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Application of microbubbles for cleaning coal powder

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Abstract

It is known that Thailand has been using natural gas as its main fuel in producing electricity at the present time. A number of these reserved natural gases are likely to be dramatically decreased in the future. However, Thailand also has abundance of another fuel resource, which are the lignite coals that are considered lower quality but cheaper compared to other fuel resources. Even though lignite is not fully accepted and has bad reputation for its harmful impact on environment is being developed and used with clean coal technology in order to lower the pollution from the coal. This aims to study characteristics of bubbles produced by three different bubble generators: porous stones, ejector nozzle and pressure tank. Moreover, this study also investigates the result of coal cleaning by using the generated bubbles in order to carry the coal to the water surface. The result shows that the size of bubbles produced by porous material are appeared larger compares to the bubbles produced by the ejector nozzle combined with pressure tank are smallest. For the coal cleaning, it is found that the bubbles from the ejector nozzle combined with pressure tank can carry more coal powder to the water surface. In addition, flotation time also affects to remove sulfur and ash of the coal. The removal of sulfur content and ash content in coals, decreased with increasing flotation time. In addition, the fixed carbon and gross calorific value of the coals were increased with increasing flotation time.

Keywords: *bubble size, clean coal technology, coal, coal analysis, flotation column, microbubble generator*

1. Introduction

Coal has been used as a source of fuel for centuries. In addition, coal is found in prodigious amounts throughout the world and has lower cost as compared to other fossil fuels (Franco & Diaz, 2009). However, coal utilization has a few negative impacts on the environment. Coal is a complex chemical mixture composed of carbon, hydrogen, and dozens of trace elements. When coal is severed as a fuel source, some of these components would convert to gaseous emissions, such as sulfur dioxide (SO_2), nitrogen oxides (NO_x), and other chemical by products through the coal combustion or thermal decomposition. These emissions have been established to possess harmful effects on the environment (He, Gu, Wang, & Zhang, 2017) and human health, which contributes to acid rain, greenhouse effect, and lung cancer (Longwell, Rubint, & Wilson, 1995; Beer, 2000). For these reasons, the introduction of environmentally friendly Clean Coal Technology (CCT) is one of our subjects of having more coal utilized.

Present commercial coal cleaning methods are mostly based on physical separation; chemical and biological methods tend to be more expensive. Typically, density separation is used to clean coarse coal while surface property-based methods are preferred for fine coal cleaning. In the density-based processes, coal particles are added to a liquid and then exposed to gravity to separate the organic-rich phase from the mineral-rich phase. In the surface property-based processes, pulverized coal is mixed with water and a little amount of collector reagent is added to increase the hydrophobicity of coal surfaces. Then, air bubbles are introduced in the presence of a frother to carry the coal particles to the top of the slurry, separating them from the hydrophilic mineral particles. Commercial surface property-based cleaning is completed through froth or column flotation (Ni et al., 2015; Park, Subasinghe, & Han, 2015; Bu, Zhang, Chen, Xie, & Peng, 2017; Babu, Patnaik, & Sunder, 2018; Bhunia, Kundu, & Mukherjee, 2018).

Microbubbles are the bubbles with diameter ranging from one to several hundred microns, and they are characterized by a great interfacial area concentration per unit gas volume and low relative velocity between the bubbles and liquid phase (Maeda, Hosokawa, Baba, Tomiyama, & Ito, 2015). These characteristics are of huge applying in enhancement of adsorption of impurities at gas–liquid interface and mass transfer between the two phases (Takahashi et al., 2003; Takahashi, 2005). Microbubbles are, therefore, utilized to improve efficiencies and performances of various industrial systems such as water treatment systems (Chu, Xing, Yu, Sun, & Jurcik, 2008; Terasaka, Hirabayashi, Nishino, Fujioka, & Kobayashi, 2011; Rehman, Medley, Bandulasena, & Zimmerman, 2015), washing processes (Oliveira, Rodrigues, & Rubi, 2009), bathing systems (Tajima et al., 2008), chemical reactors (Matsumoto, Fukunaga, & On, 2010), medical systems (Kaneko et al., 2007) and plant cultivation (Park & Kurata, 2009). Since efficiencies and performances of these systems depend on the diameter and number density of microbubbles, it is essential to optimize them in development of the microbubble generators (Serizawa, Inui, Yashiro, & Kawara, 2003; Hirai, Komura, Saechout, & Sugiya, 2009) and to understand a mechanism of microbubble generation.

