. Furthermore, particles approach the bubble surface and attach to the surface of the bubble after attenuating the thin layer of water that separates the bubble (indicated by a point to 10, 11, and 12). In this situation, the core of three phases of contact is formed.

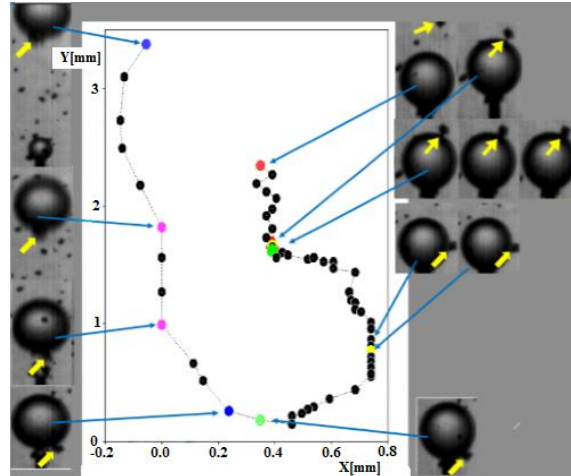


Figure 6 Trajectories of particle when interacting with a bubble; particle diameter is $212\ \mu\text{m}$, captured at 500 f/s, and air flow rate is 15 ml/h

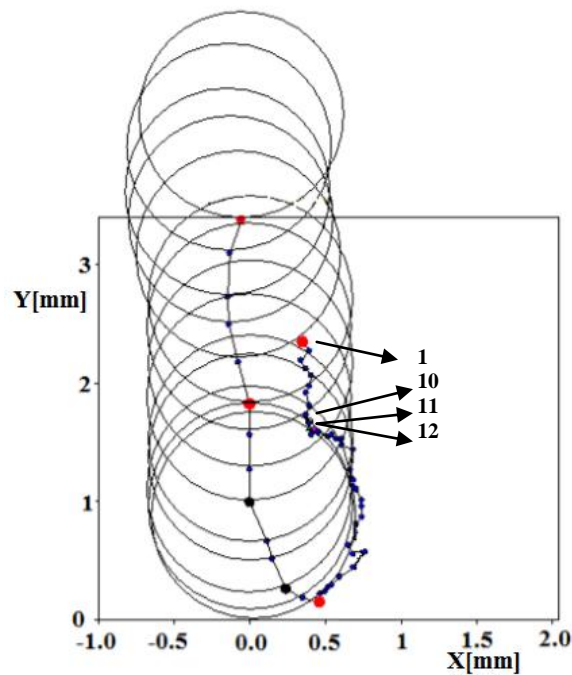


Figure 7 Particle trajectory plot with bubble surface and its trajectory

Furthermore, particles slide by following the shape of the bubble surface and stop at the bottom of bubble close to the nozzle tip. A moment later, the bubble detaches from the nozzle tip and rises. At that time, if the bubble and particle have formed a stable aggregate, the particles will remain attached and move up along the bubble.

The trajectory of the particles and their interaction with the bubble is also shown in Figure 7. Circles on the graph show the position of the bubble, and the dots show the position of the particles. Point (0,0) indicates the location of the central axis of the nozzle tip. Previous research (Verelli et al., 2012) showed that the particle collided with the bubble surface at an angle of $45\text{--}60^\circ$, while in this research, the particle collided with bubble surface at an angle of $35\text{--}80^\circ$. Particle terminal velocity has the same value as in previous research (Verelli et al., 2012) with a particle size of $38\text{--}75\ \mu\text{m}$.

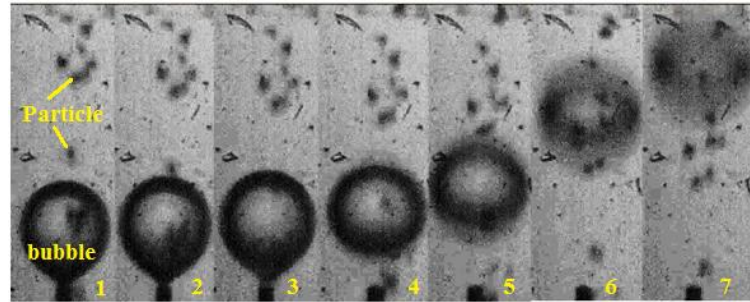


Figure 8 Bubble-particle interaction without collector reagent addition (212 μm)

Figure 8 shows bubble-particle interaction without the addition of the reagent addition. Frames 1–3 show the particle approaching the bubble surface and colliding with the bubble. Frames 4–7 show the bubble rising, the particle detaching, and the particle moving downward.

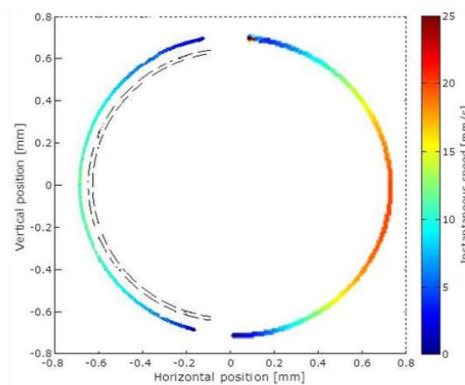


Figure 9 Illustration of bubble-particle interaction, experimental result, and numerical result (Wang et al., 2015)

