Physicochem. Probl. Miner. Process., 61(4), 2025, 205949

Physicochemical Problems of Mineral Processing

http://www.journalssystem.com/ppmp

ISSN 1643-1049

Study on the influence of ultrasonic wave on the dispersion of coal slime particles

Wang Chao [1], Song Pengfei [1], Yang Dong [2]

[1] School of Materials Science and Engineering, Anhui University of Science and Technology, Huainan 232001, China

Corresponding author: hnchiyang22@163.com (Wang Chao)

Abstract: In the process of coal slime treatment, the adhesion and agglomeration between coal slime particles considerably hinder the effective contact between coal slime particles and chemicals, which leads to a series of problems such as the reduction of sorting efficiency and product quality. In order to deeply explore the influence of ultrasonic assisted dispersion of coal slime particles, this study measured the particle size change of coal slime in different ultrasonic power and different treatment time. At the same time, by using COMSOL Multiphysics simulation software to build an acoustic-fluid coupling model, combined with the theory of acoustic radiation force under the condition of large amplitude sound source, the acoustic flow phenomenon generated by high-power ultrasound with a frequency of 20 kHz in the material cavity was simulated and analyzed, and the change law of acoustic flow velocity under different ultrasonic powers was obtained. The internal correlation between the velocity of acoustic flow and the dispersion of slime particles was revealed. The experimental results show that ultrasound has a significant effect on the dispersion of slime particles, and with the increase of ultrasonic power and the extension of treatment time, the dispersion effect of slime particles is more and more obvious. Under 600 W ultrasonic power and 5 minutes of treatment, the proportion of particles in the 0.075 – 0.15 mm size range increased by 10.98%.

Keywords: ultrasonic, auxiliary dispersion, coal slime treatment, comsol simulation

1. Introduction

In the treatment process of coal slime,the fine size is always a big problem because of its high adhesion and strong agglomeration. In the coal slime flotation operation, the selected particle size of coal slime has a significant effect on the flotation result (Reis et al., 2023). In general, the finer the coal particle size, the larger the specific surface area, the more complete the contact between the particles and flotation agents, and the higher the recovery rate. The particles in the coal slime often exist in the form of agglomerates, small particles of coal slime or impurities tend to agglomerate with large particles of coal slime or impurities, which considerably hinders the full contact between coal slime particles and reagents, and then lead to the adhesion rate of coal slime and bubbles in the flotation process. The agglomeration and adhesion of slime particles can not be stably attached to the froth, which will not only destroy the stability of the froth zone, but also lead to the reduction (Said et al., 2025) of the separation efficiency of slime and the quality of cleaned coal.

In order to solve the problems in slime flotation, Zhang (2021) put forward the idea of partially replacing polyaluminum chloride with polyferric sulfate, and optimized the slime flotation process in Yuwu Coal preparation plant. By independently developing a microemulsion (Code Ty6) made from diesel and surfactants in a certain proportion instead of kerosene, Yang et al. (2024) optimized the collector of slime flotation in Lyu Lineng Chemical preparation plant to improve the flotation efficiency; By preparing emulsified collectors with different characteristics, An et al. (2024) expounded the relationship between the emulsification of collector and the flotation speed and the flotation efficiency of coal slime. Wu et al. (2019) applied the additive Extreme Learning machine (I-ELM) to the composition identification of slime water, and established the identification model of slime water ash based on I-ELM. Wang et al. (2023) studied the influence of ultrafine grinding on the dissociation degree

DOI: 10.37190/ppmp/205949

of ultrafine coal, and came to the conclusion that the dissociation effect of air mill on Shenmu non-stick coal is better than that of stirring mill. It can be seen that most of the existing researches have studied the treatment process of coal slime from the aspects of the reform of flotation process and the optimization of flotation agents, but these methods have no direct effect on the coal slime particles themselves. This study will explore the effect of dispersion treatment of coal slime particles with the help of ultrasonic wave, improve the efficiency and quality of coal slime treatment, and provide a new idea and method for coal slime treatment process.

