Effect of the ultrasonic standing wave frequency on the attractive mineralization for fine coal particle flotation

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\textbf{ABSTRACT}

Froth flotation for mineral beneficiation is one of the most important separation techniques; however, it has several challenges for processing fine and ultrafine particles. Attractive mineralization between particles and bubbles by ultrasonic standing wave (USW) is a novel and high-efficiency method that could assist fine particle flotation. Frequency is an important ultrasound parameter, whose effectiveness mechanisms on the attractive mineralization did not comprehensively address. This study explored the effect of the USW field with various frequencies on the fine coal flotation for filling this gap. Herein, a high-speed camera and a focused beam reflectance measurement (FBRM) were used to analyze three sub-processes of the attractive mineralization, including the microbubbles’ formation, the conventional flotation bubbles (CFBs)’ dispersion, and the particles’ movement. It was found that the maximum flotation metallurgical responses were obtained under the highest examined USW frequency (600 kHz). However, the flotation outcomes by a low USW frequency (50 kHz) were even lower than the conventional flotation tests. Observation and theoretical calculation results revealed these results were originated from the influence of frequency on the carrier bubbles’ formation and the action of secondary acoustic force during USW-assisted flotation. These outcomes demonstrated that frequency is a key factor determining the success of attractive mineralization for fine particles’ flotation.

\section{1. Introduction}

Mineral separation by froth flotation is the most important ore beneficiation method, which has several challenges for the efficient separation of fine and ultra-fine particles [1]. Poor collision and adhesion efficiencies between fine particles and bubbles during the process due to the small mass and particle momentum could explain that inefficiency [2]. By decreasing ore grades and increasing the valuable mineral demands, fine and ultra-fine particle processing would be essential. Thus, different approaches based on equipment (different flotation machines, etc.), technologies (nanobubble assisted flotation, fluidized bed, etc.), and flotation chemicals (reagents) have been considered to enhance the inertial effect between particles and bubbles (bubble mineralization) and to improve the collision efficiency of fine particles [3–7].

Attractive forces, such as magnetic, electrostatic, and hydrophobic forces, have also been suggested for strengthening the mineralization process of bubbles by fine particles (attractive mineralization) [8,9]. The magnetic and electrostatic forces are mostly generated between particles and could cause the flocculation or aggregation of particles [9]. It was reported that the hydrophobic force could significantly improve the particle-bubble attachment and promote the rupture of water films between particles and bubbles [8]. However, these attractive forces are not strong enough to affect the collision between fine particles and bubbles through the turbulent flotation condition. If the collision process of particles and bubbles could be controlled and extended by the strong attractive force, the inertia effect would be ignorable. Then, the mineralization problem of fine particles and bubbles would be solved.

Several investigations indicated that the acoustic force in the ultrasonic standing wave (USW) field might potentially be an attractive force to improve the attractive mineralization process [10–12]. The sound pressure gradient in the USW field and the acoustic force are stronger than other sound field forms [13]. Particles or oil droplets could aggregate at pressure antinodes or nodes by USW, and the attraction of acoustic force played an important role through the aggregation process [14,15]. USW has been widely used in particle separation, emulsion demulsification, crude oil dehydration, and desalination [16,17]. In
recent years, more attention has been paid to USW-assisted flotation [10]. A successful and efficient mineralization process for fine coal flotation was proposed in the presence of USW field attraction [18]. Through the USW effect assessment on flotation bubbles, it was revealed that frequency as a robust ultrasound feature might be one of the most important factors through attractive mineralization [17]. However, the mechanism and its importance have not been fully addressed and understood.

For filling this gap, the effect of frequency on the attractive mineralization through the fine coal flotation has been examined in the USW field. Based on a systematical approach, this study first has been comprehensively addressed the attractive mineralization theory. Then, the effect of frequency on the attractive mineralization through three different sub-processes have been explored: the formation of micro-bubbles, the dispersion of CFBs, and the movement of particles. Image processing and focused beam reflectance measurement (FBRM) technologies were applied to analyze the behaviors of particles and bubbles during the USW process. The mechanisms were discussed via the cavitation threshold and acoustic force models.

