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# Effect of air flow rate and froth depth on the flotation performance: An industrial case study in a 10 m³ cell

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**Abstract:** The main purpose of the froth zone in flotation is to transport all the valuable particles from the pulp zone into the concentrate. However, in practice, a complete recovery of these particles is rarely achieved since some of them are detachment from the bubbles and return to the pulp zone. While this is an important topic in the mineral flotation industry, the previously published papers are mainly limited to small laboratory scales. Therefore, this study aimed to examine the effect of two main flotation variables (air flowrate and froth depth) on the flotation of iron ore in a 10 m³ industrial scale cell. It was found that, when the air flowrate increased from 45 to 146 m³/h, the velocity of the bubble coalescence also increased. In addition, when the froth depth increased from 5 to 30 cm, the product grade showed on average 2 unit increase (for instance, from 12% to 14%) due to the detachment of particles and liquid drainage. It was also found that the flotation concentrates recovery decreased with the increasing froth depth and air flowrate.

*Keywords:* entrainment, bubble coalescence, air flowrate, froth depth

## 1. Introduction

Flotation is a chemical-physical process for the selective separation of hydrophobic materials from hydrophilic particles (Mavros and Matis, 1992). The flotation zone can be divided into collection zone (pulp), froth zone, and pulp-froth interface. The overall recovery indeed depends on the performance of these three zones (Seaman et al., 2006; Yianatos et al., 2008). Pulp-froth interface zone is located at the end of the pulp zone and previous studies have shown its considerable importance and effect on flotation performance (Seaman et al., 2006). The froth zone has also considerable importance on the flotation overall performance due to transferring the particle-bubble aggregates to the outside of the cell and forming the final concentrate (Mavros and Matis, 1992). In general, the shape of a bubble changes in the froth zone. As the bubble moves away from the froth-pulp interface, its shape is angled and separated by lamella. Polyhedral bubbles initially have the same volume as the bubbles that enter the froth, but when the lamella disappears, bubbles begin to coalesce rapidly to form larger bubbles. Also, in the froth structure, channels are formed that arise from the intersection of three lamellas, which are called plateau borders and due to the surface tension, the angle between the lamellae that make up the plateaus is 120° (Gorain et al., 2009).

In the flotation process, all particles that reach the froth zone cannot fully enter the concentrate due to parameters such as entrainment, liquid drainage, detachment of particles, or bubble coalescence. Therefore, some of these particles return to the pulp zone. The hydrophilic particles usually enter the froth zone through entrainment, transfer of particles attached to the hydrophobic particles, and hetero coagulation although, entrainment has a more important effect (Cilek and Umucu, 2001). However, according to Cilek (2009), the main mechanism that gangue particles transfer to the froth is via true flotation rather than entrainment (Cilek, 2009). It should be mentioned that Eq. (1) is often used to measure the recovery of hydrophilic particles by entrainment (Cilek and Umucu, 2001):

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$$R_g = x^{0.2684} - 0.0276T_f(R_w^{-1.0311} - 0.1186V_a) \quad (1)$$

where $R_g$ is the gangue recovery, $x$ is the percentage of solids by weight in the pulp, $V_a$ is the aeration rate in $dm^3/min$, $T_f$ is the froth depths in cm, and $R_w$ is the water recovery (Cilek and Umucu, 2001).

In the upper part of the froth zone, the bubbles tend to connect due to film rupture. When the film ruptures, some of the liquid is released and moves to the bottom of the froth, leading to an increase in the liquid at the bottom of the froth. Therefore, the upper layer of the froth is usually dry in contrast to the lower area (Ata, 2012). Extensive studies have been performed on liquid drainage in two-phase foams (Pal and Masliyah, 1990; Neethling and Cilliers, 2002; Stevenson, 2006; Yianatos et al., 2018). Since mineral flotation contains large amounts of solid particles with different physical and chemical properties with high fluid content, theories have been developed that two-phase foam cannot be applied in understanding the flotation behaviour directly as solid properties affect the froth drainage dynamics (Ata, 2012).