When the ultrasonic wave propagates in the liquid, the sound pressure produces periodic alternating changes, resulting in the formation of local compression phase and expansion phase (Ma et al., 2019) in the liquid. This periodic change causes the tiny bubble nuclei dissolved in the liquid to grow in the expansion phase, and be compressed in the compression phase until collapse, which leads to a series of complex dynamic processes. The phenomena (Zhang et al., 2022) such as high temperature, high pressure and local micro-jet generated during the collapse of cavitation bubble provide favorable conditions for the dispersion of slime particles.

Therefore, this study takes the flotation slime in the cylindrical cavity as the object to study the influence of different ultrasonic power and different treatment time on the change of coal slime particle size. On the basis of theoretical analysis, using the method of simulation analysis and experimental research, the motion characteristics of coal slime in the cavity caused by high-power ultrasonic treatment are revealed. It provides the relevant theoretical analysis and experimental reference for ultrasonic assisted dispersion in coal slime treatment technology.

2. Materials and methods

2.1. Material

The coal slime used in the experiment is the flotation slime of Panji Coal Preparation Plant in Huainan City, Anhui province of China. The slime concentration is about 90 g/L, and the theoretical maximum particle size of the slime is below 0.5 mm. However, due to the long-term use of the equipment, there is 1% - 1.5% of slime with a particle size greater than 0.5 mm in the slime.

The schematic diagram of the experimental model is shown in Fig. 1. The ultrasonic device, Model LS - 1200B, is equipped with a piezoelectric transducer of PZT. Its emission frequency is 20 kHz, transmission power ranges from 0 to 800 W, and processing capacity ranges from 1 to 500 mL. It is equipped with a titanium alloy amplitude converter. The amplitude converter is cylindrical, with a length of 100 mm and a radius of 8 mm. The material chamber uses a 500 mL transparent beaker, which has a diameter of 85 mm, a height of 116 mm, and a wall thickness of 3 mm.

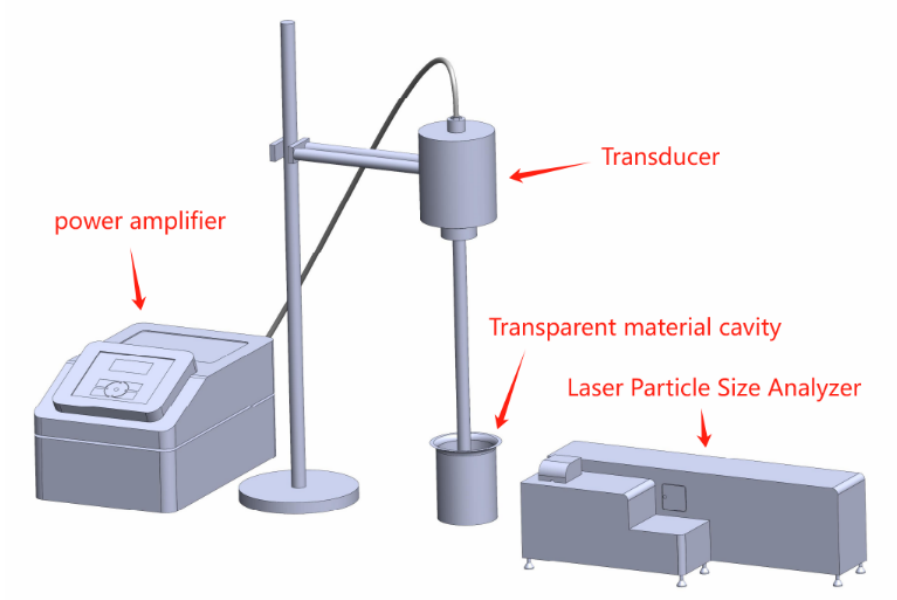


Fig. 1. Schematic diagram of experimental model

2.2. Method

When ultrasonic wave propagates in slime suspension, local high pressure and low (Chernysev et al., 2025) pressure areas will be formed due to nonlinear treatment. This pressure change leads to a nonlinear sound pressure gradient (Tang, 2023) inside the liquid. Under the treatment of the sound pressure gradient, the particles in the medium will move in a directional way, and then drive the liquid to produce macroscopic flow and form sound flow (Stone et al., 2025). The sound flow movement can intensify the degree of turbulence in the coal slime suspension, so that the coal slime is more evenly dispersed in the suspension, thus increasing the contact chance of coal particles and cavitation bubbles, coal slime particles will also be impacted and stirred in the process, thus promoting the dispersion (Silva et al., 2025) between the adhesive slime.

