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Study of the effect of airflow rate and agitation speed on entrainment of ash particles in bottom ash flotation

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Abstract: To enhance the recovery and grade of the final product, reducing the entrainment of the hydrophilic particles during flotation is critical. We conducted the improvement of entrainment to reduce the amount of ash in the concentrate with the purpose of recovering high-quality unburned carbon from the bottom ash and reusing it as fuel in power plant. In this study, we investigated the effects of airflow rate and agitation speed on the entrainment of hydrophilic particles. In the self-aerating flotation machine, it was difficult to independently control the agitation speed and airflow rate, resulting in the degree of entrainment of 0.74. By independently controlling the airflow in which hydrophobic particles can float under conditions of the degree of entrainment with 0.7 (low agitation speed: 900 rpm), the combustible recovery and unburned carbon content of concentrate were 93.71% and 93.60%, respectively. The degree of entrainment was found to be 0.57, and entrainment could be minimized through independent control of airflow rate and agitation speed. To minimize entrainment, it is effective to inject air that can suspend hydrophobic particles in a low agitation speed condition.

***Keywords*:** flotation, entrainment, airflow rate, bottom ash

1. Introduction

In South Korea, thermal power generation will account for 34.3 % of electricity production by 2021, and the increasing generation of coal ash as a byproduct has drawn attention to the need for recycling (Kim et al., 2022). However, unburned carbon in fly and bottom ash can be adsorbed on the surface of concrete, reducing its strength. Several researchers have studied the selective removal of unburned carbon from coal fly ash for recycling in cement mixtures, soil stabilizers, fertilizers, and other applications (Zhang et al., 2020; Zhou et al., 2017; Yang et al., 2019; Zhang et al., 2015; Yang et al., 2019). However, bottom ash is currently only recycled in limited applications, and the majority of it is disposed of in landfills owing to its high sulfur and unburned carbon, along with its non-uniform particle shape (Um et al., 2008). Moon et al. (2016) reported that using bottom ash with removed unburned carbon and impurities as aggregates resulted in excellent brick performance. The selective removal of unburned carbon is critical for the recycling of bottom ash in various fields. Um et al. (2008) investigated a column flotation technique for separating unburned carbon from bottom ash. Using column flotation, they investigated the effects of factors such as sample input, machine, and pH. In South Korea, recycling is possible if the unburned carbon content of the bottom ash is less than 5% (Kim et al., 2018). However, previous researches of bottom ash flotation has been conducted on flotation element technology to remove unburned carbon from bottom ash, but there has been no research that has actually focused on the content of unburned carbon in bottom ash that has been processed through flotation.

In addition, fly ash/bottom ash from which the unburned carbon has been removed can be recycled, but the recovered unburned carbon concentrate contains a large amount of ash, making it difficult to reuse the unburned carbon as an energy fuel. Ultimately, in bottom ash/fly ash flotation, it is important to research how to reduce the entrainment of ash recovered as concentrate so that both

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concentrate and tailings can be recycled. In this study, we aim to differentiate from conventional approaches by emphasizing the recovery of high-quality unburned carbon through flotation for its potential reuse as fuel in power plants. The key focus here is to reduce the amount of ash within the recovered concentrate. This is closely associated with the entrainment of hydrophilic particles (gangue particles). Flotation is a separation process that utilizes the differences in surface properties of hydrophilic and hydrophobic minerals (Wills and Finch, 2016). It was previously widely used to improve the grade of coal. Flotation studies are typically conducted using laboratory-scale self-aerating flotation machines. A self-aerating flotation machine uses the pressure difference created by the impeller's rotation to self-aspire. When the agitation speed is low, the airflow rate is minimal. One drawback of a self-aerating flotation machine is that airflow control is achieved by adjusting the agitation speed. In general, as the airflow rate increases, some hydrophilic minerals may float along with hydrophobic particles, increasing yield and recovery; however, the concentrate content may decrease (Rubinstein, 1994). Various researchers have worked on flotation to reduce the entrainment of hydrophilic particles (Johnson, 1972; Yianatos and Contreras, 2010; Warren, 1985; Laskowski, 2007, Yang et al., 2019; Wang et al., 2016). In general, as airflow increases, the degree of entrainment increases. This is because an increase in air velocity increases slurry velocity. According to Zheng et al. (2006), the degree of entrainment increases as the airflow rate increases and foam height decreases. Meng (2006) measured and adjusted the turbulence of a slurry to reduce entrainment. Entrainment is significantly affected by slurry velocity (turbulence), and factors that can regulate slurry velocity include impeller agitation speed and airflow rate.

