Effect of ultrasonic standing waves on flotation bubbles

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ABSTRACT

Ultrasonic flotation was an effective method to float fine coal. In this study, the effects of the standing waves with different frequencies on ultrasonic flotation were investigated. The dynamic processes of bubble and coal-bubble aggregation were revealed by a high-speed camera. The results showed that under the action of Bjerknes force, bubble aggregates were formed within 450 ms and coal bubble aggregates were formed within 20 ms. The bubble aggregates were statistically analyzed by image processing method. The number of aggregates and small bubbles in the ultrasonic field at 100 kHz was greater than those at 80 and 120 kHz. Besides, 100 kHz ultrasonic flotation achieved the highest yields of clean coal (35.89%) and combustible recovery (45.77%). The cavitation bubbles acted as either a “medium” or an “inclusion”, entrapping and entraining the coal particles in the flotation pulp. It promoted the aggregation of bubbles with coal particles, so the flotation efficiency was effectively improved in the presence of ultrasonic standing waves.

1. Introduction

Flotation is an effective method to recover fine coal slime [1]. The low momentum of ultrafine coal particles, which produced from the processes of mining, transporting, and crushing, lead to a serious flotation problem because the low probability of attachment between the particles and bubbles [2–4]. Researchers [5–8] have attempted to solve this problem via physical adjustment and chemical adjustment. The physical adjustment method is to change the surface properties of minerals through the action of physical means such as magnetic, electrical, acoustic, temperature regulation. While the chemical adjustment method is to change the surface properties of minerals by adding chemical reagents in the pulp. Ultrasonic flotation is a method that combines the physical and chemical adjustments [9–11], which can improve flotation efficiency and fine coal recovery [12,13]. As shown in Fig. 1, Acoustic pressure (p) traveling through a liquid that changes its internal static pressure (p0). Therefore, the negative and positive pressure areas are formed. The structural cavities grow in negative pressure areas and then rupture at positive pressure areas. The process of rupture leading to acoustic microflow and shock waves causes the temperature and pressure of the surrounding liquid to rise. These are called ultrasonic cavitation [14,15]. Particles and flotation reagents can be efficiently dispersed by the high energy from the collapse of cavitation bubbles. It also can remove the slime coated on the coal particle surface [16–18].

Research on ultrasonic flotation can be divided into two types: pretreatment ultrasonic flotation and simultaneous ultrasonic flotation. The former uses irradiation from the ultrasonic field before flotation to make a series of physicochemical variation to the flotation pulp. Ultrasonic cavitation can be used to remove the oxide film and clay layer from the surface of coal. The “fresh surface” of the coal particles becomes cleaner and exposed to the collector during the flotation process, which is conducive to improve flotation performance [16,19,20]. Ultrasonic physical crushing also changes the particle size distribution of the coal particles. Ultrasonic simultaneous flotation is the application of ultrasound waves to the entire flotation process. The effectiveness of ultrasonic flotation may depend on various synergistic effects, such as the emulsification of the reagent, cleaning of the coal surface, growth of cavitation bubbles, and aggregation of bubbles [21]. Kang et al. [15,22,23] investigated the effects of ultrasonic pretreatment on the desulfurization, surface composition and the flotation performance of high-sulfur coal. The results showed that ultrasound waves can enhance de-sulfurization performance and reduce the amounts of iron and sulfur in coal during high-sulfur coal flotation. Xu et al. [24] found that the flotation kinetics and yield of the clean coal increased with ultrasonic pretreatment time. Chen et al. [25] indicated that nano-bubbles on molybdenite particle surfaces were the main cause for the high floatability. Ozkan et al. [12,26,27] investigated the effects of simultaneous ultrasonic flotation on coal and metal flotation. The results showed that the number of dimensions of the froth decreased and the froth became

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more stable. Ultrasonic coal flotation yields higher combustible recovery and lower ash values in concentrates than conventional flotation in the condition of using similar dosages of the reagent. Mao et al. [28,29] investigated the effect of simultaneous ultrasonic flotation on the flotation of low rank coal and found that it increased the yield of the concentrate and reduced its ash content. Peng et al. [30] also indicated that clean coal yield was greatly increased by simultaneous ultrasonic flotation compared with the conventional flotation. The micro-bubble-based coating on coal surface enhanced the floatability of lignite.