The mass conservation equation (Eq. (1)) and Navier-Stokes (N-S) equation (Eq. (2)) in the process of fluid movement are (Khan et al., 2021) respectively:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \nu) = 0 \tag{1}$$

$$\rho \frac{\partial \nu}{\partial t} + (\nu \nabla) \cdot \nu = -\nabla p + (\xi + \frac{4}{3}\eta)\nabla^2 - \eta \nabla^2 \nu \tag{2}$$

where: ξ and η are the capacitance viscosity and shear viscosity of the fluid, respectively. The units of both the bulk viscosity ξ and the shear viscosity η in the International System of Units are Pascal - seconds (Pa ·s).

In the transformation of sound field quantity and flow field quantity, it is necessary to average the time, and the mass conservation equation (Eq. (3)) and N-S equation after retaining the second-order tiny term to obtain the time average (Eq. (4)) are as follows (Sun et al., 2022):

$$\nabla \cdot (\nu 0 + \langle \frac{\rho 1 \nu 1}{\rho 0} \rangle) = 0 \tag{3}$$

$$\frac{\partial U}{\partial t} + (U \cdot \nabla) \cdot U - \frac{\eta}{\rho 0} \nabla^2 U = -\frac{\nabla p_0}{\rho_0} - \frac{\langle \nabla E \rangle}{\rho 0} \tag{4}$$

where: defined as the time average of the fluid pointing speed, that is, the fluid flow rate, the second term in $U0 = \nu 0 + \langle \frac{\rho 1 \nu 1}{\rho 0} \rangle U$ is the second-order tiny term of the sound field disturbance, its value is much less than v0, U is approximately v0 after forming a stable sound flow; $\langle \nabla E \rangle$ is the time average of the energy gradient of the medium per unit volume in the sound field.

When only the sound field acts, the driving force F that induces the fluid to form the sound flow phenomenon is the sound radiation force $\nabla p0 = 0$ [16]:

$$F = -\langle \nabla E \rangle \tag{5}$$

Under the condition that the second-order microscopic term is not ignored, as long as there is a difference in energy density in the sound field, there is a force acting on the fluid to make the fluid flow (Hu et al., 2023).

A two-dimensional axisymmetric model was established in COMSOL Multiphysics software by the finite element analysis method, and the coupling method (Zhang et al., 2023) of pressure acoustics and laminar flow was adopted. With the bottom end of the amplitude bar immersed in the slurry as the boundary condition of the sound source, the propagation medium was flotation slurry with a solid concentration of 90 g/L, and the sound propagation speed was approximately 1480 m/s. Since the sound wave is longer than the thickness of the cup wall, in the setting of boundary conditions, the contact boundary between the amplitude rod and the slurry is the boundary of the hard sound field, and the remaining boundary is the boundary of the soft sound field. Since the size of the fluid grid is much larger than that of the acoustic grid, a common fluid grid is adopted. The maximum unit of the grid division is 1.19 mm, and the minimum unit is 0.017 mm.

The steady state method is adopted to solve the sound energy density distribution in the material cavity with the pressure acoustic-frequency domain interface. Through the sound energy density distribution, the axial and radial acoustic radiation force components (Kshetri et al., 2025) of the fluid are solved. The known particle velocity of the plane circular sound source in the radial direction is about 1% of the axial particle velocity. The radial component of the acoustic radiation force is ignored, so only the axial component of the acoustic radiation force, that is, the volume force of the fluid in the flow field, is solved. Taking the volume force as the power input condition (Ardebili et al., 2024) of the fluid, the laminar interface steady-state research method is used to solve the velocity distribution of the sound flow in the material cavity.