2. Materials and experiments

2.1. Coal samples

Clean coal samples were collected from Tangkou Coal Preparation Plant (Shandong, China). The ash content of coal samples was around 5%, and the contact angle of the lump coal was around 103 ± 2°. Samples were crushed and ground into a fine powder. The Tyler standard sieve was adopted to obtain the coal samples with −45 μm for flotation tests and 74–125 μm for observation tests. The particle size distribution of coal powder was determined by a laser particle sizer (Mastersizer 3000, Malvern Instruments Ltd., UK) in the alcohol solution. The \( D_{10}, D_{50}, D_{90} \) of the −45 μm coal samples were 3.86, 17.2, and 33.1 μm, respectively.

2.2. Micro flotation tests

Clean coal particle (−45 μm) size fraction was used for the micro flotation tests. For the flotation experiments, the square tube (30 × 30 × 150 mm) was filled with 5 g/L coal suspension (Fig. 1). Coal suspension was pretreated by 5 min stirring process at 600 rpm, and the aerating rate was 2 cm\(^3\)/min. The floated products were collected for 1, 2, 3, 5, and 8 min for each test (all tests are duplicated for the reproducibility assessments). The concentrate and residues were filtered and dried at 40 °C overnight and then weighed to calculate the recovery. The flotation tests were conducted without any flotation reagent. These micro flotation tests were conducted based on the USW setup (Fig. 1).

2.3. Ultrasonic standing wave setup

Sound waves in the ultrasonic standing wave (USW) setup were generated and amplified by a wave generator (SDG1010, Siglent) and a

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**Nomenclature**

| Symbols and abbreviations | USW | FBRM | CFB | Vpp | \( d_{12} \) | \( F_p \) | \( h \) | \( k_M \) | \( K \) |
|---------------------------|-----|------|-----|-----|----------|--------|------|--------|------|
| \( c_l \) | Sound speed in liquid | Ultrasonic standing wave | Focused beam reflectance measurement | Conventional flotation bubble | Peak to peak voltage | Distance between bubbles | Primary acoustic radiation force | Distance from antinode | Modified flotation rate constant | Wave number |
| \( E \) | Energy density | \( P_{V} \) | Pressure inside bubble | \( P_0 \) | Initial pressure | \( R_{oo} \) | Ultimate recovery | \( \mu \) | Viscosity | \( \omega \) | Angular frequency | \( \sigma \) | Sound speed radio |
3. Results and discussions

3.1. Flotation results

Flotation experimental results indicated (Fig. 2) that the coal recovery without USW was 22% after 8 min. In the presence of USW, the flotation recovery was greatly improved and increased to 33 and 53% by 200 and 600 kHz USW, respectively. The classical first-order flotation model \( \gamma = R_\infty(1 - e^{-kR_\infty}) \) was used (the solid line in Fig. 2) to calculate the ultimate recovery \( R_\infty \) and flotation rate constant \( k \) for comparison with the conventional flotation test (no USW, Table 1). Results (Table 1) indicated that 200 kHz USW could improve the conventional flotation test (no USW, \( 0.1144 \text{ min}^{-1} \)) with a considerable increase of 53% (600 kHz) (Table 1). However, the variation of the initial voltage was not effective at 50 kHz USW. From 0.1 to 0.5 Vpp (peak to peak voltage), which could be amplified by 200 and 600 kHz USW, respectively. The presence of USW could increase the \( R_\infty \) from 22 (no USW) to 53% (600 kHz) (Table 1). However, \( k \) decreased from 0.52 (no USW) to 0.37 \text{ min}^{-1} (600 kHz). Since different USW frequencies resulted in variations in both \( R_\infty \) and \( k \), the flotation kinetics under various USW frequencies would be challenging. Thus, the modified flotation rate constant \( k_\text{M} = R_\infty \times k \) was considered as an alternative for comparing the overall flotation responses [21, 22]. Results (Table 1) indicated that flotation was conducted at 50 kHz USW, the \( k_\text{M} \) was smaller than the conventional flotation test (no USW, \( 0.1144 \text{ min}^{-1} \)). 200 and 600 kHz USW could improve the conventional flotation \( k_\text{M} \) (0.1144 \text{ min}^{-1}) to 0.1633 and 0.2005 \text{ min}^{-1}, respectively.