Various types of microbubble generators have been developed, and most of them can be classified into four methods, i.e., the method based on bubble breakup due to shear flow or pressure wave (Sadatomi, Kawahara, Kano, & Ohtomo, 2005; Fujiwara, Takagi, Watanabe, & Matsumoto, 2003), the method using ultrasonic wave (Makuta, Takemura, Hihara, Matsumoto, & Shoji, 2006; Thiemann, Nowak, Mettin, Holsteyns, & Lippert, 2011), the method using microfluidics technology (Xu, Li, Chen, & Luo, 2006; Arakawa, Yamamoto, & Shoji, 2008; Shintaku, Imamura, & Kawano, 2008) and the method based on bubbles of dissolved gas due to depressurization at a decompression nozzle (Fujikawa, Zhang, Hayama, & Peng, 2003; Hosokawa et al., 2010).

Meanwhile, coal cleaning by selective collection of an aqueous suspension of coal particles was demonstrated on a laboratory scale (Shen & Wheelock, 2000). The microbubbles were produced by saturating water with gas under pressure and then releasing the pressure as the water was agitated. Cyclo-microbubble flotation column is an advanced column flotation technology for fine coal cleaning developed (Li, Tao, Ou, & Liu, 2003). It combines cyclone separation with column flotation to enhance pyritic sulfur rejection and separation efficiency. The cyclo-microbubble flotation column has been successfully employed to recover fine coal from discarded waste ponds and replace conventional mechanical cells. Froth flotation is used in the coal industry to clean a fine coal (Tao, Yu, Zhou, Honaker, & Parekh, 2008). A fundamental analysis has shown that use of picobubbles can significantly improve the flotation recovery of particles by increasing the probability of collision and attachment and reducing the probability of detachment. The experimental results have shown that the use of picobubbles in a column flotation increased the combustible recovery. The amenability of beneficiating a fine hard coal using column flotation has been studied using a CoalPro flotation column. Column flotation is capable of producing an acceptable clean coal concentrate of 85% combustible recovery with 81% ash rejection at maximum separation efficiency of 62%, compared to conventional flotation which has 70% recovery with 70% ash rejection at an efficiency of 42% (Han, Kim, Kim, Subasinghe, & Park, 2014).

However, under the former condition, there is a limitation because a high energy consumption to generate microbubbles and high cost for design. Consequently, it is cause of not widely used in the industry. In order to solve these problems, three types of microbubble generators were tested in order to observe how the factor affects the generation of microbubbles by using a shear flow method of microbubble generators, which for decreases the energy consumption and reduced cost for design. Furthermore, experiments on microbubble generators implementation in coal cleaning to remove excessive impurities for efficient and environmentally safe utilization of coal.

2. Objectives

This study was aimed at enhancing recovery of fine coal sample using a specially designed flotation column featuring a microbubble generator. Several kinds of the microbubble generators were also evaluated based on the size of bubbles suitable for the impurities removed from the coal.

3. Materials and methods

3.1 Microbubble generators

Figure 1 shows the three types of bubble generators used in this study. The air is introduced through small holes in an air diffuser or porous stones (Figure 1(a)), setting at the bottom of column, and the flow of the bubbles is controlled by a rotameter. However, there is a limit in the size of the bubbles produced by such methods.

In Figure 1(b), the ejector nozzle can be made with PVC pipes, the inlet and outlet diameters were 1 inch, the throat diameter is ½ inch. At the throat portion of the ejector nozzle, ¼ inch diameter air hole was drilled through the wall. When the water flow passing through the throat of the ejector, the velocity is accelerated which creates a low pressure zone that draws in and entrains a suction air. The shearing of air–water mixture in turbulent flow creates the microbubbles.