There are two types of ultrasonic waves: diffused wave and standing wave. Diffused waves emitted from the tip of a probe are fan shaped. The amplitude of the wave decreases as the spread distance increases. The sound intensity is distributed unevenly, and it is accompanied by strong cavitation to generate a large amount of energy [31,32]. Diffused ultrasonic treatment is typically used to disperse particles. Compared with ultrasonic equipment featuring a probe, the amplitudes of standing wave-type are superimposed by multiply ultrasonic waves, resulting in a formation of standing wave and a uniform distribution of the amplitude in the device. In case of such standing waves, the primary and secondary Bjerknes forces cause the bubbles to aggregate [33–35]. Mao et al. investigated the effect of diffused field on flotation bubbles. The results showed that a thin froth layer was produced in the froth zone [36], and bubble aggregates were produced in the pulp [37]. Chen et al. [35,38] focused on the effect of standing waves sound field on flotation bubbles. Coal particles were aggregated and attracted by large bubbles due to the Bjerknes force via an observation device where an acoustic transducer was attached on the one side of the square glass tube. They also studied the generation of stable cavitation effect in the device of a plate transducer was assembled at the bottom of a glass container. The tiny bubbles formatted in tap water. The dynamic process of these phenomena had also been reported.

More and more attention has been paid to the effect of ultrasound on flotation bubbles. However, the effect of ultrasonic two-side standing waves on flotation bubbles have not been well investigated. In this paper, to ensure that the intensity of the ultrasonic standing waves (USW) is uniform and no blind zone is formed, the ultrasonic transducers are placed horizontally on the two sides of devices. USW at different frequencies was used to promote the flotation of fine coal. A high-speed camera and an image processing method were used to study the effects of USW on flotation bubbles and the mechanism of bubble aggregation. Finally, the authors explained the mechanism of flotation promotion using USW through studying the behavior of bubble aggregates in the ultrasonic field of the waves.

2. Materials and experiments

2.1. Coal sample

The coal sample was collected from the Sitai Coal Preparation Plant in Shanxi province, China. The particle sizes distribution of coal sample used in ultrasonic flotation were obtained by screening through standard sieves (GB6005-85 ISO565-1983), as shown in Table 1. The ash content of the original sample was 34.29%. The sample fraction of 0 ~ 0.045 mm had the highest ash. The coal sample was hard to float. The industrial analysis and element analysis of coal sample were shown in Table 2 and Table 3. The coal sample had high ash, high volatilization, low sulfur, and low fixed carbon.

2.2. Bubble observation in the field of ultrasonic standing waves

The bubble generation and observation device (Fig. 2a) consisted of three parts: an ultrasonic device, a photographing and recording device, and a plexiglass container.

The ultrasonic device consisted of an ultrasonic transducer and an ultrasonic generator (KMD-D2, KMDcsb, Shenzhen, China). The latter had a rated power of 1500 W and could be connected to multiple ultrasonic transducers. Three kinds of ultrasonic transducers (80 kHz, 100 kHz, and 120 kHz) were used in this experiment.

The photographing and recording device included a high-speed camera (Q1M high-speed camera system, NAC, Japan), a prime lens (Nikon, Japan), and a computer. A total of 1,000 frames were captured at a resolution of resolution 1280 × 1024 over 10 s. The ultrasonic transducers were installed on both sides of the plexiglass container and a bubble generator installed at the bottom. The shooting lens was focused on the middle of the container. Panel lighting was also required for photography. A magnifying lens (Fig. 2b) was used to observe the

Table 1: Results of screening test of coal sample.

| Size fraction/mm | Yield/% | Ash/% | Cumulative oversize |
|-----------------|---------|-------|---------------------|
|                 | Yield/% | Ash/% |                     |
| +0.3            | 0.91    | 13.31 | 0.91                |
| 0.15 – 0.3      | 1.93    | 4.31  | 2.84                |
| 0.074 – 0.015   | 12.09   | 3.79  | 14.93               |
| 0.045 – 0.074   | 11.20   | 8.10  | 26.13               |
| 0 – 0.045       | 73.87   | 44.30 | 100                 |
| Total           | 100.00  | 34.29 |                     |

Fig. 1. Pressure variation in the liquid (p₀ is the liquid pressure, p is the acoustic pressure, p_s is the pressure in liquid when ultrasound is introduced).
aggregation of the bubble from the above of container.