3.2. Sub-processes of attractive mineralization

Attractive mineralization could be divided into two main processes: the carrier bubbles’ formation and the particles’ movement. In the USW field, nuclei might grow into the microbubble forms in water or on the particle surfaces (carrier bubbles) due to the diffusion or coalescence (Fig. 3(a)). Carrier bubbles could represent the particles’ movement through a USW field. Under the action of acoustic radiation forces between carrier bubbles and CFBs, CFBs could obtain a high capture amount of particles (Fig. 3(b)).

Furthermore, the collision and adhesion probabilities of coal particles and CFBs were extremely high by the attractive mineralization in the USW field. The mineralization results between coal particles and CFBs with and without USW treatment at 600 kHz showed that CFBs could be mineralized with nearly 100% probability under the action of acoustic forces (Fig. 4). In other words, the formation of carrier bubbles is the prerequisite of attractive mineralization by USW. The mechanism of carrier bubbles formed on particles would be similar to the sub microbubbles formation into the water. However, it would be complicated to observe the process of forming carrier bubbles on particles. Thus, focusing on the microbubbles generated in water could help to understand such a process better.

3.2.1. Microbubbles’ formation

Exploring the behaviors of microbubbles generated by different frequencies USW at 0.5 Vpp of initial voltage indicated that almost no visible bubbles could be observed at 50 kHz (Fig. 5). When the frequency increased to 600 kHz, large numbers of bubbles were formed and suspended in the whole glass tube. It indicated that the formation of carrier bubbles might be closely related to ultrasound frequency, and high frequency would be more conducive.

ImageJ software was used to count the number of microbubbles during USW treatment. The statistical analysis of microbubbles formed under different frequencies and intensities demonstrated that the number of bubbles increased with the frequency under the same initial voltage (Fig. 6). At 200 and 600 kHz, the number of bubbles was raised with the increase of intensity.

However, the variation of the initial voltage was not effective at 50 kHz USW. These results indicated that the formation of carrier bubbles would require proper frequency and sufficient intensity. These results depicted that the attractive mineralization could hardly be achieved in

| Flotation condition | \( k \) (\text{min}^{-1}) | \( R_\infty \) (%) | \( R^2 \) | \( k_\text{M} \) (\text{min}^{-1}) |
|---------------------|-----------------|----------------|-------|-----------------|
| No USW              | 0.5171          | 22.12          | 0.9628| 0.1144          |
| 50 kHz USW          | 0.2590          | 21.12          | 0.9958| 0.0547          |
| 200 kHz USW         | 0.5101          | 32.02          | 0.9656| 0.1633          |
| 600 kHz USW         | 0.3743          | 53.56          | 0.9787| 0.2005          |

Table 1

Output of non-linear regression fitting based on the classical first-order equation for various USW frequencies.
the USW field of 50 kHz due to the absence of carrier bubbles; thus, the flotation efficiency was not improved as compared to the conventional method. Still, exploring the micro-processes of microbubbles formation (Fig. 7) showed several bubbles could be formed in a continuous treatment with 50 USW field (Fig. 7(b)), which is in contradiction with the mentioned results (Fig. 5(a)). These bubbles coalesced under the action of the attraction but then collapsed immediately. The size of these bubbles did not increase after prolonged processes of coalescence, and they collapsed (Fig. 7(a)), which could be the main reason for the provided results in Fig. 5(a). Interestingly, the collapse phenomenon was hard to observe at 200 kHz after the bubbles’ coalescence, and the bubbles’ size continued to increase (Fig. 7(d)). This phenomenon could be the main reason for the formation of microbubbles in water, where high-frequency USW might be more effective for the formation of carrier bubbles (Fig. 7(c)).