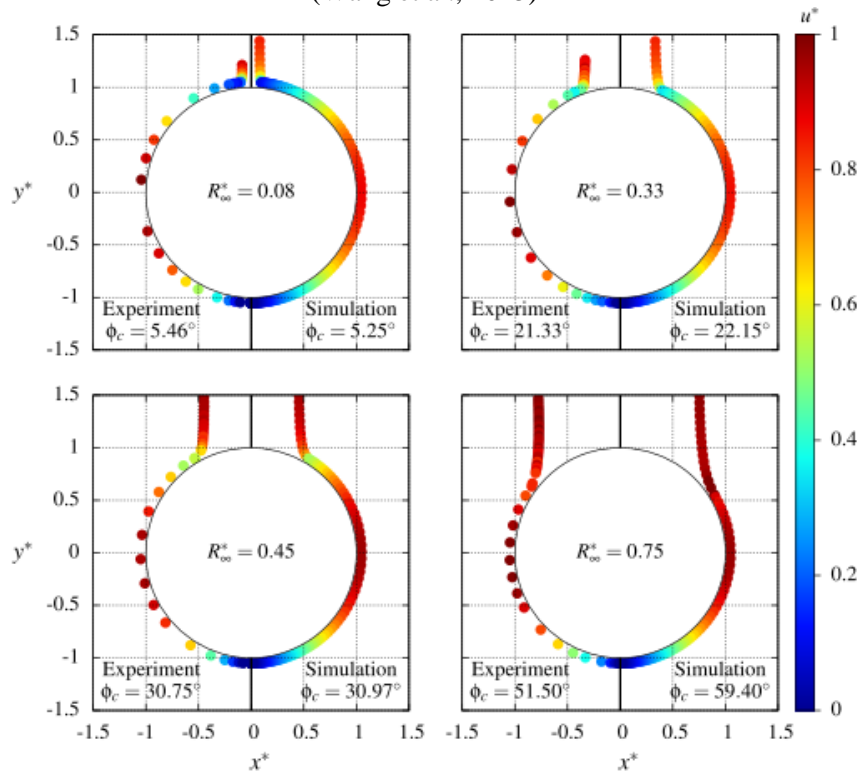


Figure 10 Illustration of bubble-spherical particles interaction, experimental result, and numerical result (Lecrivain et al., 2015)

Sliding movements on the bubble surface have different velocity values. It was observed that after collision with the bubble surface at quadrant 1, the particle slides slowly, and it then accelerates when moving into quadrant 2. After that, the particle decelerates and remains at the bottom of the bubble surface as a stable aggregate or detaches from the bubble surface. This observation result is similar to results found in previous works. Figures 9 and 10 show particle movement in experimental and numeric calculations from the 45° angle up to the 120° angle of the previous experiments by Wang et al. (2015) and Lecrivain et al. (2015).

Forces acting on the attached particle in the bubble are gravitational force, buoyancy force, inertia force, capillary force, and drag force, as shown in Figure 11.

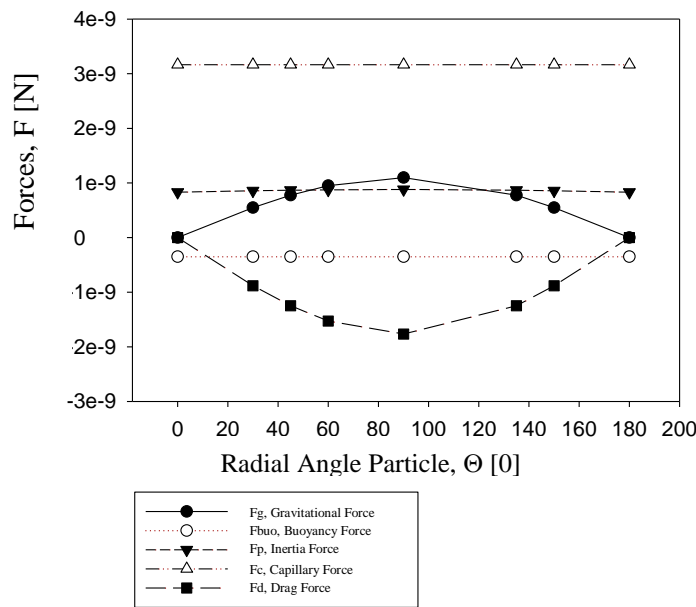


Figure 11 Graphic of radial angle particle vs. forces acting on particle

From those forces, drag force and gravitational force are the most significant forces in respect to particle position. The literature shows gravitational force works at a low value on 0° and increases to its maximum value in the equator region (90°), and later decreases to its minimum value on 180°. This also happens in drag force, but its increasing and decreasing values are contrary to gravitational force. So, for every size of particle, resultant force will tend to have the same value with gravitational force, with its maximum value around the equator force. This phenomenon causes the particle to accelerate when it approaches the equator region and decelerate when it leaves the equator region.

4. CONCLUSION

Observation using a high speed video camera shows the mechanism of interaction between bubble and particle. Bubble-particle interaction consists of several processes: collision, bouncing, sticking, sliding, and formation of stable bubble-particle aggregates. Bubble-particle interaction is influenced by particle size, hydrophobicity characteristics of the particle, and movement of the bubble. The particle detaches easily from the bubble surface medium without reagent (collector) addition. It was observed that the collector reagent affects bubble-particle interaction. In the flotation process, formation of stable bubble-particle aggregates is desired, so that the optimum separation efficiency is achieved. This study provides a better understanding of the mechanisms of particle-bubble interaction and the factors affecting it qualitatively.

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