According to the pre-experiment, it is found that when the ultrasonic power is less than 200W, the vortex generated by the acoustic radiation force is not enough to arouse the suspension of the slime particles in the material cavity, so the ultrasonic power is selected as 200W, 400W and 600W in the experiment, and the treatment time is selected as 1, 3 and 5 minutes. The single factor experiment method was adopted in the experiment. The particle size distribution of coal slime before and after ultrasonic treatment was analyzed using a laser particle size analyzer, model ASALD - 7101. A shift toward smaller particle sizes or increased uniformity in distribution was interpreted as indirect evidence of improved dispersion. In order to eliminate accidental error, repeated experiment method was adopted, and the average value of three experiments was taken as the final result. The experimental scheme is shown in Table 1.

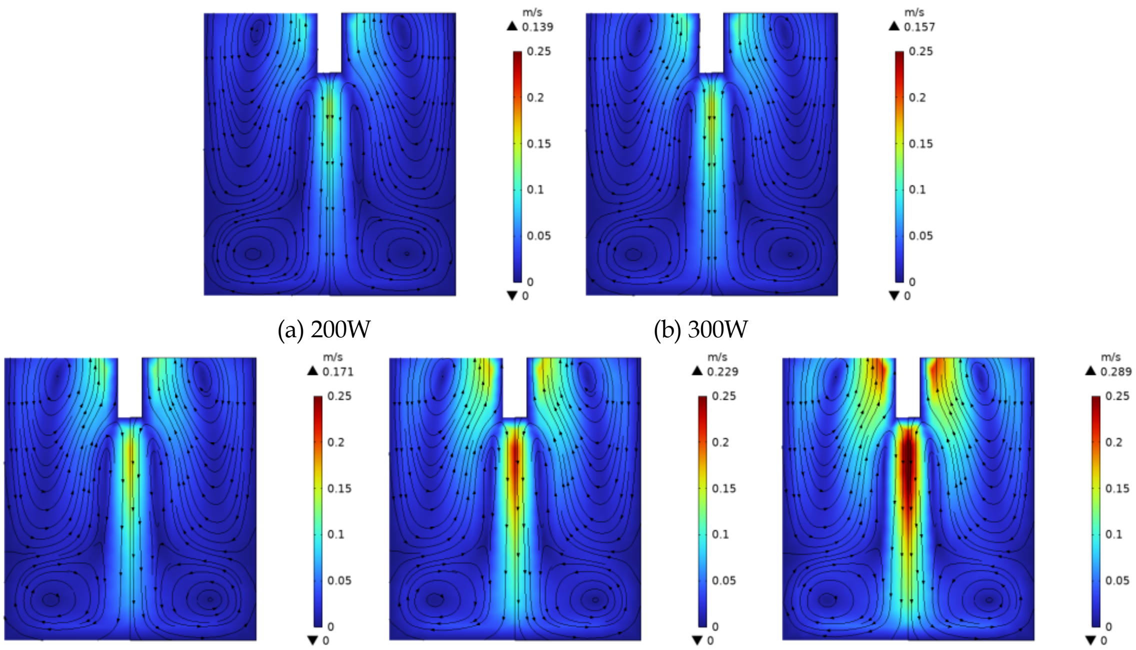
Table 1. Experimental protocol

Experiment number	Ultrasonic power /W	Treatment time /min
1	200	1
2	200	3
3	200	5
4	400	1
5	400	3
6	400	5
7	600	1
8	600	3
9	600	5

3. Results and discussion

3.1. Numerical simulation

The velocity distribution of acoustic flow at the ultrasonic power of 200 W, 300 W, 400 W, 500 W and 600 W is shown in Fig. 2.