In addition, the ejector nozzle can be used with pressure tank (see Figure 1(c)), the air is dissolved in the liquid into a tank by pressurizing the air-liquid mixture. When this supersaturated liquid is flashed using a reducing valve, microbubbles are generated. The size and number of the microbubbles depend on the pressure in the pressure tank and the decompression process.

3.2 Experimental setup

A schematic diagram of the experimental setup is shown in Figure 2. It consisted of column flotation, a microbubble generator, rotameter for air, rotameter for water, a high pressure pump and a pressure tank.

All experiments were carried out in a 28 L column flotation with glass walls (12.5 cm wide, 30 cm long and 75 cm high). The middle portion of column has a glass plate with a width of 12.5 cm and a thickness of 0.6 cm above the base of column 5 cm but the glass plate high varied 35 cm and 50 cm. To ease clean coal collection, a glass with a platform was mounted at the top of the column flotation. Half the surface of the platform was leveled with the top end of the column flotation, and the other half was an inclined channel so that liquid or coal could easily flow out of the column for coal collection. The microbubble generators used in the experiments as shown in Figure 1, the air flow rate is measured by an air rotameter and controlled by a valve. The water in the experimental setup was recirculated by a high pressure pump, and a water rotameter was used to measure discharge.

3.3 Measurement of the size of microbubbles

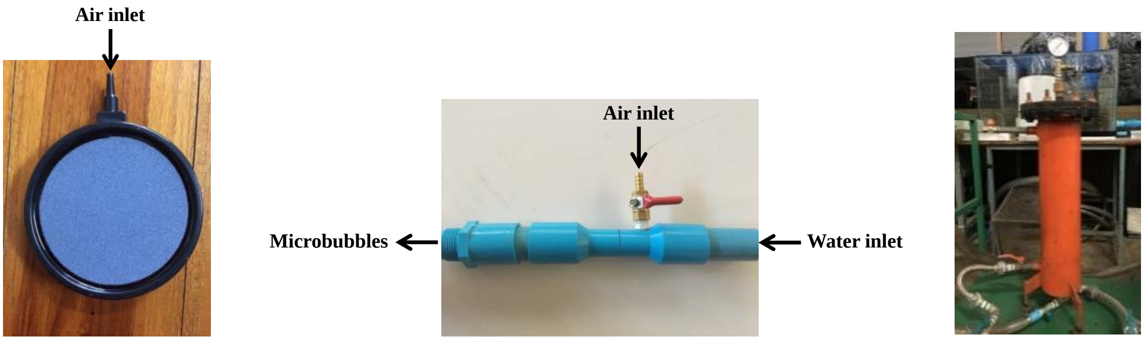
The diameter of the microbubbles produced at different liquid pressure and air flow rates were measured. The schematic diagram for measuring bubble diameter is shown in Figure 3. Air was introduced into water at the bottom of a column flotation. Produced microbubbles were introduced into a bubble chamber, which a glass plate 0.2 cm thickness, 12 cm wide and 16 cm long. The space between the 2 glasses 0.2 cm for the small bubbles can be trapped in a bubble chamber. Bubble diameters were determined by analyzing bubble pictures captured from a digital microscope camera, which set at the top of chamber. For analysis, images processing method the MATLAB software was used.

Image processing method via MATLAB coding was employed to average the bubble diameter from the picture that captured from digital microscope camera. In this process, transforming the original images to grayscale images is shown in Figure 4(a). Next, the gray levels of target object (bubbles) and background are very different. It is easy to accomplish the image with a direct threshold, just as shown in Figure 4(b). Then, the image was directly used to detect the bubble edge for determine the diameter of each bubble as shows in Figure 4(c). Finally, the results of average diameter of bubbles was calculated by dividing the number of bubbles as shows in Figure 4(d). An average diameter of bubbles was received from 10 pictures.

3.4 Materials and methods

Lignite coal samples used in this study were obtained from Mae Moh Mine, Lampang, Thailand. The coal samples was first crushed in a jaw crusher and then further crushed in a hammer crusher. Finally, a gyratory crusher was used to grind the coal samples to a finer size. After crushing and grinding, the coal was screened with sieve and shaker to about 250 µm to be used as a feed in all flotation experiments. Then stored in plastic bags until required for flotation tests.