In this study, we investigated the effects of agitation speed and airflow on the degree of entrainment. Airflow cannot be independently controlled by self-aerating flotation machines. This is because as the agitation speed increased, the airflow increased simultaneously. Many industrial flotation facilities have recently installed forced-air flotation machines. Forced-air flotation machines allow for independent control of agitation speed and airflow, reducing the degree of entrainment. However, the extent to which the interaction between airflow rate and agitation speed influences the degree of entrainment is not yet clear. In previous studies on the flotation of bottom ash and fly ash, all flotation machines were self-aerating. This study aims to use a forced-air flotation machine to reduce the degree of entrainment in bottom ash flotation and enhance the grade of floated unburned carbon. We compared the degree of entrainment in terms of unburned carbon grade in the froth as well as the amount of water and ash recovered in the froth in response to changes in airflow and agitation speed in flotation experiments using self-aerating and forced-air flotation machines. According to Tabosa et al. (2016), the degree of entrainment is influenced not only by impeller speed and air velocity but also by the geometric structure of the cell. Based on the cell volume, Anzoom et al. (2020) investigated the degree of entrainment of hydrophilic particles. Therefore, we analyzed the degree of entrainment concerning the cell volume and impeller size, as a function of mechanical parameters (airflow rate, agitation speed, cell volume, and impeller diameter) in flotation separation machines.

2. Materials and methods

2.1. Bottom ash samples

In this study, bottom ash generated from a coal-fired power plant in Gyeongsangnam-do, South Korea, was used. The flowsheet for the bottom ash separation is shown in Fig. 1. The unburned carbon content of the landfill bottom ash sampled was ~ 25 %. Following particle size analysis, the unburned carbon content was calculated based on particle size. Table 1 summarizes the results of the particle size and unburned carbon content analyses. Particles larger than + 1.19 mm were found to account for ~ 10 % of the bottom ash samples, while the particles 0.09 - 0.6 mm in size accounted for ~ 70 % of the yield, with the unburned carbon amount reaching 91 %.

Table 2 summarizes the XRF analysis results for bottom ash, which revealed a Fe_2O_3 content of ~ 5 %. Bottom ash contains Fe_2O_3, interfering with the adsorption of collectors and unburned carbon during flotation using oil as a collector. Therefore, dry magnetic separation was used as a flotation pretreatment process.

The magnetic separation between magnetic and nonmagnetic materials was performed using a magnetic force of 2000 gauss. The flotation experiments were fed nonmagnetic materials with Fe_2O_3 and unburned carbon contents of 4.8 and 49.5 %, respectively.

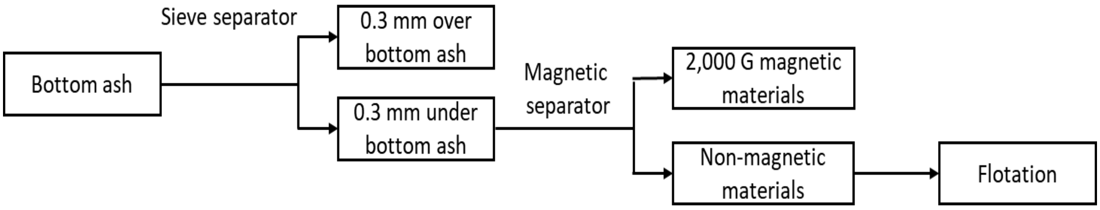


Fig. 1. Flow sheet of experiments of bottom ash

Table 1. Particle size and proximate analysis of bottom ash

Particle size [mm]	Weight [wt.%]	Content of unburned carbon [%]	Amount of unburned carbon [%]	Content of Ash [%]
+ 4.76	4.2	-	-	-
1.19 - 4.76	5.7	17.9	3.9	82.1
0.60 - 1.19	4.7	11.6	2.1	88.4
0.30 - 0.60	23.6	40.7	37.2	59.3
0.15 - 0.30	33.7	35.1	45.8	64.9
0.09 - 0.15	13.1	15.6	7.9	84.4
0.04 - 0.09	9.8	5.8	2.2	94.2
– 0.04	4.9	4.6	0.9	95.4

