ISSN 1392-1207. MECHANIKA. Vol. 29, No. 5, 2023: 425–431

Study on Motion Mechanism of Suspended Particles in Water Under Ultrasound

Pu LIU*, Yonglie ZHAN, Kailun QUAN***, Zhengqiang TANG******

*College of Mechanical Engineering, Sichuan University of Science and Engineering, Yibin, 644000, China, E-mail: 248161979@qq.com

**College of Mechanical Engineering, Sichuan University of Science and Engineering, Yibin, 644000, China, E-mail: zhanyonglie@163.com. (Corresponding author)

***College of Mechanical Engineering, Sichuan University of Science and Engineering, Yibin, 644000, China, E-mail: 507918398@qq.com

****College of Mechanical Engineering, Sichuan University of Science and Engineering, Yibin, 644000, China, E-mail: 1278908687@qq.com*

https://doi.org/10.5755/j02.mech.33704

1. Introduction

After the ultrasonic wave propagates in the water, the underwater ultrasonic field is formed. When there are particles in the ultrasonic field, the particles will be affected by the inherent properties of the ultrasonic field [1, 2], such as the cavitation and mechanical action of ultrasound [3, 4]. Studying the characteristics of particles in the ultrasonic field and making use of them makes ultrasonic applications in many important technologies, such as ultrasonic cleaning [5], ultrasonic atomization and applications in sewage treatment [6, 7]. From the point of view of the principle of action, the acoustic radiation force generated by the ultrasonic wave propagating in the medium acts on the surface of the particle. The continuous and high frequency ultrasonic vibration is applied to it. Affected by the ultrasonic radiation force, the state of particles in the medium will change [8-10]. Tang et al. [11] proposed a method to calculate the sound pressure field and sound field force of multiple sound sources on particles. It analyzed the influence of scattered waves and applied sound force on particles with different size parameters. Alexander A Doinikov et al. [12] used the acoustic streaming effect of ultrasound to effectively manipulate particles. Both of them use the radiation force in the ultrasonic field and the acoustic streaming effect to control the particles.

Papež P et al. [13] proposed the dissipation model of ultrasonic wave in water and explored the influence of frequency and temperature on the sound field. They analyzed the influencing factors of sound field through the dissipation model of ultrasonic field. Kyoden T et al. [14] observed the solidification process of ultrasonically irradiated liquid suspension particles, showing the effect of ultrasound on particles.

Zhai et al. [15] proposed an orthogonal ultrasonic method. By observing the distribution characteristics of the sound field, it is found that orthogonal ultrasound improves the sound energy characteristics of the sound field.

The above research reflects the inherent properties of the ultrasonic field and the exploration of the influencing factors of ultrasonic propagation. The state of the particles and the effect of ultrasonic on the particles were analyzed. However, the analysis of the acoustic pressure condition on the surface of the particles when the ultrasonic waves act on the surface of the particles has rarely been elaborated. This work will analyze the effect of acoustic radiation force on particles and the motion characteristics of particles in ultrasonic field. An analysis idea of the response of particle surface to ultrasonic wave after suspended particles in water are affected by ultrasonic wave is provided.

2. Model analysis

When modeling and simulating the response of ultrasonic waves to suspended particles in water, a model of the particles in water is created. The response of water particles to ultrasonic action is studied to describe the details of the motion characteristics of suspended particles in water. In order to facilitate the calculation, an ultrasonic water environment model was established, as shown in Fig. 1.

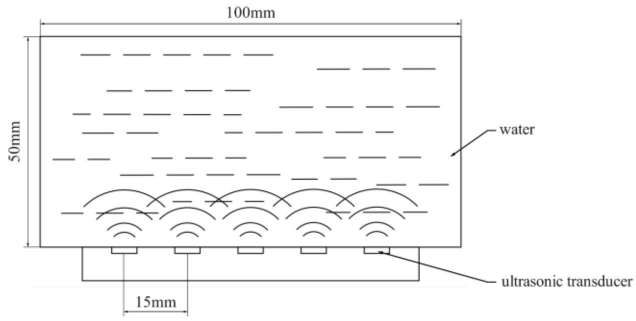


Fig. 1 Simplification of ultrasonic device

When numerically simulating the sound field generated by ultrasonic waves, the medium is regarded as a combination of numerous volume elements, and the following assumptions are made.

1. Ignore the viscoelastic attenuation and thermal conductivity of the medium, and in the model, ensure the energy uniformity and temperature constancy of the ultrasonic waves in the propagation process.