### 2.3. Image processing method

To explore the effects of USW on the aggregation of bubbles, the sampling images captured in Section 2.2 were taken at 200-frame intervals to avoid overlapping. 0.3 mg/L frothing reagent was added to the observation device. The images were processed using the following procedure, as shown in Fig. 3:

1. The original image was subjected to non-local average denoising, and its brightness and contrast were enhanced to suppress useless information.
2. Grayscale and binarization were performed on the image to highlight the outline of the target and enable contour detection in the next step.

### Table 2

Results of industrial analysis of coal sample.

| M<sub>ad</sub> | A<sub>ad</sub> | V<sub>daf</sub> | FC<sub>daf</sub> |
|--------------|--------------|----------------|-----------------|
| 2.12%        | 34.29%       | 33.06%         | 66.94%          |

### Table 3

Results of elemental analysis of coal sample.

| C<sub>daf</sub> | H<sub>ad</sub> | O<sub>ad</sub> | N<sub>ad</sub> | S<sub>ad</sub> |
|----------------|--------------|--------------|--------------|--------------|
| 79.41%         | 4.96%        | 13.39%       | 0.98%        | 1.26%        |

Fig. 2: Bubble generation and observation device.

(a) Bubble generation and observation device.

(b) Bubble observation system.
3. The Hough transform was applied for circle detection to optimize contour detection.
4. The bubbles were separated by calculating the distance between each pixel of the original image and the nearest zero-pixel point, and the watershed algorithm was used to perform distance-based segmentation.
5. Flood filling was performed to remove small, connected areas that might have appeared due to noise or other interference to reduce incorrect segmentation. This allowed us to accurately count the number and area of the bubbles.

Fig. 3. Image processing method.

Fig. 4. Simultaneous ultrasonic flotation device.
2.4. Simultaneous ultrasonic flotation

The simultaneous ultrasonic flotation cell was shown as Fig. 4. The ultrasonic frequency used were identical to those used in the observation device as described above. 250 g of the coal sample was used for each simultaneous ultrasonic flotation experiment. The coal sample was wetted before it was added into the 2.5L flotation cell and then the flotation machine and ultrasonic generator were turned on at the same time. The collector was added after stirring for two minutes and then the frothing reagent was added after another 1.5 min of stirring. Subsequently, the inflatable device was turned on 30 s later. The flotation froth was then collected for 4.5 min. The products were filtrated and dried at 75 °C for 4 h before weighed. Each frequency conducted three trials. Reagents and flotation parameters were listed in Table 4.

3. Results and discussion

3.1. Bubble aggregation

Fig. 5 shows the bubble aggregation captured by the observation device. In the absence of the ultrasound, the bubbles were evenly dispersed in the whole observation device. When ultrasound was added, bubbles gathered regularly to form aggregates of different shapes and sizes, which was different from the diffused ultrasonic field. Fig. 5 (a) - (b) show the formation process of bubble aggregates in the USW field within 450 ms. Fig. 5 (c) shows that cavitation bubbles was attached the larger bubbles to form aggregates. In the flotation process, the attachment of bubbles and particles occurred in a short time. The bubble aggregation process was completed in a very short time, which would be helpful to the recovery of fine particles in the USW flotation process [34,39].

Fig. 6 shows the mechanism of bubble aggregation. Based on the Bjerknes force theory, Walton and Reynolds, Leighton et al. proposed an expression to illustrate the bubble aggregate in the field of USW as well as its graphical representation. Ultrasonic field led to the variation of liquid environmental pressure. The variation in the sizes of the bubbles under changing liquid pressure were given by [40]:

\[ \frac{R R}{R_0} + \frac{3}{2} = \frac{1}{\rho} \left[ \left( P_0 + \frac{2\sigma}{R_0} - P_i \right) \left( R_0^3 - \frac{2\pi R^2}{R_0^2} \right) P_0 - P_0 \right] \]  

(1)

where \( R_0 \) is the radius of the bubble at equilibrium, \( P_0 \) is hydrostatic pressure, \( P_i \) is vapor pressure, \( \rho \), \( \sigma \), and \( \mu \) are the density, surface tension, and viscosity of the liquid, respectively, \( \kappa \) is the polytropic index of gas within the bubble, and \( P(t) \) is the time-varying acoustic pressure.