(a) 200W (b) 300W

(c) 400W (d) 500W (e) 600

Fig. 2. Distribution of sound flow velocity under different ultrasound powers

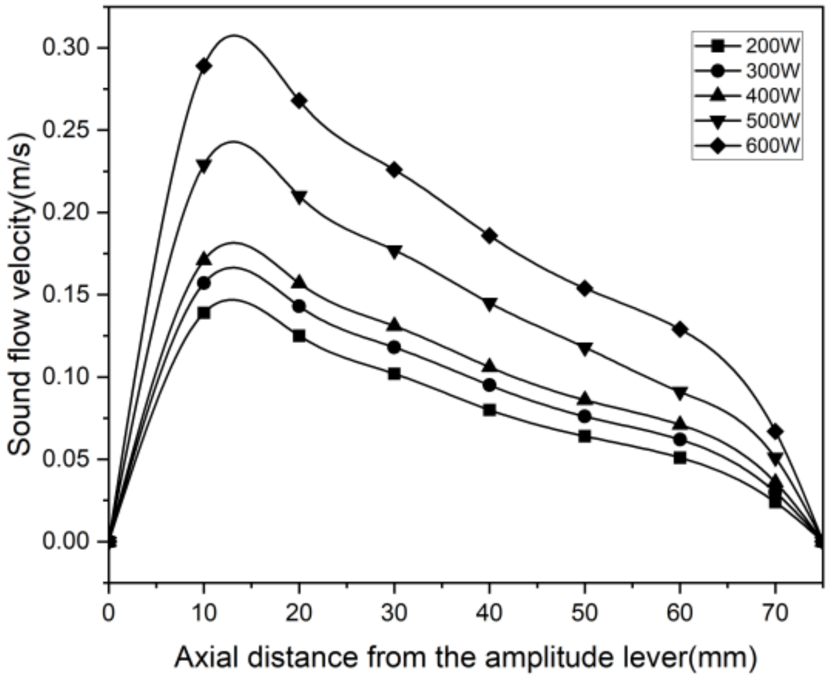


Fig. 3. Distribution of axial acoustic flow velocity in the feeding chamber under different power levels

It can be seen from Fig. 2 that under the treatment of ultrasound, the fluid forms a jet at the sound source boundary at the bottom of the axial acoustic flow bar and moves along the axial direction. After contacting the bottom of the material cavity, reciprocating eddy currents are formed along the left and right sides towards the wall. With the increase of ultrasonic power, the speed of sound flow increases, and the intensity and range of eddy current also expand accordingly. At the same time, the liquid flow generated by the acoustic flow effect pushes the cavitation bubbles to move in the liquid, redistributes the cavitation bubbles in the beaker and accelerates the cracking process of the cavitation bubbles, promotes the contact between the coal slime particles and the cavitation bubbles in the material cavity, and makes the adhesion and agglomeration of coal slime particles better dispersed. It can be seen from Fig. 3 that the acoustic flow velocity peaks at about 10mm away from the bottom of the amplitude converter. The acoustic flow velocity peaks corresponding to the ultrasonic power of 200W, 300W, 400W, 500W and 600W are 0.139m/s, 0.157m/s, 0.171m/s, 0.229m/s and 0.289m/s, respectively. Under the treatment of liquid viscous force, the acoustic flow velocity begins to decay after reaching the peak value, and the velocity at the bottom of the material cavity and the walls on both sides approaches 0 m/s. In the process of fluid movement, the axial component of the acoustic radiation force drives the acceleration. When the axial component of the acoustic radiation force is the same as the viscous force of the fluid, the fluid reaches the maximum speed, and then the fluid decelerates. According to Fig. 2 and Fig. 3, it can be seen that when other conditions remain unchanged, the velocity of acoustic flow at the same position in the material cavity increases with the increase of ultrasonic power, which is an important factor affecting the velocity distribution of acoustic flow.

3.2. Experimental result

The distribution of the original particle size of the slime measured by laser particle size analyzer is shown in Table 2, and the experimental results are shown in Fig. 4 and Fig. 5.