2. The given material is considered to be homogeneous, linearly elastic and isotropic in the given region.

3. The propagation of acoustic waves in two dimensions is carried out in the plane strain formulation, a step that allows the model to be simplified in order to observe the characteristics of the particle's motion state in the model.

After the volume element is disturbed by ultrasound the pressure changes from the original p_0 to p', and the resulting pressure difference is:

$$p = p' - p_0, \quad (1)$$

where: p is the sound pressure, in the sound field, the sound pressure is often a function of time and space, that is $p=p(x, y, z, t)$, the sound pressure value at a certain moment is called the instantaneous sound pressure, the maximum instantaneous sound pressure value at a certain time period is the peak sound pressure, the instantaneous sound pressure to time after taking the root mean square value that is the effective sound pressure p_e, that is:

$$p_e = \sqrt{\frac{1}{T}\int_0^T p^2 dt}. \quad (2)$$

To observe the sound energy per unit volume, i.e., the sound energy density, the general expression is:

$$\varepsilon = \frac{1}{2}\rho_0\left(u^2 + \frac{1}{\rho_0^2 c_0^2} p^2\right), \quad (3)$$

where: u is the velocity of a volume element in the acoustic field. When under the influence of no disturbance in the ultrasonic field, the medium water and suspended particles are macroscopically stationary, i.e., the velocity u is considered to be 0. When eliminating u, the average energy density is found to be:

$$\bar{\varepsilon} = \frac{{p_e}^2}{\rho_0 c_0^2}. \quad (4)$$

In the ultrasonic sound field, the value of Rayleigh radiation pressure caused by the nonlinearity of the equation of state is:

$$\Delta p = \frac{\gamma - 1}{2}\bar{\varepsilon}, \quad (5)$$

where: γ is the specific heat capacity ratio.

The volume element equation of motion derived from Newton 's second law is:

$$\rho dxdydz \frac{d\vec{U}}{dt} = \vec{F} = -\nabla P dxdydz \Rightarrow$$
$$\Rightarrow \rho \frac{d\vec{U}}{dt} = -\nabla P, \quad (6)$$

where: $\vec{U}$ is the velocity vector, which is a function of x, y, z, t, and ∇P is the divergence of sound pressure in the ultrasonic field. According to the conservation of mass of volume element, the continuity equation can be expressed as [16]:

$$\frac{\partial \rho(x,y,z,t)}{\partial t} = -\nabla \cdot [\rho(x,y,z,t)] \cdot \vec{U}(x,y,z,t). \quad (7)$$

Fig. 2 is a motion diagram of particles in the ultrasonic field affected by acoustic radiation force. The velocity v and acceleration a of particles are related to the acoustic radiation force. The position of the particle will change under the influence of the ultrasonic radiation force F. The position coordinate (x, y) will be a dynamic coordinate. The study of the acoustic radiation force in the sound field allows to observe the motion and characteristics of the particles in a specific space.

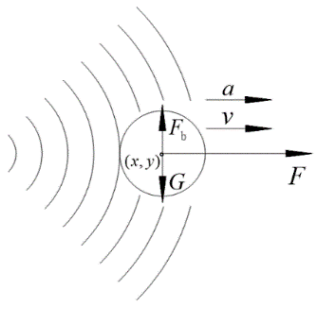


Fig. 2 Schematic diagram of particle motion

In the ultrasonic field, the ultrasonic wave radiates to the surface of the volume element, generating the surface acoustic radiation force of the volume element. The force direction is different. It causes the volume element to be unbalanced and drives the volume element to move irregularly.

The ultrasonic field properties are set according to the model assumptions. The motion characteristics of particles and the distribution of particles in the ultrasonic field under the action of ultrasound are explored. The formula (1) ~ (5) derives the acoustic radiation pressure from the characteristics of the ultrasonic field. The motion equation of volume element is obtained by Formula (6). Formula (7) reveals the continuity equation of the volume element.

3. Model simulation

The simplified model is simulated by COMSOL finite element analysis software, as shown in Fig. 3. The pressure acoustics and flow particle tracking module are used to simulate the particles in water. The ultrasonic excitation source adopts an array structure and is placed at the bottom of the model. The environmental medium is constant temperature (293.15 K) liquid water. Based on the assumption that the acoustic wave is uniform, the ultrasonic excitation source emits 25 kHz ultrasonic wave, and the acoustic wave is uniform. Based on the assumption of sound wave uniformity, the ultrasonic excitation source emits 25 kHz ultrasonic wave. A perfect matched layer is set to absorb the sound waves propagating to the boundary.