Table 2. XRF analysis of bottom ash

SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3	K_2O
59.15	15.89	4.94	3.16	1.70	2.29	1.44
Na_2O	TiO_2	Cl	P_2O_5	WO_3	MnO	SrO
3.78	1.16	5.97	0.30	0.10	0.06	0.05

Table 3. The Fe_2O_3 and unburned carbon content of magnetic and non-magnetic materials

	Yield [wt.%]	Content of Fe_2O_3 [%]	Content of unburned carbon [%]
magnetic materials [2000 Gauss]	13.97	18.17	6.1
Non-magnetic materials	86.03	2.93	49.5

2.2. Flotation experiment methods

The flotation experiments were conducted on a self-aerating Denver flotation machine, as illustrated in Fig. 2. An airflow meter was installed to measure the airflow rate based on the agitation speed of the self-aerating type. The airflow in the forced-air flotation machine was controlled using an airflow meter and compressor, as depicted in Fig. 2(b) and (c).

At a density of 10 %, a slurry of water and bottom ash was agitated for 10 min. Subsequently, collectors and frothers were added, followed by 3 min of agitation. The flotation flowsheet is shown in Fig. 3. The operating conditions for the flotation experiments are listed in Table 4.

(a) Denver aeration flotation (b) Air flow meter (c) Air Compressor

Fig. 2. (a) Self-aerating Flotation machine, (b) and (c) air injection system

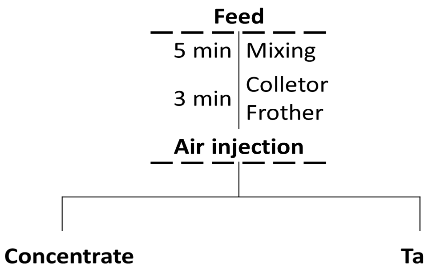


Fig. 3. Flowsheet of bottom ash flotation

Table 4. Operating conditions of flotation experiments

Operating parameter	Conditions
Solids/Water ratio	10 %
Collector	Waste cooking oil (6kg/ton)
Frother	methyl isobutyl carbinol (450g/ton)
Agitation speed	900 ~ 1500 rpm
pH of the pulp	7 (natural pH)

The unburned carbon and ash contents of the recovered froth were determined using proximate analysis. The separation efficiencies of self-aerating and forced-air flotation machines are discussed in terms of ash recovery (R_a), combustible recovery (R_c), entrained water recovery (R_w), and concentrate carbon content. The combustible recovery is expressed in terms of the weight (C) and unburned carbon content of the concentrate (Cc) and is expressed as follows (Anzoom et al., 2020; Yu et al., 2023):

$$Rc\ [\%] = \frac{Cc_c}{Ff_c} \times 100 \tag{1}$$

The flotation data were used to calculate water recovery (Eq. (2)) and ash recovery (Equation (3)): The degree of entrainment is defined as Equation (4) (Wang et al., 2016; Yang et al., 2019).

$$Rw\ [\%] = \frac{W_c}{W_f} \times 100 \tag{2}$$

$$Ra\ [\%] = \frac{Cc_a}{Ff_a} \times 100 \tag{3}$$

$$ENT = \frac{R_a}{R_w} \tag{4}$$

where R_c, R_w, and R_a represent combustible recovery, entrained water recovery, and ash recovery, respectively. C and F are the weight masses of the feed and concentrate, respectively. C_c, C_a, f_a, f_c, W_f, and W_c represent the unburned carbon content, ash content in the concentrate, unburned carbon, ash contents in the feed, amount of water in the feed, and the amount of water recovered in the concentrate, respectively.

3. Results

3.1. Separation efficiency of self-aerating flotation machine

The airflow rate in the self-aerating flotation machine was measured according to the variation in agitation speed, and the results are shown in Fig. 4. Self-aerating flotation is the intake of air via the pressure difference generated by impeller rotation. Impellers with diameters of 7.1 and 9.8 cm and stators with diameters of 9.6 and 13.5 cm were used. As the agitation speed increased, so did the airflow. Larger stators and impellers resulted in higher airflow rates. This is a characteristic of a self-aerating flotation machine in which the airflow rate increases as the agitation speed increases.