The resonant frequency of a bubble is given by:

\[ \omega = \frac{1}{R_0\sqrt{\rho}} \left[ 3\kappa \left( P_0 + \frac{2\sigma}{R_0} - P_i \right) - \frac{2\pi \sigma^2}{\rho R_0^2} \right]^{1/2} \]  

(2)

where \( \omega \) is the resonance frequency at a resonant bubble size of \( R_0 \), \( \rho \), \( \sigma \), and \( \mu \) are the density, surface tension, and viscosity of the liquid respectively, \( \kappa \) is the polytropic index of the gas, and \( P_0 \) and \( P_i \) are the hydrostatic pressure and vapor pressure, respectively.

Whether the natural frequency of the resonance bubbles was greater or less than the driving frequency was determined by the following: [41]

\[ v_{CR} = 3Hz m^{-1} \]  

(3)

where \( v_C \) is the linear resonance frequency:

\[ \dot{r} + \omega^2 r = \left( \frac{P_i}{\rho R_0^2} \right) \sin \omega t \]  

(4)

where \( \omega \) is the resonant frequency of the bubble.

The direction of motion of the bubble along the pressure gradient was given by Equation (4) in comparison with the driving force.

A bubble in a liquid subjected to an acoustic pressure field undergoes volume pulsations. If the gradient of sound pressure was non-zero, it can couple with oscillations of the bubble to create a flat force on it. This was the primary Bjerknes force. The Bjerknes force was the most potent driving force for the motion of bubbles in a non-flowing liquid. Bubbles with frequencies lower than that of the resonance due to the sound field traveled up the pressure gradient and those higher than it traveled down the gradient. Therefore, in the field of the USW, the former was aggregated at the antinodes and the latter at the nodes [40,42,43].

In addition, bubble aggregation under ultrasound conditions exhibited a regular stripe-like distribution (Fig. 7). In the field of USW, the bubbles were concentrated at a location (antinode or node). The aggregates were regularly arranged in a row under the action of the Bjerknes force, and there was a clear gap between the stripes, which was consistent with the principle shown in Fig. 6. Characteristics of the ultrasonic field of the circular transducer used in the experiment were analyzed by the following [44]:

\[ P_i = 2p_0 \sin \frac{\pi}{A} (a^2 + z^2)^{3/2} - z \sin (\omega t - ka) \]  

(5)

where \( P_0 \) is the initial sound pressure, \( a \) is the radius of the circular transducer, \( z \) is the distance to the source of sound, \( \lambda \) is wavelength, and \( k = 2\pi/\lambda \).

Calculated by Eq. (5), the wavelengths (\( \lambda \)) of the ultrasound waves used in this experiment were 18 mm (80 kHz), 15 mm (100 kHz), and 12 mm (120 kHz), respectively. Nevertheless, the measured interval between stripes in Fig. 7 was 10–15 mm (the deviation was 2–3 mm). Bubble aggregates regularly appeared at specific positions (nodes or antinodes) in accordance with the theoretical representation.

Fig. 8 shows the images of bubbles before and after treatment by USW (80, 100, and 120 kHz). The bubbles were dispersed in the cell without ultrasound, but they quickly merged and agglomerated when an USW with was added. There are both large and small bubbles in the aggregates, forming a stable and firm structure. The frequencies of USW had an obvious effect on the shape and distribution of flotation bubbles in the aggregates.

Fig. 9 shows the histograms of bubble size distributions without and with 80–120 kHz ultrasonic field. The statistical results showed that all the distributions of bubble size were lognormal. The number of bubbles in non-ultrasound field was greater but the distributions were wider than that in ultrasound field. In 80 kHz ultrasonic field, the distribution of bubble size was multimodal, and the total number of bubbles reduced which mainly due to the decrease of proportion of small bubbles (less than 1 mm³). It may be caused by the aggregating or merging of small bubbles in the ultrasonic field. As for 100 kHz and 120 kHz ultrasonic field, the bubble sizes changed to unimodal distributions and the distributions of bubble size were narrower compared to 80 kHz. The 100 kHz ultrasonic field had a most significant amount of bubble aggregates and small bubbles.