3.2.2. CFBs dispersion

Dispersion assessments at a 5 cm$^3$/min aerating rate indicated that the acoustic radiation forces on CFBs at 50 kHz could relatively be larger than at 200 and 600 kHz. The aggregation effect of CFBs in the same condition occurred due to acoustic radiation forces’ action (Fig. 8). In other words, the aerating process was affected by the USW field due to the attractive mineralization process. In detail, the pressure node of USW coincided with the intermediate axle of the glass tube at 50 kHz, and CFBs would gather at the pressure nodes due to the primary acoustic radiation force. There were many pressure nodes in the tube at 200 and 600 kHz; thus, the aggregation location was hard to distinguish. However, plenty of microbubbles formed at 200 and 600 kHz their number and sizes were significantly lower than microbubbles’ formation test results (Fig. 8 vs. Fig. 5). This phenomenon could be due to the attenuation of sound intensity during the aerating process.
Outcomes of image analyses by the ImageJ software during USW treatment (Fig. 9) indicated that without ultrasound treatment, most of the bubbles (64%) ranged from 200 to 400 μm, and the maximum bubble size relatively was 800 μm. When USW was applied, bubbles were gathered and merged, and the percentage of CFBs (200–400 μm) decreased from 64% to 11, 9, and 5% at 50, 200, and 600 kHz, respectively. In other words, the percentage of the tiny bubble (~200 μm) obviously increased by increasing the frequency (from 14% to 16, 29, and 65% at 50, 200, and 600 kHz, respectively).

3.2.3. Particles’ movement

The aggregation phenomena of coal particles in USW fields of 0.5 Vpp initial voltage at 50, 200, and 600 kHz indicated that by increasing the frequency, the aggregation phenomenon of fine coal particles gradually becomes distinguishable (Fig. 10). The maximum size of the aggregates was larger than 0.5 mm at 200 and 600 kHz. The results illustrated that the aggregation between fine coal particles could be related to the behaviors of microbubbles (see Fig. 5). Without the formation of microbubbles or carrier bubbles, fine coal particles could not be moved and aggregated under the action of acoustic radiation force.

The mean chord lengths were used to evaluate the size of the aggregates provided with the FBRM data for samples before and after ultrasound treatment (Fig. 11). The average values of the mean chord length before 50, 200, and 600 kHz ultrasound treatment were around 75, 76, and 78 μm, respectively. After 5 s treatment, the average values of the mean chord length changed to 51, 126, and 178 μm, respectively. When the ultrasound formed the flocs at 200 and 600 kHz, the mean chord length had been increased immediately. In other words, the effect by 600 kHz ultrasound on the aggregation was larger than 200 kHz, which supports the other results (Fig. 10). No aggregation effect was observed approximately at 50 kHz. It indicated that the nuclei on particles collapsed instead of continued growth at 50 kHz. When bubbles collapse, particles would be dispersed due to their powerful impact. As a result, the collision probability of particles and bubbles could be reduced by 50 kHz USW, which could deteriorate the flotation results.

3.3. Attractive mineralization-Mechanism discussion

Cavitation has been used to refer to situations in which bubble growth from gas nuclei in water. The dynamic model of cavitation, called the Rayleigh-Plesset equation, was given as follows [23]:

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**Fig. 6.** The number of microbubbles formed at different ultrasound frequencies and intensities.

**Fig. 7.** Micro-processes of bubble formation in 50 and 200 kHz USW fields at 0.25 Vpp (a. bubbles formation at 50 kHz; b. images captured by a high-speed camera at 50 kHz; c. bubbles formation at 200 kHz; d. images captured by a high-speed camera at 200 kHz).
Three cavitation behaviors could be deduced according to this model: oscillation, growth, and collapse. Collapse is a typical phenomenon of transient cavitation, which might produce a local mechanical shock in water. In addition, bubbles could grow due to the diffusion effect when sound pressure is lower than the saturation pressure of gas dissolved in water (called stable cavitation). Large numbers of microbubbles could be formed due to USW’s stable cavitation and coalescence effects [24].