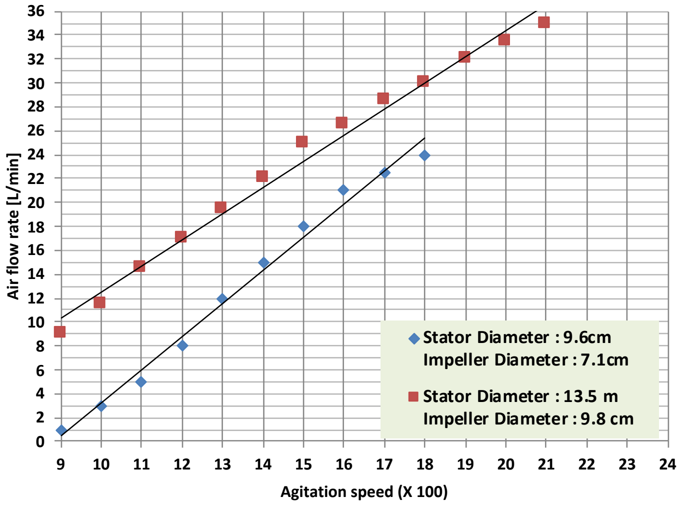
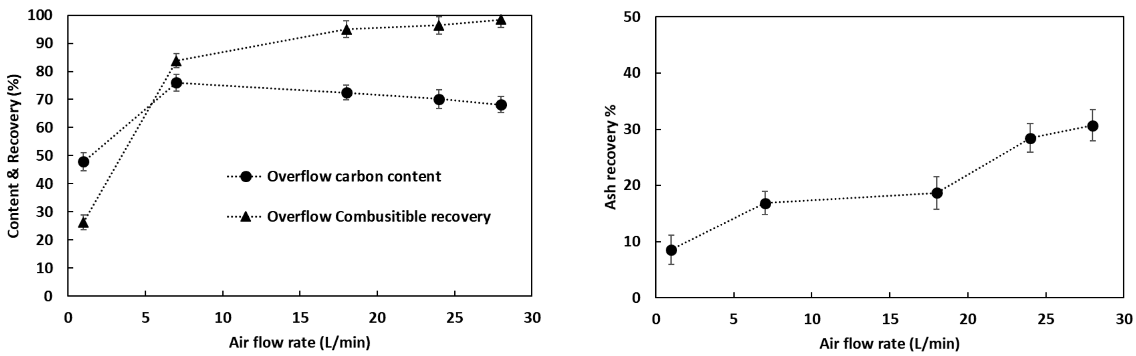


Fig. 4. Airflow rate according to the agitation speed variation

The impact of changes in airflow rate on recovery was investigated using a self-aerating flotation machine. The dosage of the waste cooking oil collector is 6 kg/ton, M.I.B.C of 450 g/ton is used as a frother. The solid pulp is maintained at pH 7, density 10 %, temperature 25 ℃. Fig. 5(a) depicts the unburned carbon content and combustible recovery of the concentrate as a function of airflow variation. In a self-aerating flotation machine, the agitation speed and airflow increase simultaneously. An increase in airflow implies an increase in agitation speed. The concentration of unburned carbon in the concentrate decreased as the airflow rate increased. Combustible recovery, conversely, increased. Under an airflow of 8 L/min (agitation speed of 1200 rpm), the unburned carbon content was the highest at 76 %. However, a lower ash content indicates more unburned carbon, and a higher combustible recovery indicates a greater amount of ash recovered from the concentrate, indicating entrainment. Fig. 5(b) depicts ash recovery as a function of airflow variation. The high airflow and agitation speed increased turbulence in the slurry, resulting in ash entrainment.



(a) (b)

Fig. 5. Effect of (a) unburned carbon content, combustible recovery, and (b) ash recovery on airflow rate variation

The entrainment of hydrophilic particles is closely related to water recovery. Fig. 6 depicts the linear relationship between water and ash recovery. This implies that the entrained ash in bottom ash flotation was caused by the entrainment phenomenon. The degree of entrainment in the self-aerating flotation machine was 0.8, as shown in Fig. 7.