3.2. Simultaneous ultrasonic flotation

Fig. 10 shows results of USW flotation. Compared with conventional flotation, the yields of clean coal and combustible recovery as well as the flotation improvement index from USW flotation were higher, and the amount of clean coal slightly increased. Ultrasonic flotation at 100 kHz had a higher clean coal yield (35.89%) and a higher combustible recovery rate (45.77%) than that at 80 and 120 kHz. Ultrasonic flotation

| Collector Type | Frothing reagent |
|----------------|------------------|
| Type           | Kerosene         |
| Dosage         | 500 g/t          |
| Air flow rate  | 3,000 rpm        |
| 300 L/h        | 100 g/L          |
was thus superior to conventional flotation, and 100 kHz was the ideal ultrasonic flotation frequency to achieve the highest yields of clean coal and flammable recovery. The results of USW flotation were the comprehensive performance of various ultrasonic effects. The cleaning and emulsification effect of ultrasonic had been widely investigated [45–49]. In previous work, Wang [50] had discussed the cleaning effect of ultrasonic waves. The increase in the number of fine particles was caused by the ultrasonic cleaning of the high-ash, fine slime [51,52]. In the liquid environment, pH and temperature variation were also conducive to ultrasonic flotation [53]. Bubble aggregation caused by ultrasonic field was also an important factor for the flotation results.

In the flotation process, this kind of coal-bubble aggregation was generated, as shown in Fig. 11. USW aggregation also worked for mineralized bubbles that had attached to coal particles. The formation of
aggregates led to the increase of clean coal recovery, combustible recovery, and flotation improvement index. The existence of “inclusions” was an important reason for the increase of clean coal ash.

The role of USW field in the whole flotation process could be described as providing energy and promoting aggregation. The energy generated by ultrasonic cavitation improved attachment efficiency.
between fine particles and bubbles. Cavitation bubbles acted as a “medium” between fine particles and other bubbles to promote their coalescence to form aggregates at a very short time (about 20 ms). These coal-bubble aggregates had a favorable effect on flotation, which went up into the foam layer during the flotation process and eventually became clean coal. Therefore, the yield and combustible recovery of clean coal were improved but the ash content of clean coal was increased.

3.3. Mechanism of the effect of ultrasonic standing waves on the flotation process

Fig. 12 shows the mechanism of USW in the flotation process. In the USW field, cavitation bubbles were generated due to the variation of liquid pressure. In the process of ultrasonic flotation, cavitation bubbles attached to coal particles to form mineralized bubbles or directly attached to larger bubbles. Then, in the process of bubble aggregation, part of the cavitation bubbles acted as the “medium” between the mineralized bubbles, allowing them to merge into larger aggregates or connect each other. There were two types of aggregation, the process of bubbles wrapping coal particles called entrapment and the process of bubbles connecting coal particles called entrainment [54–56]. A little amount of the entrapment may wrongly collect some non-coal particles to increase the ash content of clean coal slightly. The entrainment selectively attached clean coal particles to promote the flotation efficiency. The flotation results that a higher clean coal yield and a higher
combustible recovery as well as a higher flotation improvement index were caused by the interaction of entrapping and entraining.

4. Conclusions

Bubble aggregation is an effective method to recover clean coal from fine coal particles. In the dynamic process, it was found that under the Bjerknes force, the distribution of bubble aggregates was related to the frequency of the ultrasonic field. In the meantime, the frequency has a significant effect on the generation of bubble aggregates and the number of small bubbles. 100 kHz was found to be the ideal ultrasonic frequency of the standing waves because it had the largest number of bubble aggregates and small bubbles. Moreover, ultrasonic flotation at 100 kHz obtained the highest clean coal yield (35.89%) and the highest combustible recovery rate (45.77%). The bubble aggregates led to a slight increase in the amounts of clean coal ash in case of ultrasonic flotation because of the entrapment of the aggregation had low selectivity. Therefore, the flotation recovery was effectively improved by adding bubble aggregates in USW field.

This study provides a new way for the recovery of fine particles. The future of this research is to explore the low-frequency or high-frequency USW field, and to regulate the recovery of fine particles by adjusting the standing waves frequency.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to have influenced the work reported in this paper.