Prior to each test, the flotation feed was conditioned at 50% solids (consist of coal and water). Then add kerosene used as collector to enhance the hydrophobicity of the coal particle surfaces into the flotation feed. Conditioning was conducted in a conditioning tank that was equipped with a motor and three blades placed vertically of the tank. The impeller rotation speed was kept constant at 620 rpm.



(a) Porous stones (b) Ejector nozzle (c) Pressure tank

Figure 1 Microbubble generators

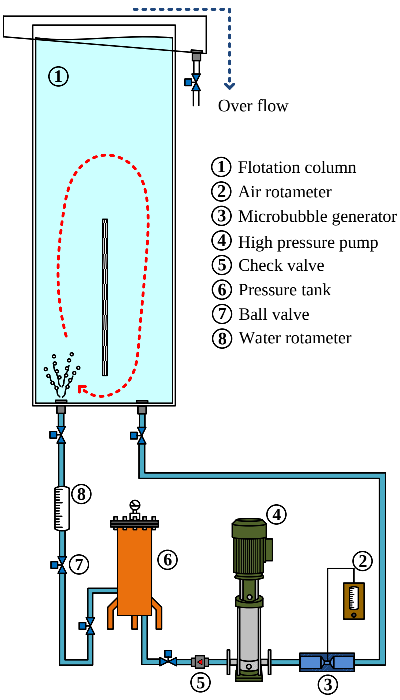


Figure 2 Experimental setup

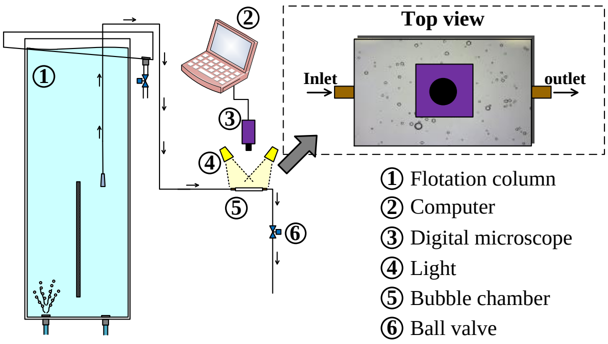
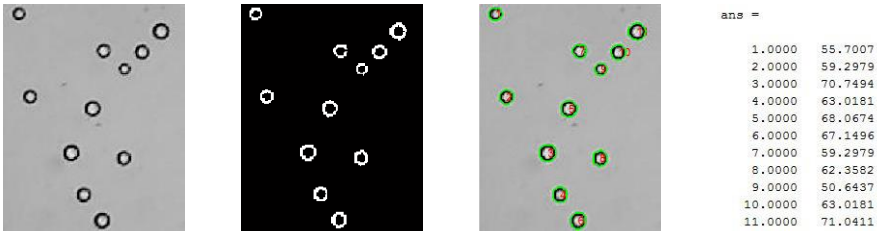


Figure 3 Experimental apparatus for the measurement of bubble diameter



(a) Original image (b) Image processing (c) Result image (d) Diameter of a bubble

Figure 4 Bubble image processing via MATLAB software

At the beginning of the experiments, tap water was added into the flotation column from the top to the desired level. Flotation was started with generating bubbles. Water flow rate and air flow rate were kept constant. Pine oil was mixed thoroughly as the flotation frother. The feed slurry entered the column in the upper portion of the flotation column, 45 cm below the overflow lip. After being fed into the column, the clean coal is concentrated by rising bubbles ascend to the top and the tailings coal is gathered at the bottom of the flotation column. The concentrate and tailings products were collected and dried in the hot air dryer at 110°C for 24 hours. Experiments were carried out at different flotation times keeping all other parameters constant. The details of these experiments are shown in Table 1.