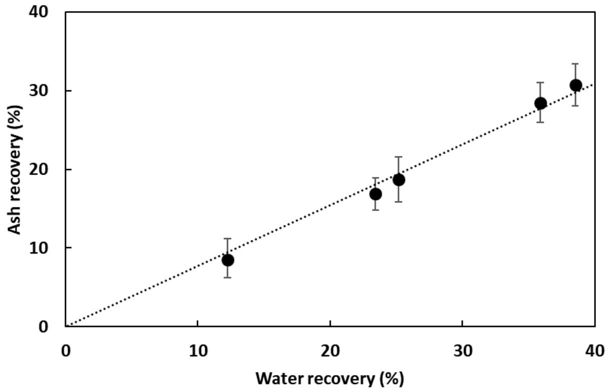


Fig. 6. Relationship between ash recovery and water recovery of concentrate.

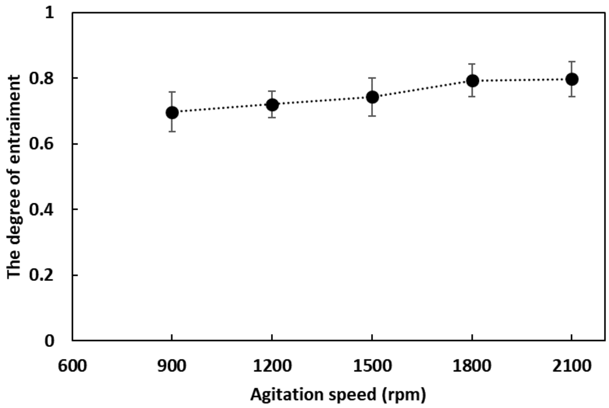
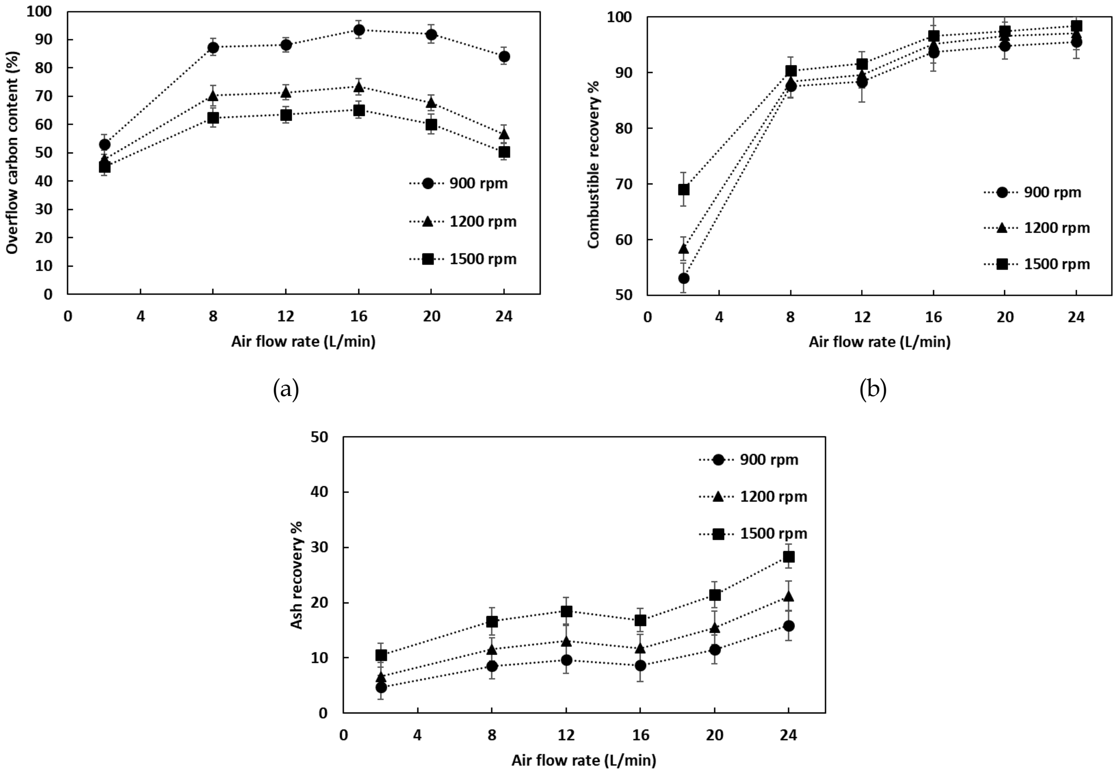