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References

[1] R.H. Yoon, The role of hydrodynamic and surface forces in bubble/particle interaction, Int. J. Mineral Process. 58 (1–4) (2000) 129–143.
[2] O. Tao, G.H. Luthrell, R.-H. Yoon, A parametric study of froth stability and its effect on column flotation of fine particles, Int. J. Miner. Process. 59 (1) (2000) 25–43.
[3] R. Sivamohan, The problem of recovering very fine particles in mineral processing — A review, Int. J. Miner. Process. 28 (3–4) (1990) 247–288.
[4] M. Polat, H. Polat, S. Chander, Physical and chemical interactions in coal flotation, Int. J. Miner. Process. 72 (1–4) (2003) 199–215.
[5] H. Wang, Improvement in flotation and filtrability of coal slime by selective flocculation, J. Min. Sci. 39 (4) (2003) 410–414.
[6] A. Roby, D. Tao, Nanobubble column flotation of fine coal particles and associated fundamentals, Int. J. Miner. Process. 124 (Complete) (2013) 109–116.
[7] R.K.T. Jha, J. Satrun, N. Hiroshio, M. Ita, M. Tsuneoka, Suppression of floatability of pyrite in coal processing by carrier microencapsulation, Fuel Energy Abstracts 92 (5) (2011) 1032–1036.
[8] H. Li, S. Chander, Kinetics of emulsification of dodecane in the absence and presence of nonionic surfactants, Colloids Surfaces A Physicochem. Eng. Aspects 235 (1-3) (2004) 113–120.
[9] C. Li, X. Li, M. Xu, H. Zhang, Effect of ultrasonic radiation on the flotation of fine graphite particles: Nanobubbles or not? Ultrason. Sonochem. 69 (2020) 105243, https://doi.org/10.1016/j.ultsonch.2020.105243.
[10] Santosh Deb Barma, Prasanta Kumar Baskey, Danda Srinivasa Rao, Sachida Nanda Sahu, Ultrasonic-assisted flotation for enhancing the recovery of fly ash particles from low-grade graphite ore, Ultrason. Sonochem. 56 (2019) 386–396.
[11] C. Gungoren, O. Ozdemir, X. Wang, S.G. Ozkan, J.D. Miller, Effect of ultrasound on bubble-particle interaction in quartz-amine flotation system, Ultrason. Sonochem. 52 (2019) 446–454.
[12] S.G. Ozkan, Further investigations on simultaneous ultrasound coal flotation, Minerals 7 (10) (2017) 177.
[13] E.C. Gilek, S. Ozgen, Effect of ultrasound on separation selectivity and efficiency of flotation, Miner. Eng. 22 (1-4) (2009) 1209–1217.
[14] K.S. Suslick, S.J. Doktycz, E.B. Flint, On the origin of sonoluminescence and its mechanism, J. China Coal Soc. (2017).
[15] N.E. Altun, J.-Y. Hwang, C. Hicyilmaz, Enhancement of flotation performance of oil using ultrasound, Fuel Energy Abstracts 114-117 (2012) 80–92.
[16] M. Xu, Y. Xing, X. Gui, Y. Cao, D. Wang, L. Wang, Effect of ultrasonic pre-treatment on oxidized coal flotation, Energy Fuels 31 (12) (2017) 14367–14373.
[17] Y. Chen, X. Bu, V.N.T. Truong, Y. Peng, G. Xie, Guanyuan Xie, Study on the effects of pre-conditioning time on the floatability of molybdenite from the perspective of cavitation threshold, Miner. Eng. 141 (2019) 105845, https://doi.org/10.1016/j. minereng.2019.105845.
[18] S.G. Ozkan, H.Z. Kuyumcu, Investigation of mechanism of ultrasound on coal flotation, Int. J. Miner. Process. 81 (3) (2006) 201–203.
[19] S.G. Ozkan, Effects of simultaneous ultrasound treatment on flotation of hard coal slimes, Fuel 93 (2012) 576–580.
[20] Yaqiang Mao, Wencheng Xia, Bu Xiangning, Yuran Chen, Tianwei Wang, Yaoli Peng, Discussion on ultrasonic enhanced lignite flotation and its action mechanism, J. China Coal Soc. (2017).
[21] Y. Mao, Y. Peng, X. Bu, G. Xie, E. Wu, W. Xia, Effect of ultrasonic on the true flotation of lignite and its entrainment behavior, Energy Sources 40 (8) (2018) 940–950.
[22] Y. Peng, Y. Mao, X. Bu, Y. Li, Yanfeng Li, Ultrasonic flotation cleaning of high-ash lignite and its mechanism, Fuel 220 (2018) 558–566.