The acoustic radiation forces on coal particles were weak by kHz-order USW as compared to that on bubbles. The main acoustic forces on bubbles could be divided into primary and secondary acoustic radiation forces. The primary acoustic radiation force on bubbles is given by [25]:

\[
F_p = \langle \mathbf{P} \rangle = -\frac{4\pi K^2}{R^2} \hat{A} \sin 2\pi f \hat{A} \cdot F(\lambda, \sigma, K^* R) \quad (2)
\]

\[
F(\lambda, \sigma, K^* R) = \frac{\sigma (K^* R) \left[ 3\lambda - (K^* R)^2 \right]}{\sigma^2 \left( K^* R \right)^2 + \left[ 3\lambda - (K^* R)^2 \right]^2} 
\]

The secondary acoustic radiation force on bubbles was given by:

\[
F_s = \rho_l \frac{4\pi d}{2\pi} \langle \dot{V}_1 \dot{V}_2 \rangle = \frac{4\pi \rho_l d}{8 \pi} \left( \hat{R}_1 \hat{R}_2 \dot{R}_1 \dot{R}_2 \right) 
\]

The variation of bubble size was given by (1 and 2 are interchangeable):

\[
\frac{1}{\dot{R}_1} \left( 1 - \frac{\hat{R}_1}{c_1} \right) R_1 \dot{R}_1 + \frac{3}{2} \left( \frac{\dot{R}_1}{c_1} \right)^2 - \frac{p_{1w}}{\rho_1 \dot{c}_1} \left( 1 - \frac{\hat{R}_1}{c_1} \right) + \frac{\dot{R}_1}{\rho_l c_1} \frac{d}{dt} \rho_{1w} - \frac{\rho_l}{d c_1^2} (2 \dot{R}_1^2 \dot{R}_1 + R_1^2 \dot{R}_1) 
\]

\[
p_{1w} = \left( P_0 + \frac{2\sigma}{R_0} \right) \left( \frac{R_{10}}{R_1} \right)^{3\kappa} - \frac{2\sigma}{R^2} \frac{4\mu}{R_1} + P_0 - P_{aw} 
\]

\[
P_{aw} = \left( P_0 + \frac{2\sigma}{R_0} \right) \left( \frac{R_{10}}{R_1} \right)^{3\kappa} - \frac{2\sigma}{R^2} \frac{4\mu}{R_1} + P_0 - P_{aw} 
\]
The secondary acoustic radiation force could be an attraction force or a repulsion force, which would depend on the distance between bubbles or the vibration of bubbles. If the attractive effect of secondary acoustic radiation force could be controlled, this powerful attraction might promote the flotation of fine particles [26]. In general, the experimental outcomes showed that the formation of carriers was related to the frequency of ultrasound, and the carriers could hardly be generated in the low-frequency USW field. The cavitation thresholds could explain this phenomenon for different frequencies. The common models of cavitation threshold include rectified diffusion threshold, Blake threshold (low transient cavitation threshold), and transient cavitation threshold, which could typically be used to predict the cavitation behaviors [12]. The calculation results of cavitation thresholds at 50, 200, and 600 kHz were provided in Fig. 12. Nuclei in water might grow into microbubbles when the sound pressure is larger than the rectified diffusion threshold and lower than the Blake threshold [27]. Blake threshold and rectified diffusion threshold are both independent of frequency when nuclei size is small. However, when the nuclei size is close to the resonance radius, the Blake threshold would be smaller than the sound pressure of collapse [12]. The resonance radius is reduced when the frequency increases. It could be translated that the sound pressure area, in which nuclei grow by the diffusion effect (gas diffusion area), would be increased with the frequency. Thus, it could be included that carrier bubbles would become hard to collapse as the frequency increased. At 50 kHz, the gas diffusion area between Blake threshold and rectified diffusion threshold was small, meaning that carrier bubbles could hardly be produced. This also could be the reason that the low-frequency (20–50 kHz) ultrasound traditionally has been usually used for degassing and dispersion [28]. In a high-frequency (200–600 kHz) USW field, nuclei could grow stably without collapse due to the diffusion effect. The results suggested that more bubbles would be produced at 600 kHz than 200 kHz USW due to the larger gas diffusion area. Meanwhile, it could be concluded from Fig. 12 that the effect of the carrier bubbles' formation might be enhanced to a certain extent by increasing the sound intensity. This enhancement would be limited since strong transient cavitation might be introduced by excessive sound pressure that would be deteriorated the microbubbles’ formation.