Fig. 7. Degree of entrainment of self-aerating flotation machine

A low-agitation-speed environment is advantageous for reducing ash entrainment in a self-aerating flotation machine. Low agitation speeds, however, present the challenge of low airflow, resulting in a lower combustible recovery in the concentrate. To address this problem, adjusting parameters such as froth height and wash water is more crucial than adjusting mechanical parameters (agitation speed and airflow rate).

3.2. Separation efficiency of forced-air flotation machine

A forced-air flotation machine was used during bottom ash flotation to reduce the ash recovery due to entrainment and improve unburned carbon content in the concentrate froth. The interaction between agitation speed and airflow rate was analyzed concerning the degree of entrainment. The dosage of the collector is 6 kg/ton, M.I.B.C of 450 g/ton is used as a frother. The solid pulp is maintained at pH 7, density 10 %, temperature 25 ℃, mixed at 900 rpm, and adjust airflow rate at 2~ 24 L/min. Fig. 8 illustrates the unburned carbon content and combustible recovery of the concentrate to agitation speed and airflow rate. The airflow rate improved the content and recovery in all agitation speed conditions. However, at a certain airflow rate (above 16 L/min), the unburned carbon content decreased, indicating an increase in turbulence due to the high airflow, leading to entrainment. The combustible recovery increased owing to the floating of ash particles. A high agitation speed causes ash entrainment, resulting in a decrease in the unburned carbon content of the concentrate. The ash recovery concerning agitation speed and airflow rate is shown in Fig. 8(c).



(a) (b) (c)

Fig. 8. Effect of (a) unburned carbon content, (b) combustible recovery, and (c) ash recovery of concentrate on agitation speed at different airflow rates

The ash recovery rate was the lowest at low agitation speeds. This was consistent with the results obtained using a self-aerating flotation machine. However, the forced air type increased the airflow at 900 rpm, increasing the content and recovery of the concentrate. Table 5 compares the separation efficiencies of the two types of flotation machines. The unburned carbon content and recovery of the forced-air type were improved by providing sufficient airflow at an agitation speed of 900 rpm. The content and recovery increased by approximately 2-3 times. Importantly, 8 % equivalent ash recovery was achieved. Surprisingly, the separation efficiency of the forced-air system at 900 rpm outperformed the self-aerating system at 1500 rpm. For practical process operations, a low agitation speed offers several advantages. At 1500 rpm, both machines exhibited comparable content and recovery performances. Finally, the ash recovery was proportional to the agitation speed and airflow rate. A forced-air flotation machine has the following characteristics: 1) It can reduce the entrainment of hydrophilic particles by independently adjusting the agitation speed and airflow. 2) It enhances the concentrate content and recovery. 3) Excellent separation efficiency at low agitation speeds, resulting in energy savings in practical operations. Entrainment reduction research has primarily focused on variables such as froth height and wash water. Significant improvements in entrainment were achieved by independently adjusting the agitation speed and airflow rate. This aspect should be considered by flotation researchers.

Table 5. Comparison of separation efficiency between self-aerating and forced-air flotation machines

Particle size	Self-aerating flotation cell		Forced-air flotation cell	
Agitation speed (rpm)	900	1500	900	1500
Air mass flow (L/min)	1	18	16	16
Overflow carbon content (%)	47.86	72.44	93.6	65.26
Overflow ash recovery (%)	8.54	18.69	8.65	16.83
Overflow combustible recovery (%)	26.3	94.94	93.71	96.67

Fig. 9 compares the ash and water recoveries of the two types of flotation machines. According to numerous researchers, ash and water recoveries exhibit a linear relationship. The crucial point is the difference in recovery between the two flotation machines. The forced-air flotation machine can reduce ash entrainment by adjusting the airflow, particularly at 900 rpm agitation speed conditions, where water and ash recoveries were observed to be low.

The degree of entrainment in the forced air flotation machine, as shown in Fig. 10, was 0.6 at 900 rpm. This indicates a significant improvement in entrainment when compared to the self-aerating flotation machine.