In the pressure acoustic setting, the ultrasonic entering the medium water is defined in the form of plane wave. It is used as the boundary condition of ultrasonic radiation. The parameters of suspended particles and environmental media are shown in Table 1 andTable 2.

Table 1

Main physical parameters of suspended particles

Attribute	Value
Density, $kg \cdot m^{-3}$	1500
Particle size, mm	0.1

Table 2

Parameters of environmental media (water)

Parameters	Value
Density, $kg \cdot m^{-3}$	998
Sound velocity, m/s	1481
Heat capacity at constant pressure, $J \cdot (kg \cdot K)^{-1}$	4187
Dynamic viscosity, Pa·s	1.01×10^{-3}

The simplified two-dimensional model was modeled by finite element analysis software., as shown in Fig. 3. Then the simulations were performed. The simulation process uses an array structure of transducers placed at the bottom of the model tank as the excitation source. The medium is liquid water and its temperature is constant (293.15 K). The set-up transducer emits ultrasonic waves in the form of a point source, which emits sound waves with uniformity, and a matching layer is set up to absorb the sound waves propagating to the boundary, so that the reflection of the ultrasonic waves acting on the inner tank wall is ignored.

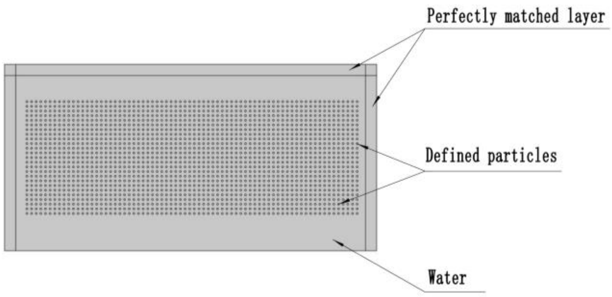


Fig. 3 Geometric modeling of the simulation model

The partitioning process performed on the mesh ensures the presence of at least 8 layers of mesh on a wavelength, while the accuracy needs to be controlled on the surface of the particle model. The physical field and boundary conditions of the periodic ultrasonic wave are set. The acoustic energy of the particle surface and the acoustic radiation force in different directions are calculated by simulation. The mechanical behavior of particles in water is analyzed. At the same time, the motion characteristics of the particles under unbalanced radiation force in the ultrasonic field are analyzed.

4. Results and discussion

The model uses a 25 kHz transducer to simulate the sound pressure distribution of suspended fine particles in water. The distribution and change of acoustic radiation force on the surface of suspended particles in water can be visually observed after they are affected by ultrasonic waves. Furtherly, it provides a scientific reference for the study of the motion of suspended particles in the ultrasonic field.

4.1. Aggregation of particles under ultrasound

In the time period from the ultrasonic emission to the arrival boundary, the sound pressure analysis of the multi-row distribution of particles is carried out. The influence of acoustic pressure change in ultrasonic field on particle distribution was clarified to observe the aggregation effect of particles in ultrasonic field. The Cut Line 2D in the definition model is shown in Fig. 4. In the numerical simulation calculation, the sound pressure on the cross section reflects the magnitude of the sound pressure on the surface of the suspended particles in the water, and the fluctuation of the particles in this direction after being affected by the ultrasonic wave.

At the mesoscopic level, the propagation of ultrasonic waves in a very short time is observed. The sound pressure response of suspended particles at different time points is studied. The sound pressure calculation of the horizontal section line in Fig. 4, a is carried out, and the results are shown in Fig. 5. Above the intermediate source, the acoustic focusing situation is obvious. The sound pressure of these particles fluctuates greatly, up to 25000 Pa. And the vibration effect is obvious. It can also be seen from Fig. 5 that the positive sound pressure part in the middle of the intercept line is more than the negative sound pressure part. This means that during the period from 1.14×10^{-4}s to 2.24×10^{-4}s, the suspended particles in the water will be pushed to the sound source under the dominant effect of positive sound pressure.