Secondary acoustic radiation force is an interaction force between two bubbles, which could be calculated by the formulas (3)–(7). Fig. 13(a)–(c) illustrated the secondary acoustic radiation force at the different frequencies. When the sizes of bubbles were 1 μm, the secondary acoustic radiation force increased with the frequency. The attraction between tiny bubbles was improved as the frequency increased. This could support the phenomenon, which the number of microbubbles increased with the frequency (Fig. 5). When the bubble radius met the resonance frequency at 10 μm, the secondary acoustic radiation force between bubbles reached the maximum value. The results showed that the secondary acoustic radiation force could be reduced when the bubble size was far from the resonance radius. When bubble size was around 300 μm, the secondary acoustic radiation force decreased as the frequency increased. The results indicated that the attraction between large bubbles was stronger under low-frequency USW, leading to a powerful coalescence phenomenon of large bubbles (Fig. 8).

The secondary acoustic radiation force between large (300 μm) and tiny bubbles (<100 μm) might be attractive or repulsive. Thus, the way to strengthen the attractive mineralization would reduction of the repulsive force probability. Fig. 12(d–f) showed the secondary acoustic radiation force between large bubbles and microbubbles at 50, 200, and 600 kHz. Similar results for the secondary acoustic radiation force direction were reported in other investigations [25,29]. The area of the repulsive force between large bubbles and tiny bubbles at 50 kHz was larger than 200 and 600 kHz, which made it difficult for attractive mineralization. As frequency increased, the area of repulsive force decreased, which improved the attractive mineralization probability. Carrier bubbles kept growing at 600 kHz USW due to the diffusion and coalescence effects. This means that the attraction effect between carrier bubbles and CFBs was more likely to occur. Meanwhile, the attraction between microbubbles and large bubbles was reduced with increasing frequency. Hence, it could be predicted that the attractive mineralization would become hard to realize when the frequency was too high.

![Fig. 11. Mean chord length of coal particles before and after USW treatment.](image1)

$$P_{\text{ex}} = P_m \sin(\omega t)$$ (7)

![Fig. 12. Cavitation thresholds at 50 kHz (a), 200 kHz (b), and 600 kHz (c).](image2)
4. Conclusion

- Comparing to the conventional flotation, high-frequency (200 and 600 kHz) USW could promote the recovery and flotation rate of fine particles, while these metallurgical indexes could be dropped by low-frequency (50 kHz) USW. The maximum recovery was obtained by 600 kHz USW, which increased from 22% (without USW) to 53% (with 600 kHz USW).
- The formation of carrier bubbles was closely related to ultrasound frequency, and high-frequency (600 kHz) was more conducive. Bubble carriers could hardly be formed by low-frequency (50 kHz) USW even if the sound intensity was improved.
- Carrier bubbles could be produced during the aeration process in USW, but the size of carrier bubbles would be decreased due to the attenuation of sound intensity. In addition, the effect of the coalescence of CFBs in USW was reduced with the frequency.
- The analysis of the cavitation threshold showed that increasing the frequency of USW could promote the formation of carrier bubbles. The force analysis indicated that the secondary acoustic radiation forces between carrier bubbles increased with the frequency, and high-frequency USW was more likely to produce the attraction between carrier bubbles and CFBs instead of repulsion.