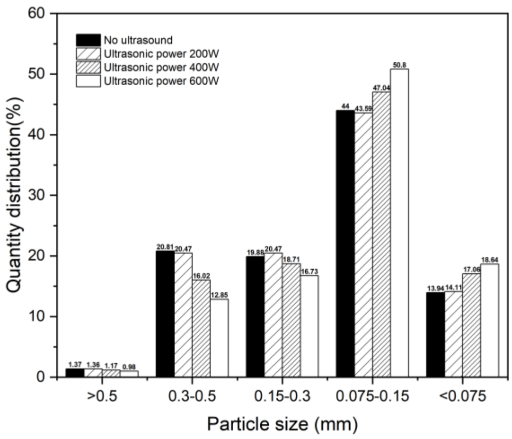
Table 2. Original particle size composition of flotation feed coal slurry

Particle size /mm	> 0.5	0.3-0.5	0.15-0.3	0.075-0.15	< 0.075
Mass fraction /%	1.37	20.81	19.88	44.00	13.94

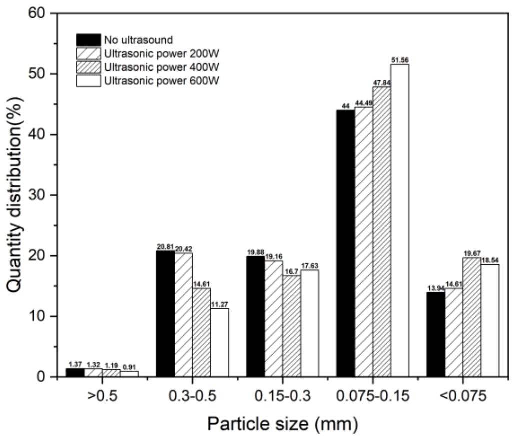
In order to more intuitively analyze the influence of ultrasonic power and ultrasonic treatment time on the change of coal slime particle size, the experimental data from the laser particle size analyzer are directly presented in Fig. 4 and Fig. 5 as column charts showing the coal slime particle size change under different power and treatment time conditions.

As shown in Fig. 4, with the extension of ultrasonic treatment time, the change in coal slime particle size exhibits a slow increasing or decreasing trend. The variations in particle size distribution were primarily observed in the 0.3 – 0.5 mm and 0.075 – 0.15 mm fractions. Under the same power, the particle size change rates of 0.3–0.5 mm slime corresponding to treatment times of 1, 3 and 5 minutes are 0.25%, 2.05% and 2.07%, respectively, while those within the 0.075 – 0.15 mm fraction are 0.13%, 1.47% and 4.18%, respectively. This indicates that prolonging the ultrasonic treatment time can promote the dispersion effect of coal slime particles.

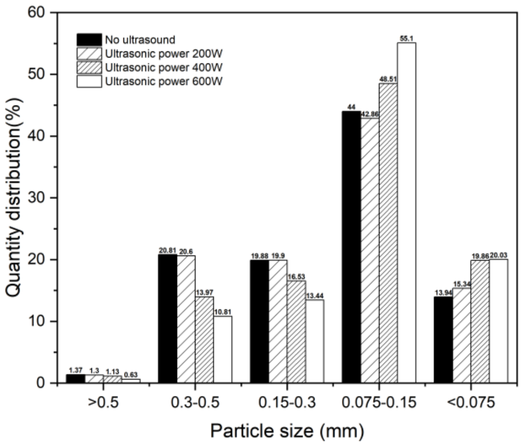
As can be seen from Fig. 5 (a), under the 200W ultrasonic power, the change of treatment time has little influence on the change of coal slime particle size. The particle size of 0.3-0.5mm and 0.075mm- particle size has a slight change trend, while the particle size of other particle sizes does not change basically. It can be seen from Fig. 5 (b) and Fig. 5 (c) that with the increase of ultrasonic power, the change trend of coal slime particle size gradually increases. Among them, the particle size of >0.5mm, 0.3-0.5mm and 0.15-0.3mm show an overall decreasing trend, and the decreasing trend of 0.3-0.5mm particle size is the most obvious. Under the treatment of 600W ultrasound, the maximum change rate reached 10.02%; The particle size of 0.075-0.15mm and <0.075mm showed an overall increasing trend, and the growth trend of 0.075-0.15mm particle size was the most obvious, and the maximum change rate was 10.98%. With the increase of ultrasonic power, the change trend of coal slime particle size is more obvious, indicating that the change of ultrasonic power has a more significant impact on the change of coal slime particle size.