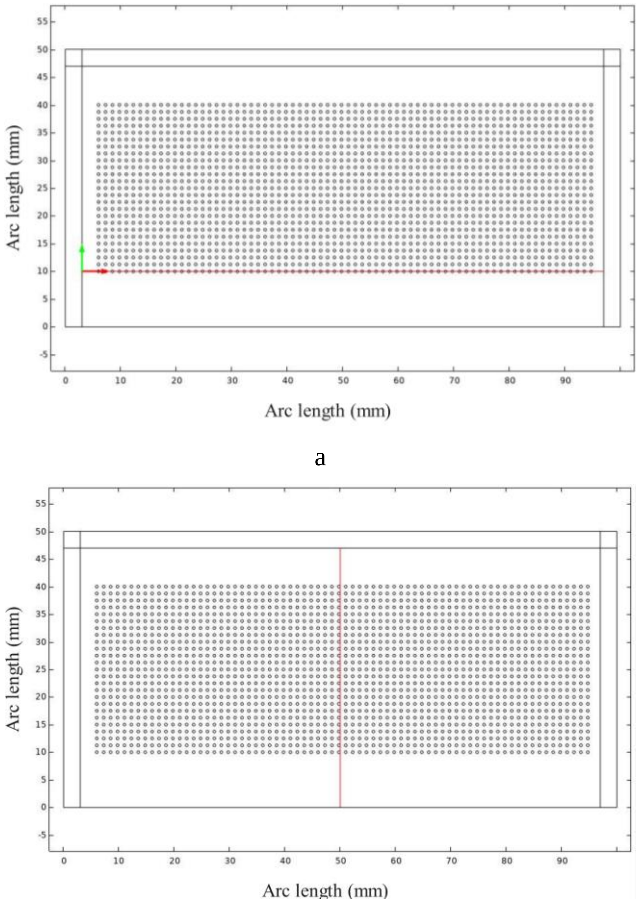


Fig. 4 Two-dimensional intercept line defined on the surface of a particle in water: a) define the bottom horizontal line; b) the defined middle vertical line

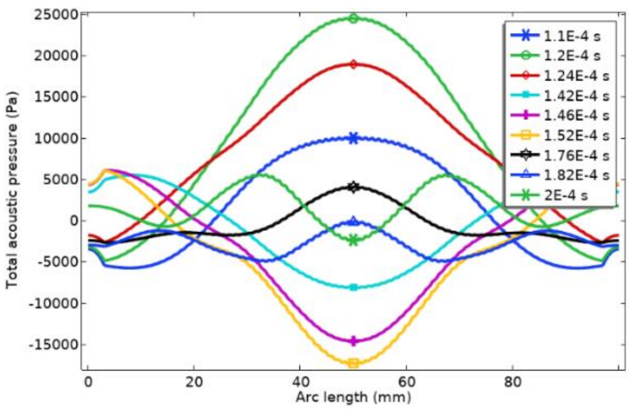
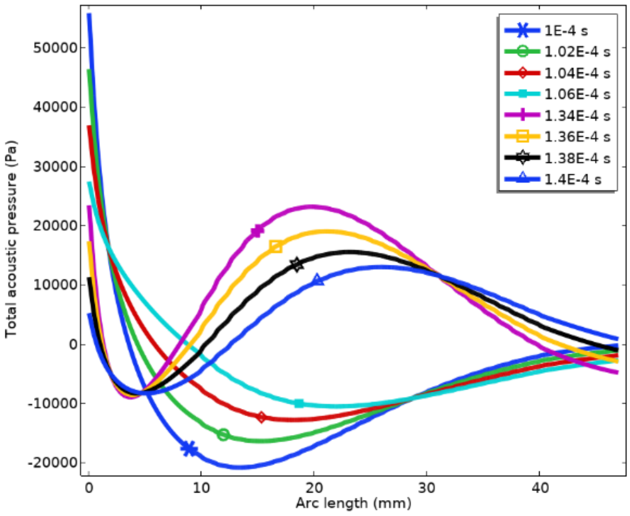


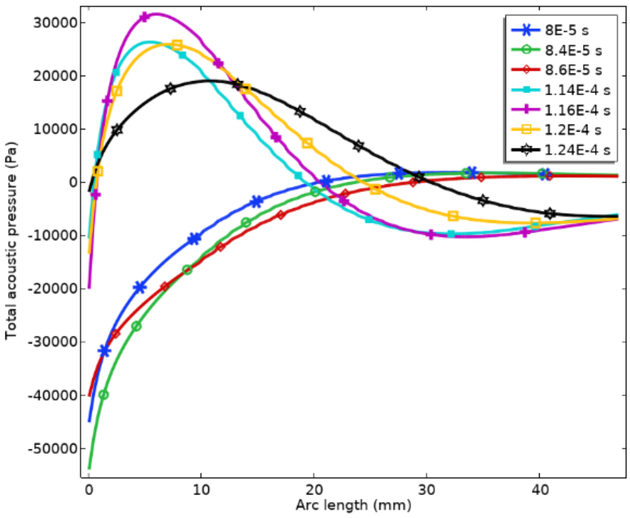
Fig. 5 Sound pressure distribution of the bottom horizontal transversal

A vertical intercept line above the middle position of the ultrasound generation source is given as Fig. 4, b shown. It is used to study the propagation characteristics of ultrasonic waves in the vertical direction. The simulated results are shown in Fig. 6. As shown, the sound pressure magnitude can reflect the focusing and acoustic wave collapse of ultrasonic waves in the vertical direction.