In the flotation process, particles are initially attached to the bubble surface in the pulp zone, but not all of the attached particles enter the concentrate. In fact, some of the particles are detached either in the pulp or in the froth zone. It should be mentioned that particle detachment in the froth zone is different from the pulp zone (Ata, 2009). Detachment of the particles from the bubble can take place in different ways. The most probable way in the froth zone is the collision of the bubble-particle aggregates with the pulp-froth interface. Other forms usually occur in the pulp zone which is more turbulent (Seaman et al., 2006). When the particle-bubble velocity decreases at the pulp-froth interface, the released kinetic energy causes the particles which are attached to the bubble to oscillate and detach (Seaman et al., 2006). According to Falutsu (1994), the main reason for detachment of the particles in the froth zone is related to the energy change and deceleration due to changes in the environment and collisions with the interface (Falutsu, 1994). Another reason for the detachment of the particles from the bubbles is bubbles coalescence. When the bubbles are coated with particles, it is expected that some of the particles detach from the bubble surface after the coalescence due to the reduction in the bubble surface (Bournival and Ata, 2010). Although, a combination of surface loss and fluctuations created after the coalescence may be the cause of the particle-bubble detachment (Ata, 2009).

One of the main reasons for the coalescence of bubbles in the froth is film rupture (a thin layer of liquid that separates two adjacent bubbles). When the amount of water in the froth is less than a critical value, the probability of bubble coalescence increases. The presence of particles and surfactants is effective on the thin film rupture and film collapse has been studied both experimentally and theoretically in flotation (Ata, 2012; Farrokhpay, 2011). Bubble collapse has been shown to occur when the liquid part of the froth is less than the minimum allowable value for bubble regeneration (Langevin, 2015).

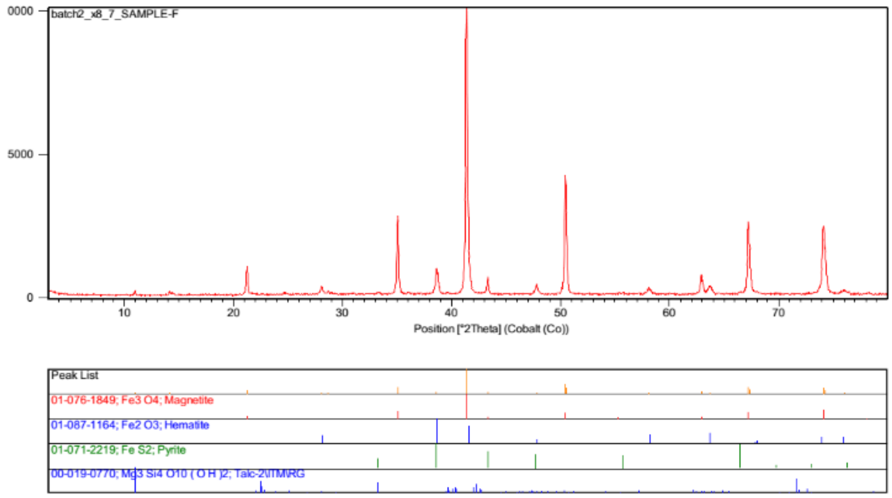
Ireland (2009) showed that liquid drainage takes longer when the bubbles are separated by a thick liquid film. Wang et al. (2019) have also found that coating the bubble surface with particles may increase the time at which bubbles coalesce. Ata et al. (2003) investigated the bubble size changes in the froth zone in a flotation column in the presence of particles of varying degrees of hydrophobicity. They observed that the bubble size increase rate depends on the degrees of hydrophobicity of the particles (Ata et al., 2003). For example, maximum froth stability is created for relatively hydrophobic particles (Farrokhpay, 2011). Hydrophilic particles that have entered the froth zone through the entrainment reduce the bubble coalescence due to increased viscosity and blockage of the drainage channels (Zhang, 2016). Castro et al. (2013) have researched the effects of mineral salts and frothers. By measuring the diameter of the bubbles in the froth zone, they showed that at certain concentrations of mineral salts and frothers, the bubble collapse rate decreases (Castro et al., 2013). This subject has also been investigated by Arancibia-Bravoa et al. (2019). It has been also found that the coalescence of bubbles also depends on mechanical disturbances such as vibrations and bubble oscillation (Ireland, 2009).