[23] K. Yasaki, T. Tuziuti, Y. Iida, Dependence of the characteristics of bubbles on types of sonochemical reactors, Ultrason. Sonochem. 12 (1–2) (2005) 43–51.
[24] W. Wang, D. Liu, T. Yuan, L. Jin, H. Wang, Enrichment of residual carbon in entrained-flow gasification coal fine slag by ultrasonic flotation, Fuel 278 (2020).
[25] Shin Ichi Hatanaka, Kyuichi Yasui, Teruyuki Kozuka, Toru Tuziuti, Hideto Mitome, Influence of bubble clustering on multibubble sonoluminescence, Ultrasonics 40 (1-4) (2000) 655–660.
[26] N. Bremor, M. Arora, S.M. Dammer, D. Lohre, Interaction of cavitation bubbles on a wall, Phys. Fluids 18 (12) (2006), 121505.
[27] V.N.T. Yuran Chen, X.B. Truong, Guanyuan Xie, A review of effects and applications of ultrasound in mineral flotation, Ultrason. Sonochem. 64 (2020), 105003.
[28] R. John, D. Fornasiero, R. Hayes, Bubble-particle attachment and detachment in flotation, Int. J. Miner. Process. 56 (1) (1999) 133–164.
[29] T.G. Leighton, A.J. Walton, M.J.W. Pickworth, Primary Bjerkenes forces, Eur. J. Phys. 11 (1) (1990) 47–50.
[30] M. Minnaert Sr. D. XVI, On musical air-bubbles and the sounds of running water, Phil. Mag. 16 (104) (1933) 235–248.
[31] T.G. Leighton, M.J.W. Pickworth, A.J. Walton, P.P. Dandy, Studies of the cavitation effects of clinical ultrasound by sonoluminescence: I. Correlation of sonoluminescence with the standing wave pattern in an acoustic field produced by a therapeutic unit, Phys. Med. Biol. 33 (11) (1988) 1239–1248.
[32] A.O. Maksimov, T.G. Leighton, Acoustic radiation force on a parametrically distorted bubble, J. Acoust. Soc. Am. 143 (1) (2018) 296–305.
[33] I.M. Brekhovskikh, Yu.P. Lyunov, Fundamentals of Ocean Acoustics, Springer-Verlag, 1991.
[34] Hongxi Zhang, Hongjin Bai, Xianmao Dong, Zhihong Wang, Enhanced desulfurizing flotation of different size fractions of high sulfur coal using sonochemical method, Fuel Process. Technol. 97 (2012) 9–14.
[35] A.R. Vilda, R. Morales, T. Saint-Jean, L. Gaete, V. Vargas, J.D. Miller, Ultrasonic treatment on tailings to enhance copper flotation recovery, Miner. Eng. 99 (2016).
[36] Hongxi Zhang, Xiaoyan Ma, Xianmao Dong, Zhihong Wang, Enhanced desulfurizing flotation of high sulfur coal by sonochemical method. 2012,93 (1): 13-17.
[37] D. Feng, C. Aldrich, Effect of preconditioning on the flotation of coal, Chem. Eng. Commun. 192 (7-8) (2005) 975–983.
[38] M.S. Celik, Effect of ultrasonic treatment on the floatability of coal and galena, Separation Science 24 (14) (1989) 1159–1166.
[39] Weidong Wang, Llzhang Jin, Study on ultrasound simultaneous flotation of coal fines, J. China Coal Soc. (2020) 1–7.
[40] Yu, Yuxian, Liqiang Ma, Wu. Lun, Guichuan Ye, Xianfeng Sun, The role of surface cleaning in high intensity conditioning, Powder Technol. 319 (2017) 26–33.
[41] William J. Oats, Orhan Ozdemir, Anh V. Nguyen, Effect of mechanical and chemical clay removals by hydrocyclone and dispersants on coal flotation, Miner. Eng. 23 (5) (2010) 413–419.
[42] Shashank G. Guivad, Aniruddha B. Pandit, Ultrasonic emulsification: Effect of ultrasonic and physicochemical properties on dispersed phase volume and droplet size, Ultrason. Sonochem. 15 (4) (2008) 554–563.
[54] Leonard J. Warren, Determination of the contributions of true flotation and entrainment in batch flotation tests, Int. J. Miner. Process. 14 (1) (1985) 33–44.

[55] Bo Wang, Yongjun Peng, The behaviour of mineral matter in fine coal flotation using saline water, Fuel 109 (7) (2013) 309–315.

[56] Bo Wang, Yongjun Peng, Sue Vink, Effect of saline water on the flotation of fine and coarse coal particles in the presence of clay minerals, Miner. Eng. 66–68 (2014) 145–151.