(a) Ultrasonic treatment time 1 minute

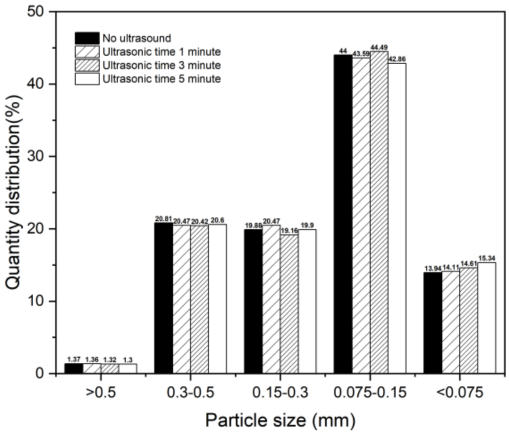


(b) Ultrasonic treatment time 3 minutes

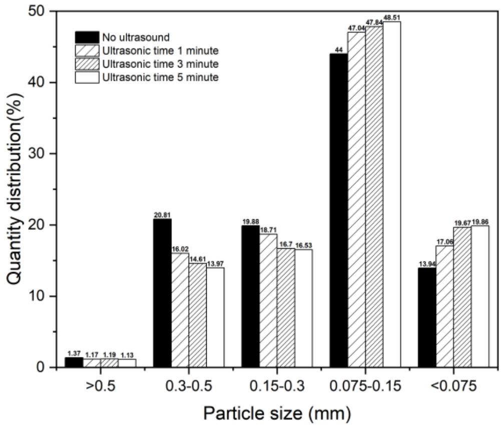


(c) Ultrasonic treatment time 5 minutes

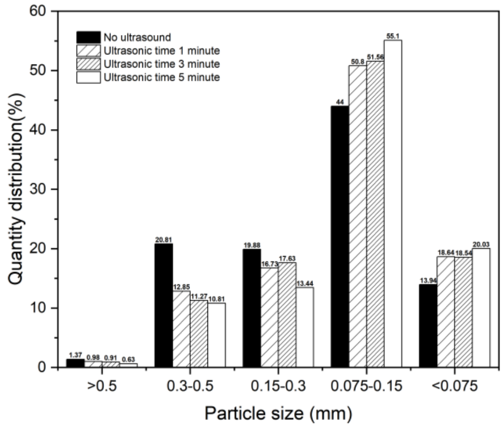
Fig. 4. Grain size distribution change of coal slime under different treatment times



(a) Ultrasonic power 200W



(b) Ultrasonic power 400W



(c) ultrasonic power 600W

Fig. 5. Distribution change of coal slime particle size under different powers

4. Conclusions

(1) Through ultrasonic treatment, it can promote the dispersion effect of slime particles and reduce the adhesion and agglomeration phenomenon between slime particles. And the dispersion effect of coal slime particles becomes more and more significant with the increase of ultrasonic power and the extension of ultrasonic treatment time.

(2) The simulation results show that when ultrasonic waves propagate in liquid, sound flow will be generated in the material cavity to promote the dispersion of slime particles, and the dispersion effect of slime particles is closely related to the size of the acoustic flow velocity. The intensity of eddy currents generated in the material cavity and the size of the acoustic flow velocity increase with the increase of ultrasonic power.

(3) Ultrasonic power is a significant factor affecting the dispersion effect of coal slime. Under the same treatment time, with the increase of ultrasonic power, the change of coal slime particle size showed a significant upward trend, and the maximum increase in the proportion of particles in the 0.075–0.15 mm range reached 10.98%, which increased by 6.8% compared with the maximum change rate of 4.18% generated by changing the treatment time under the same ultrasonic power.

This study not only reveals the law and mechanism of ultrasonic effect on the dispersion of coal slime particles, but also provides an important experimental basis and theoretical support for the further application of ultrasonic dissociation dispersion in the field of coal separation.

References

AN M.-Y., LIAO Y.-F., XIE H.-S. et al. 2024. *Research progress of coal slime flotation enhanced by emulsified collector*. Mineral Protection and Utilization, 44(1), 105-114.