According to the above review, several factors such as particle size and hydrophobicity, frothers, air flowrate, and pulp density can affect the froth phase in flotation. Common observations in the froth zone are not only related to each other but they can affect both froth stability and froth recovery. Therefore, the froth zone and then whatever happens in this phase can play an important role in determining the recovery and grade of concentrates. In this paper, the effect of air flowrate and froth depth on the flotation of iron ore is discussed.

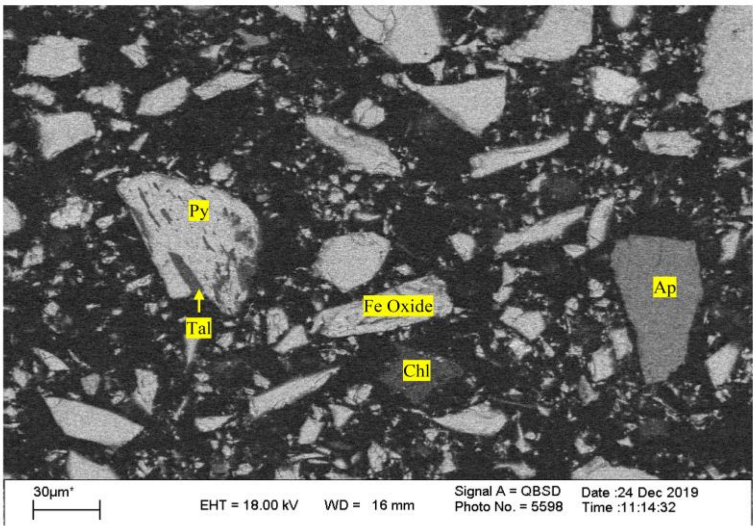
## 2. Materials and methods

The experiments were performed in one of the flotation lines of Gol-e-Gohar Iron Company (Kerman, Iran), which is used to desulfurize iron ore concentrate. These experiments were performed on the first flotation cell, RCS10. The expressed cell was induced air and had a capacity of 10 $m^3$. Also, because the purpose of flotation is to reduce sulfide minerals (mainly pyrite), Potassium amyl xanthate (PAX) and methyl isobutyl carbinol (MIBC) were used as collector and frother, respectively. It should be mentioned that no washing water was added to the flotation cell during the experiments.

Chemical analysis of the feed showed the average grade of Fe and S as 65.75% and 1.03%, respectively. Mineralogy studies (XRD and SEM) showed magnetite as the main mineral. The sample also contained hematite, pyrite, and talc. Pyrite was the main sulphur-bearing mineral in the sample (Fig. 1).




(a)




(b)

Fig. 1. XRD (a) and SEM (b) results on the sample

As stated, the effect of air flowrate and froth depth parameters on the froth zone and consequently, on the flotation recovery was investigated. Due to the small number of parameters, the full factorial design was used for this purpose where all possible combinations of the factors and levels could be investigated. Therefore, the amount of air flowrate and froth depth were changed in three levels as shown in Table 1. These levels were chosen based on the previous laboratory test results, as well as the flotation industrial cell limitations.

Table 1. Factors and levels intended for experiments

| Values | Levels | | |
|---|---|---|---|
| | -1 | 0 | +1 |
| ***Air flowrate - $Q_g$ ($m^3/h$)*** | 45 | 95.5 | 146 |
| ***Froth depth - $D_f$ (cm)*** | 5 | 17.5 | 30 |

## 3. Results and discussion

As shown in Table 2, when froth depth increases, the amount of froth leaving the flotation cell decreases, but on the other hand, its grade increases. In other words, it can be said that with increasing the froth depth, the ratio of sulfide minerals to the total particles entering the concentrate increases. In contrast, when air flowrate increases, the rate at which particles enter the concentrate also increases, but with a lower sulfur grade.