CRediT authorship contribution statement

Yuran Chen: Conceptualization, Investigation, Software, Writing - original draft. Saeed Chehreh Chelgani: Writing - review & editing, Formal analysis. Xiangning Bu: Writing - review & editing, Funding acquisition, Methodology. Guangyuan Xie: Supervision, Conceptualization.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

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References

[1] T. Miettinen, J. Ralston, D. Fornasiero, The limits of fine particle flotation, Miner. Eng. (2010), https://doi.org/10.1016/j.mineng.2009.12.006.
[2] Z. Brabcová, T. Karapantsios, M. Kostoglou, P. Basaróvá, K. Matis, Bubble-particle collision interaction in flotation systems, Colloids Surfaces A Physicochem. Eng. Asp. 473 (2015) 95–103, https://doi.org/10.1016/j.colsurfa.2014.11.040.
[3] G. Ai, X. Yang, X. Li, Flotation characteristics and flotation kinetics of fine wolframite, Powder Technol. 305 (2017) 377–381, https://doi.org/10.1016/j.powtec.2016.09.068.
[4] Z. Yang, Y. Xia, C. Wei, Y. Cao, W. Sun, P. Liu, H. Cheng, Y. Xing, X. Gui, New flotation flowsheet for recovering combustible matter from fine waste coking coal, J. Clean. Prod. 225 (2019) 209–219, https://doi.org/10.1016/j.jclepro.2019.03.324.
[5] J.N. Kohmuench, M.J. Mankosa, H. Thanasekaran, A. Hobert, Improving coarse particle flotation using the HydroFloat™ (raising the trunk of the elephant curve), Miner. Eng. 121 (2018) 137–145, https://doi.org/10.1016/j.mineng.2018.03.004.
[6] M.J. Mankosa, J.N. Kohmuench, L. Christodoulou, E.S. Yan, Improving fine particle flotation using the StackCell™ (raising the tail of the elephant curve), Miner. Eng. 121 (2018) 83–89, https://doi.org/10.1016/j.mineng.2018.05.012.
[7] F. Zhang, L. Sun, H. Yang, X. Gui, H. Schonherr, M. Kapp, Y. Cao, Y. Xing, Recent advances for understanding the role of nano-bubbles in particles flotation, Adv. Colloid Interface Sci. 291 (2021), 102403, https://doi.org/10.1016/j.cis.2021.102403.
[8] D. Tao, A. Sobhy, Nanobubble effects on hydrodynamic interactions between particles and bubbles, Powder Technol. 346 (2019) 385–395.
[9] L. Luo, A.V. Nguyen, A review of principles and applications of magnetic flocculation to separate ultrafine magnetic particles, Sep. Purif. Technol. 172 (2017) 85–99.

[10] L. Jin, W. Wang, Y. Tu, K. Zhang, Z. Lv, Effect of ultrasonic standing waves on flotation bubbles, Ultrason. Sonochem. 73 (2021) 105459, https://doi.org/10.1016/j.ultsonch.2020.105459.

[11] Y. Chen, V.N.T. Truong, X. Bu, G. Xie, A review of effects and applications of ultrasound in mineral flotation, Ultrason. Sonochem. (2020), https://doi.org/10.1016/j.ultsonch.2019.104739.

[12] Y. Chen, H. Zheng, V.N.T. Truong, G. Xie, Q. Liu, Selective aggregation by ultrasonic standing waves through gas nuclei on the particle surface, Ultrason. Sonochem. 63 (2020), 104924, https://doi.org/10.1016/j.ultsonch.2019.104924.

[13] P.R. Gogate, A.L. Prajapat, Depolymerization using sonochemical reactors: a critical review, Ultrason. Sonochem. 27 (2015) 480–494, https://doi.org/10.1016/j.ultsonch.2015.06.019.

[14] P.R. Gogate, A.L. Prajapat, Depolymerization using sonochemical reactors: a critical review, Ultrason. Sonochem. 27 (2015) 480–494, https://doi.org/10.1016/j.ultsonch.2015.06.019.

[15] Y. Chen, C. Ni, G. Xie, Q. Liu, Toward efficient interactions of bubbles and coal particles induced by stable cavitation bubbles under 600 kHz ultrasonic standing waves, Ultrason. Sonochem. 64 (2020), https://doi.org/10.1016/j.ultsonch.2020.105003.

[16] X. Bu, G. Xie, Y. Peng, L. Ge, C. Ni, Kinetics of flotation. Order of process, rate constant distribution and ultimate recovery, Physicochem. Probl. Miner. Process. 53 (2017) 342–365, https://doi.org/10.5277/pnpm170128.