Table 1 Experimental details for coal cleaning

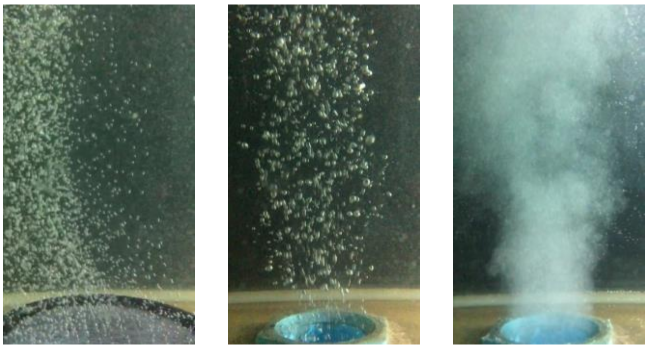
Parameter	Value
Coal size	< 250 microns
Collector dosage (kerosene)	8 kg/t
Frother dosage (pine oil)	0.15 kg/t
Impeller speed	620 rpm
Conditioned time	5 minutes
Water flow rate	20 l/min
Air flow rate	0.7 l/min
Feed position (below the overflow lip)	45 cm
Flotation time	30, 60, 90, 120, and 150 minutes
Drying temperature	110°C

4. Results

4.1 Comparison of bubbles generated by the microbubble generators

Figure 5 shows the photographs of bubbles from each generator. Comparison of bubbles generated by the microbubble generators: porous stones, ejector nozzle and ejector nozzle combine with pressure tank. In the experimental, the water flow rate and air flow rate were kept constant at 50 l/min and 0.7 l/min, respectively. It is clearly seen that each generator can generate the fine bubble but there were differences in terms of size and quantity of bubbles. For case of compressing the air through the porous stone, there is a large bubble and present near to the generator only. The bubble cannot be circulated or accumulated in water for a long of times. While the bubbles from the ejector nozzle are smaller when compare with the bubbles from porous stone. In addition, the bubbles from using the ejector nozzle combine with pressure tank are the smallest. The water becomes milky due to the presence of a lot of fine microbubbles.

Average diameter of the bubbles generated from porous stones, ejector nozzle and ejector nozzle combine with pressure tank were 385 µm, 57 µm and 54 µm, respectively.



(a) Porous stones (b) Ejector nozzle (c) Ejector nozzle with pressure tank

Figure 5 Comparison of the bubble from the microbubble generators

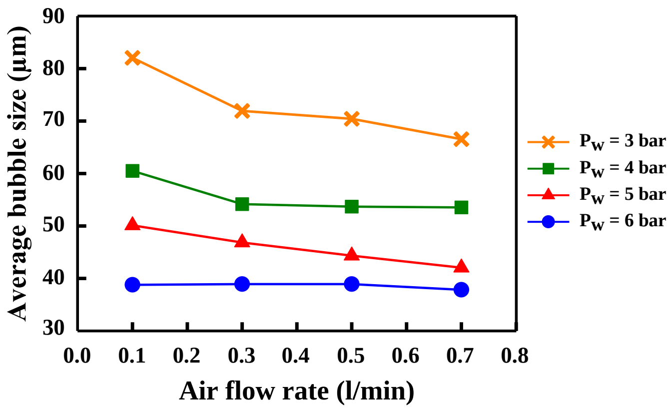


Figure 6 Relations between mean diameter of bubbles and air flow rate for different water pressures

4.2 Effect of pressure on bubble size from ejector nozzle and pressure tank

Figure 6 shows the effect of air flow rate on the mean diameter of bubbles for different water pressures (P_w). The ejector nozzle combined with the pressure tank are used because it is expected to increase the number density of bubbles formed in the flotation column. Under a given air flow rate, the mean diameter decreases with the increase of the water pressure. For a low water pressure, the mean diameter increases sharply. But for a higher water pressure, it increases slowly. Thus, it is important to increase the water pressure in order to enhance the number density by increasing the air flow rate and suppress the average diameter of bubbles.