Table 2. The mass flowrate ($M_S$) and S grade results

| No. | $D_f$ (cm) | $Q_g$ ($m^3/h$) | $S$ (%) | Mass flowrate (MS) (Mg/h) |
|---|---|---|---|---|
| 1 | 5 | 45 | 12.67 | 0.98 |
| 2 | 17.5 | 45 | 14.07 | 0.57 |
| 3 | 30 | 45 | 15.67 | 0.30 |
| 4 | 5 | 95.5 | 12.1 | 1.24 |
| 5 | 17.5 | 95.5 | 13.42 | 0.95 |
| 6 | 30 | 95.5 | 14.42 | 0.74 |
| 7 | 5 | 146 | 11.26 | 1.74 |
| 8 | 17.5 | 146 | 12.78 | 1.48 |
| 9 | 30 | 146 | 13.15 | 1.10 |

According to the diagram, the increase in air flowrate causes a decrease in the S, which is almost the same for both froth depths (5 and 30 cm). Regarding the mass flowrate rate into concentrate, increasing the froth depth reduces the rate of particles entering the concentrate, but increasing air flowrate to a significant amount can affect the increase in the froth depth and reduce its effect (Fig. 2). For example, when froth depth is 30 cm and the air flowrate increases from 45 to 146 $m^3/h$, the mass flowrate rate of the particles into the concentrate increases from 0.3 to 1.1 Mg/h. At the same time, the S decreases from 15.7% to 13.1%. It is observed that when the air flowrate increases from 45 to 146 $m^3/h$ when froth depth is 5 cm, the mass flowrate was almost doubled.

The results of the analysis of variance and p-value show that the effect of the examined parameters on flotation concentrate recovery is significant and is at the 95% confidence level (Table 3).

Fig. 3 shows the effect of increasing air flowrate and froth depth on the flotation concentrate recovery. It is observed that when air flowrate increases from 45 to 146 $m^3/h$, at froth depths of 5 and 30 cm, the value of R increases from 11% to 17%, and from 4% to 12%. It seems that the $Q_g$-R graph is a convex curve at the low froth depth (i.e., 5 cm), and a concave curve at the high froth depth (i.e., 30 cm). It can be concluded that the effect of increasing air flowrate on the flotation concentrate recovery at the low froth depth is more considerable than at the high froth depth.

It is observed that changes in air flowrate and froth depth can affect the froth zone behaviour. They can affect, for example, the entrainment and drop back of the particles to the pulp zone. As shown in Fig. 4a, the minimum S content (i.e., 12%) occurs when the air flowrate is 146 $m^3/h$ and froth depth is 5 in decreasing the concentrate grade. However, when the froth depth increases, the particles with less

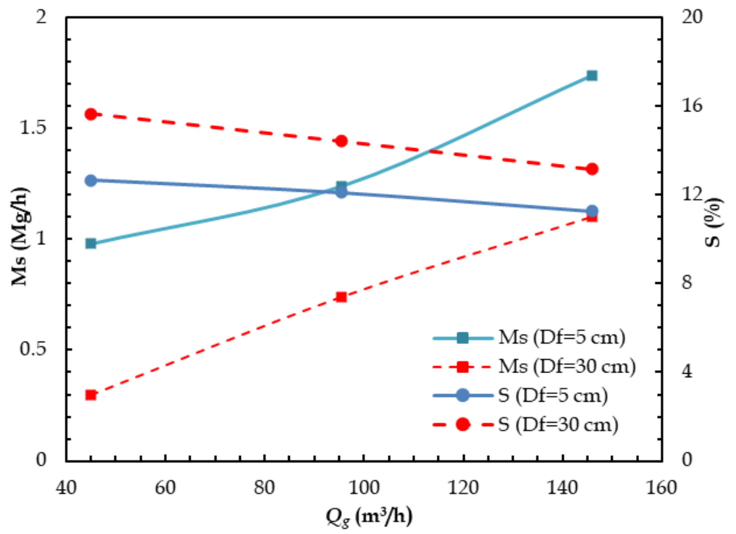



Fig. 2. Effect of air flowrate and froth depth on the mass flowrate ($M_S$) and S grade