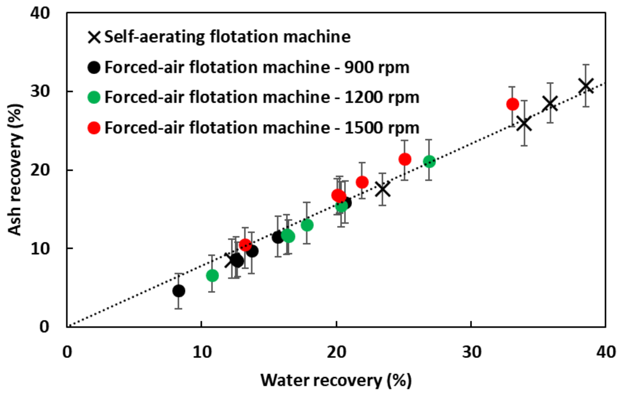


Fig. 9. Comparison of ash and water recovery between self-aerating and forced-air flotation machines

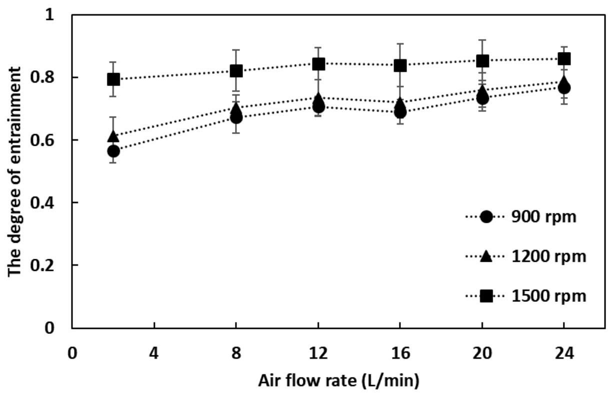


Fig. 10. Degree of entrainment of forced-air flotation machine

3.3. Effect of separation efficiency on cell volume and impeller diameter

The water recovery increased with an increase in the superficial air velocity on the cross-section of the cell. The impact of cell volume on entrainment in a forced-air flotation machine was studied. The content and recovery of the concentrate for 1, 2, and 4 L flotation cells were compared at agitation speeds and airflow rates of 900 rpm and 16 L/min, respectively. The dosage of the collector is 6 kg/ton, M.I.B.C of 450 g/ton is used as a frother. The solid pulp is maintained at pH 7, density 10 %, temperature 25 ℃, mixed at 900 rpm, and adjust airflow rate at 16 L/min. The weight of concentrate product recovered as cell volume variation is affected by scraping and flotation time. In this study, scrapers proportional to the cell volume cross-sectional area were used to recover for the same flotation time. The results are summarized in Table 6.

When the cell volume is increased, the superficial gas velocity and ash recovery decrease. In the 4 L cell, ash recovery decreased while the combustible recovery decreased. This is due to the effect of impeller size on cell volume. Laboratory-scale Denver-subtype flotation machines require an impeller that is proportional to the cell volume. The degree of entrainment was investigated using impellers of varying diameters. The cell volume used in this study was 4 L. The dosage of the collector is 6 kg/ton, M.I.B.C of 450 g/ton is used as a frother. The solid pulp is maintained at pH 7, density 10 %, temperature

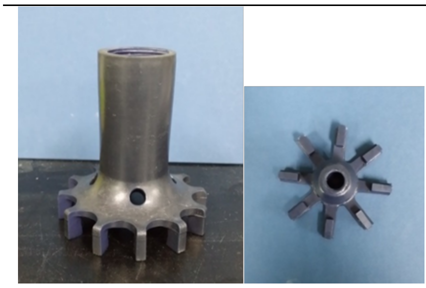
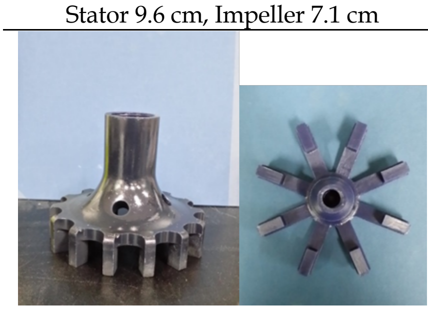
Table 6. Comparison of separation efficiency for cell volume differences