ARDEBILI N.K., MENZ D.M., SALAHSHOOR H., et al., 2024. *Focal Volume, Acoustic Radiation Force, and Strain in Two-Transducer Regimes.* IEEE transactions on ultrasonics, ferroelectrics, and frequency control, 71(10), 1199-1216.

CHERNYSHEV V.A., POILOV Z.V., SEN'KINA D.I., et al., 2025. *Change in Foamability and Foam Stability of Nonionic Collectors of Slimes in Ultrasound Treatment.* Journal of Mining Science, 60(6), 1035-1042.

HU J., WANG Z., LI Z., 2023. *Experimental study on evolution characteristics of cavitation bubbles under multi-boundary conditions.* Journal of Drainage and Irrigation Machinery Engineering, 41(4), 393-399, 416.

KHAN A., SANAULLAH K., KONSTANTINOVICH E.S., et al. 2021. *A study of the hydrodynamics of steam-assisted coal particles removal.* International Journal of Energy and Environmental Engineering, 12(2), 1-10.

KSHETRI G.K., COOK A., NAMA N., 2025. *Numerical investigation of acoustic radiation force and microstreaming in a viscoelastic fluid.* Physical review. E, 111(2-2), 025102.

MA L., JI Y.C., SHEN G., et al. 2019. *Experimental study on influencing factors of ultrasonic cavitation phenomenon.* Journal of Applied Acoustics, 38(6), 999-1003.

REIS A.S., MENDES T.F., JUNIOR I.P., BAROZZO, M.A.S., 2023. *Influence of bubble size on performance of apatite flotation of different particle size*. Particulate Science and Technology 41(7), 1044-1052.

SAID B.B., RUDOLPH M., GOLDMANN D., et al. 2025. *Upscaling and optimization of reagents systems in froth flotation: A DoE and numerical-optimization-based methodology*. Minerals Engineering, 228109308-109308.

SILVA A.L., PRATES M.L., PEREIRA M.A., et al., 2025. *Ultrasonic Dispersion for Iron Recovery from Slime Tailings: Microprocesses Unveiled through Molecular Dynamics Simulations*, Langmuir, 41, 11, 7235–7250.

STONE C., AZARPEYVAND M., CROXFORD A., et al., 2025. *Characterising bulk-driven acoustic streaming in air*. Ultrasonics, 152107638.

SUN S., LIU B., FU M., et al., 2022. S*tudy on bubble distribution in ultrasonic cavitation under acoustic flow*. Acoustical Technology, 41(4), 526-533.

TANG S., 2023. *Structural Design and Analysis of Acoustic Flow Field of Ultrasonic Control Devices*. Huaiyin Institute of Technology.

WANG J., LI Q., FU X., 2023. *Study on the influence of ultrafine grinding on the dissociation degree of ultrafine coal.* Coal Technology, 42(7), 235-237.

WU L., LIU Y., 2019. *Application of I-ELM in slime flotation. Coal Technology*, 38(3), 162-165.

YANG C., HAO B., FAN M., et al. 2024. *Optimization of collector for slime flotation in Lv Lineng Coal Preparation Plant*. Comprehensive Utilization of Mineral Resources, 45(3), 86-91.

YU J., LIU B., XU X., et al., 2019. *Study on Spatial distribution characteristics of ultrasonic cavitation effect in cylindrical cavity*. Acoustic Technology, 39(2), 127-133.

ZHANG W., 2021. *Optimization Design of slime flotation process in Coal preparation plant: A case study of Yuwu Coal Preparation Plant.* Coal, 30(11), 63-66, 82.

ZHANG S., WANG X., YUE W., et al., 2023. S*imulation and Analysis of second-order time-averaged sound flow under Vibration Excitation.* Computer Simulation, 40(4), 317-322.

ZHANG Y., WU W., WANG J., et al. *Mechanism of steady-state cavitation of bubbles on dendrite growth in ultrasonic field*. Acta Physica Sinica,2022,71(24), 271-280.