Table 3. The variance analysis of effective parameters on the flotation concentrate recovery

| Source | Sum of Squares | $D_f$ | Mean Square | F Value | P-Value |
|---|---|---|---|---|---|
| Model | 131.14 | 2 | 65.57 | 92.44 | < 0.0001 |
| froth depth | 36.17 | 1 | 36.17 | 50.99 | 0.0004 |
| air flow rate | 94.98 | 1 | 94.98 | 133.90 | < 0.0001 |
| Residual | 4.26 | 6 | 0.71 | | |
| Cor Total | 135.40 | 8 | | | |

hydrophobicity may detach from the bubbles and drop back to the pulp zone, resulting in an increased product grade.

It was found that the sulphur grade in the upper area of the froth zone is much higher than the concentrate (Fig. 4b). Liquid drainage in the froth zone is one of the main reasons for this behaviour. Since hydrophilic particles are usually suspended between the lamellae and the Plateau borders (Farrokhpay, 2011) and they may come out of the froth zone with water, which increases the grade in this area. Losing weak bubbles can be also another reason. Because the bubbles that are coated with weaker particles burst faster (Ata, 2012; Wang et al., 2019) and as a result, they come out of this area through liquid drainage. It should be noted that the explained factors can affect the pulp zone as well (Ostadrahimi et al., 2021).

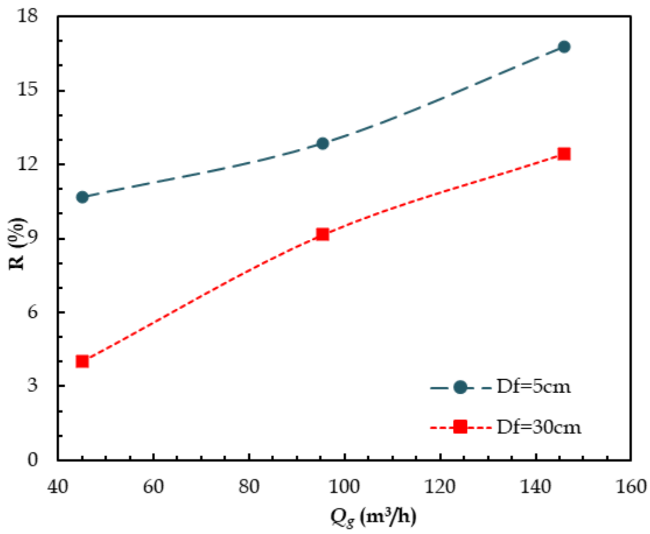
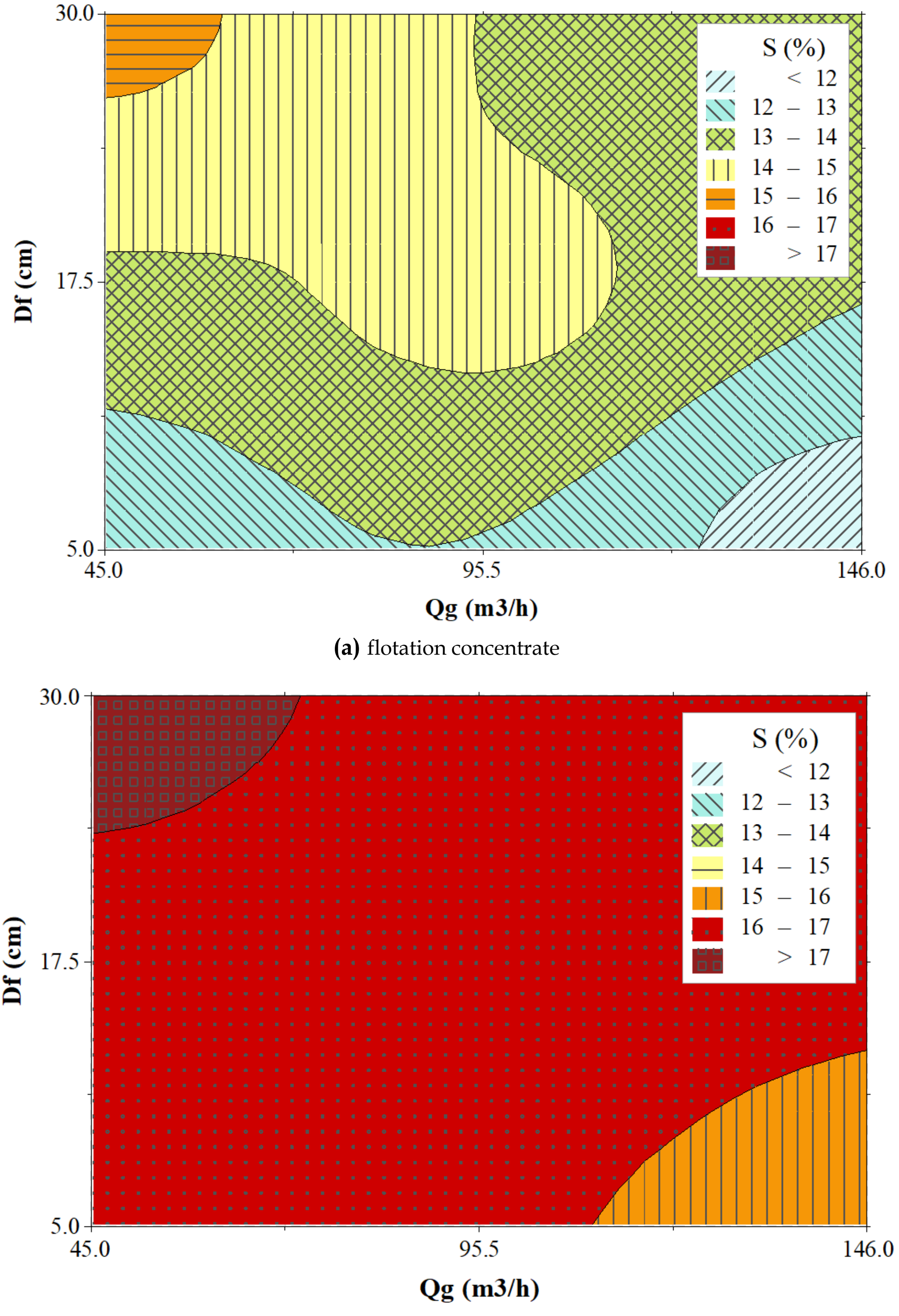