Cell volume	1 L	2 L	4 L
Weight of concentrate (%)	47.25	49.56	42.77
Overflow carbon content (%)	82.6	93.60	94.88
Overflow ash recovery (%)	13.85	8.65	4.34
Overflow combustible recovery (%)	78.85	93.71	81.98
Superficial air velocity (m/s)	0.013	0.01	0.007

25 ℃, mixed at 900 rpm, and adjust airflow rate at 16 L/min. Table 7 presents the flotation results for various impeller diameters. In an experiment using an impeller with a diameter of 9.8 cm under the cell volume of 4L, the combustible recovery was low at 81.98%, but under the condition of an impeller with a diameter of 13.5 cm, the combustible recovery increased significantly to 91.47%. Compared to the cell volume (4 L), the impeller with a diameter of 9.6cm is judged to have a low combustible recovery rate due to the reduced function of stirring and circulation within the mineral slurry. The ash recovery rate increased slightly from 11.24% to 13.33%, but this was due to the increased weight of the overflow. Flotation researchers should remember that cell volume and impeller diameter affect not only the combustible recovery but also the ash recovery by entrainment.

We could reduce the degree of entrainment while simultaneously increasing the unburned carbon content and combustible recovery by adjusting turbulence-related factors in the flotation machine, such as agitation speed, cell volume, and impeller diameter, and injecting the required airflow rate for the floating of hydrophobic particles. Although froth layer height and wash water are important factors in reducing entrainment, significant improvements can be made by adjusting mechanical parameters such as airflow rate, agitation speed, cell volume, and impeller diameter to reduce the degree of entrainment.

Table 7. Comparison of separation efficiency for impeller diameter

Impeller size	Overflow Weight (%)	Overflow carbon content (%)	Overflow ash recovery (%)	Overflow water recovery (%)	Overflow combustible recovery (%)
 Stator 9.6 cm, Impeller 7.1 cm	42.77	94.88	4.34	11.24	81.98
 Stator 13.5 cm, Impeller 9.8 cm	48.93	92.54	7.23	13.33	91.47

4. Recommendation

Previous studies on the flotation of fly ash and bottom ash have primarily focused on the removal of unburned carbon. The amount of overflow ash particles has not been considered. Consequently, while the separated bottom ash can be recycled, the recovered concentrate contains a significant amount of ash, making recycling difficult. This study aims to reduce entrainment to enable recycling of both unburned carbon concentrate and bottom ash. Under conditions of low agitation speed, high airflow rates increase the floatability of hydrophobic particles while reducing the entrainment of hydrophilic particles. This has the advantage of low power consumption for flotation machines, so forced-air flotation machines are being adopted at many mineral processing sites. Various flotation element technologies exist to reduce entrainment, but controlling the airflow rate and agitation speed can decrease the degree of entrainment.

5. Conclusions

Reducing the entrainment of hydrophilic particles during flotation is critical for increasing recovery and product quality. The separation efficiency and degree of ash particle entrainment in bottom ash flotation using self-aerating and forced-air flotation machines are compared in this study. The self-aeration flotation machine exhibited the ash recovery of 8.54% at 900 rpm, with the degree of entrainment of 0.7. However, the carbon content and combustible recovery of the concentrate were low at 47.86% and 6.32%, respectively. At 900 rpm, the airflow rate is measured at 1 L/min. At 1500 rpm with an airflow rate of 18 L/min, combustible recovery of 94.94% was achieved. However, the Ash recovery of concentrate was 18.69%, with a carbon content of 72.44%. The degree of entrainment is 0.74. Even at a low agitation speed of 900 rpm, the forced-air flotation machine injected 16 L/min of air, resulting in a carbon content and combustible recovery of 93.6% and 93.71%, respectively. The degree of entrainment is 0.57. To reduce the entrainment of hydrophilic particles, it is optimal to inject air suitable for the float of hydrophobic particles at low agitation speed. Furthermore, at 4 L cell volume conditions, the ash recovery is 4.34% due to the low superficial air velocity. Increasing the impeller size at a 4L cell volume condition increased the combustible recovery to 91.47%. While research has focused on variables such as wash water and froth layer height, it is clear that controlling the agitation speed and airflow rate can contribute to reduce improvement.

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