4.3 Effect of flotation times for coal cleaning

In the experiment, it uses an ejector nozzle combined with a pressure tank to generate bubbles. The microbubbles will increase the probability of collision and reducing the probability of detachment. The flotation times varied at 30, 60, 90, 120 and 150 minutes. The results show that flotation time at 30 minutes, the maximum coal concentrate was 495.6 g. When the flotation time increased from 60 to 150 minutes, the coal concentrate was decreased to 432.4, 375.2, 325.8, 242.8 g, respectively. The water and bubbles effect to the coal concentrate on the water surface recirculated to the bottom of the column.

Finally, the coal concentrate and tailings were proximate analyzed to determine the amount of residual components after cleaned and separated including sulfur, ash, volatile matter, fixed carbon, gross calorific value. The proximate analysis of coal samples as shown in Table 2.

The results show proximate analysis (dry basis) of the components in coal, which raw coal and cleaned coal (consist of concentrate and tailing). The effects of flotation time on removed sulfur and ash of the coal sample in the interval 30-150 minutes are shown in Table 1. These experiments were performed with samples of concentrate coals and tailing coals. The results showed that the removal of sulfur content in the concentrate coals and tailing coals, decreased with increasing flotation time. The concentrate coals at 10.2% sulfur content was achieved at 150 minutes of flotation time. While the tailing coals at 7.1% sulfur content was achieved at 120 minutes of flotation time.

For ash content in coal, the results show that in the concentrate coals and tailing coals were decreased slightly with increasing flotation time. The coal powders entrapped in the froth were removed with an increase in flotation time, thereby decreasing the ash content of the clean coal. The concentrate coals at 20.3% ash content at 60 minutes of flotation time. While in the tailing coals at 20.5% ash content at 150 minutes of flotation time.

In addition, volatile matter in concentrate coals and tailing coals are increased slightly with flotation time about 3.2-3.4% at 60 minutes of flotation time.

Finally, the fixed carbon of clean coal increased along with the gross calorific value, with an increase of the flotation time. The concentrate coals reached 49.6% of fixed carbon and gross calorific value of 22.3% at 60 minutes of flotation time. In addition, the tailing coals reached 48.0% of fixed carbon and gross calorific value of 21.7% at 150 minutes of flotation time.

Table 2 Proximate analysis of raw coals, concentrate coals and tailing coals, dry basis (db), –250 µm

Coal sample	Flotation time (minutes)	Sulfur (wt. %)	Ash (wt. %)	Volatile matter (wt. %)	Fixed carbon (wt. %)	Gross calorific value (MJ/kg)	Gross calorific value (kcal/kg)
Raw coals	-	7.91	42.11	43.00	14.89	15.09	3606
Concentrate coals	30	8.79	35.25	42.58	22.16	18.45	4410
	60	7.89	33.56	44.16	22.28	18.37	4391
	90	7.57	35.65	43.36	20.98	17.89	4276
	120	7.61	41.85	41.68	16.47	15.09	3608
	150	7.10	36.73	44.38	18.89	17.16	4101
Tailing coals	30	7.54	36.30	44.45	19.25	17.25	4122
	60	7.50	37.26	43.06	19.66	17.02	4069
	90	7.68	37.82	43.78	18.40	16.72	3996
	120	7.35	34.79	43.98	21.23	17.59	4204
	150	7.73	33.49	44.47	22.04	18.37	4391

(Laboratory Section, Geology Department, Mae Moh Mine Planning and Administration Division, EGAT)

5. Conclusion

The following major conclusions can be shown by this study:

1. The size of the bubbles generated form porous stone is larger than the ejector nozzle. In addition, using ejector nozzle combined with the pressure tank will generated the bubbles are smallest.

2. The bubble size decreased with increasing the pressure of the water in pressure tank. On the other hand, the number of the bubbles increased with increasing the water pressure.

3. The small bubbles or microbubble can increases the probability of collision between the coal particles and bubbles. So the amount of concentrate coal has increased.

4. Flotation time affects to remove sulfur and ash of the coal. The removal of sulfur content in coals, decreased with increasing flotation time. Also, ash content decreased with increasing flotation time. In addition, the longer flotation time has the effect that the microbubbles stay for a longer time in the water. Microbubbles can be attributed to the high collision probability, high attachment probability and low detachment probability because of the introduction of the hydrophobic attractive force.

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