Fig. 3. Effect of air flowrate and froth depth on the flotation concentrate recovery




**(a)** flotation concentrate



(b) the upper area of the froth zone

Fig. 4. Effect of air flowrate and froth depth on the S grade

It has been reported that higher air flowrate results in decreased bubble loading (Ostadrahimi et al., 2019), which leads to the formation of weaker bubbles. In the current study, when the amount of air flowrate increased from 45 to 146 $m^3/h$, the time of bubbles coalescence and bursting reduced from 9 s to 5 s. In other words, the rate of bubbles coalescence increased by about 80%, which showed a negative effect on the flotation concentrate recovery. However, due to the significant effect of the air flowrate on increasing the presence of particles in the froth zone, this effect was not noticeable in our case (Fig. 5).

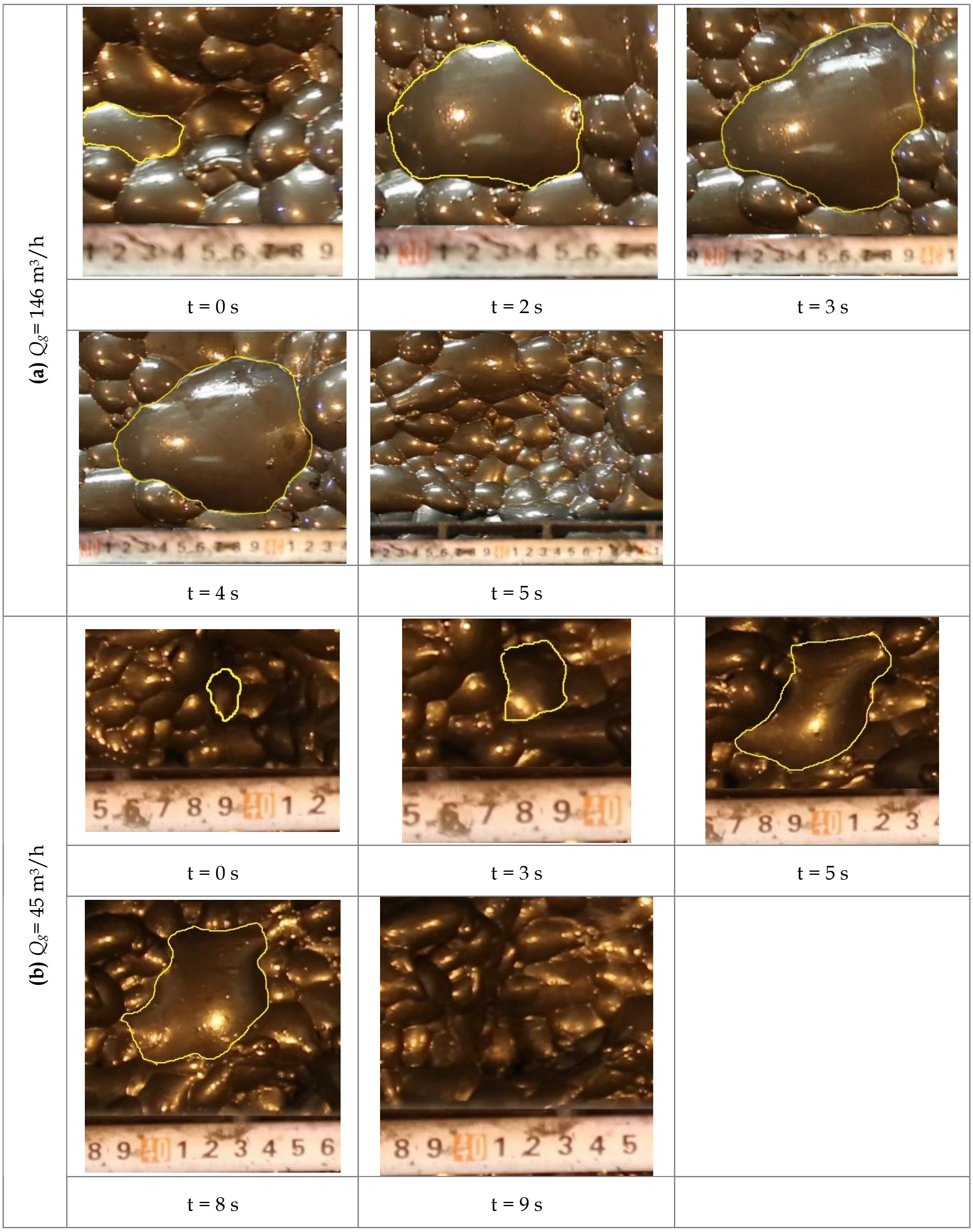



Fig. 5. Effect of the air flowrate on the bubble coalescence

## 4. Conclusions

It is known that the froth zone has great importance on the flotation process performance. However, Interestingly, the froth zone can have both positive and negative effects on the output concentrate. In the froth zone, the bubble motion force guides the attached particles upward to the flotation cell. At the same time, gravity causes the particles to move downwards. If these particles can stay longer in the froth zone, the effect of gravity may become dominant and therefore, the weakly attached particles detach from the bubbles and drop back to the pulp zone. Therefore, by increasing the froth depth and decreasing the air flowrate, the froth retention time increases, and consequently, the amount of drop-back particles also increases.

It was found that the flotation concentrates S grade increases with increasing the froth depth and decreasing the air flowrate. However, at the same time, the mass flowrate of the concentrates decreases. In the current study, increasing the froth depth and reducing the air flowrate resulted in enhancement of the S grade by about 39%, while at the same time, the mass flowrate decreased considerably by 480%.

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