For the time point with positive initial sound pressure, the sound pressure on the vertical line varies with the arc length from 1×10^{-4}s to 1.06×10^{-4}s, and a sharp decrease in the curve can be observed from 0 to 15 mm. In the time period from 1.34×10^{-4}s to 1.4×10^{-4}s, there is a fluctuation in the sound pressure value, with the maximum fluctuation at 5 to 20 mm on the cut-off line. For the time point where the initial position is negative, the sound pressure value is maximum at about 10 mm from the bottom.



a



b

Fig. 6 Variation of sound pressure of vertical cut-off line: a) the starting sound pressure is positive; b) the starting sound pressure is negative

Whether the initial sound pressure is positive or negative, there is an area where the sound pressure fluctuates greatly. As can be seen from Fig. 6, this area is usually 5 ~ 20 mm from the bottom. This characteristic provides a simulation basis for optimizing the actual ultrasonic cleaning. This characteristic provides a simulation basis for optimizing the actual ultrasonic cleaning. According to the simulation results of the model, the best position of vibration effect is determined. That is the maximum position of ultrasonic vibration fluctuation. Place the object to be cleaned in this area to achieve the best cleaning effect.

4.2. Analysis of particle movement

The observation of acoustic acceleration in the ultrasonic field can not only reflect the sound field state changing with time, but also reflect the change of particle motion characteristics. The acoustic acceleration in the ultrasonic field is measured when the particle motion is analyzed. The total acoustic acceleration on the x-component is shown in Fig. 7. It can be seen from the figure that within 8×10^{-5} s to 2.4×10^{-4} s, the total acoustic acceleration change of the sound field is the largest. At the same time, at 1.16×10^{-4} s, the acoustic acceleration is 0.23 m/s^2, which is the maximum value in this period.

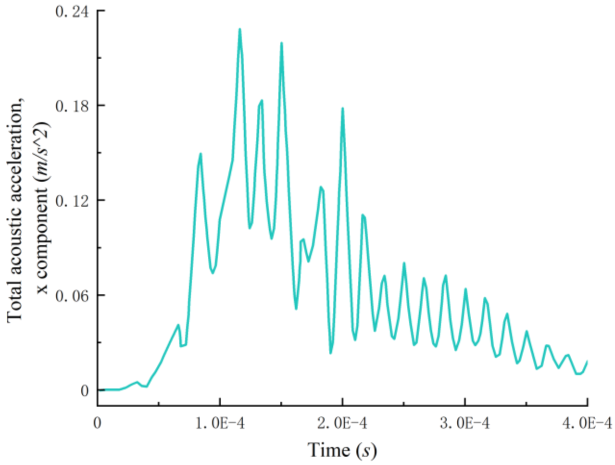


Fig. 7 Total acoustic acceleration on the x-component

The acoustic acceleration as a whole reflects the overall state change of the acoustic field. The maximum value of the total acoustic acceleration *x* component of the ultrasonic field obtained is of great significance in observing the state of particle motion. It reflects the overall response of the particles to ultrasound.

Determine the initial position of the particles in the ultrasonic field, as shown in Fig. 8. As the ultrasonic wave enters, the particle surface will be subjected to acoustic radiation force. The acoustic radiation force promotes the movement of particles, and the dynamic characteristics of particles will change.

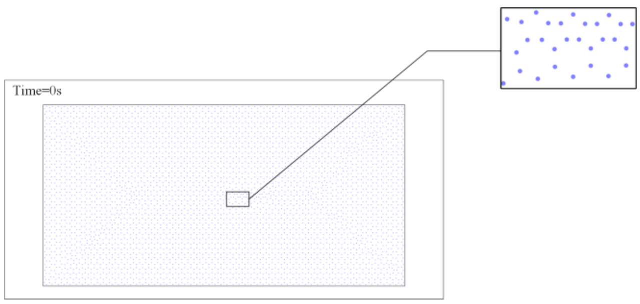
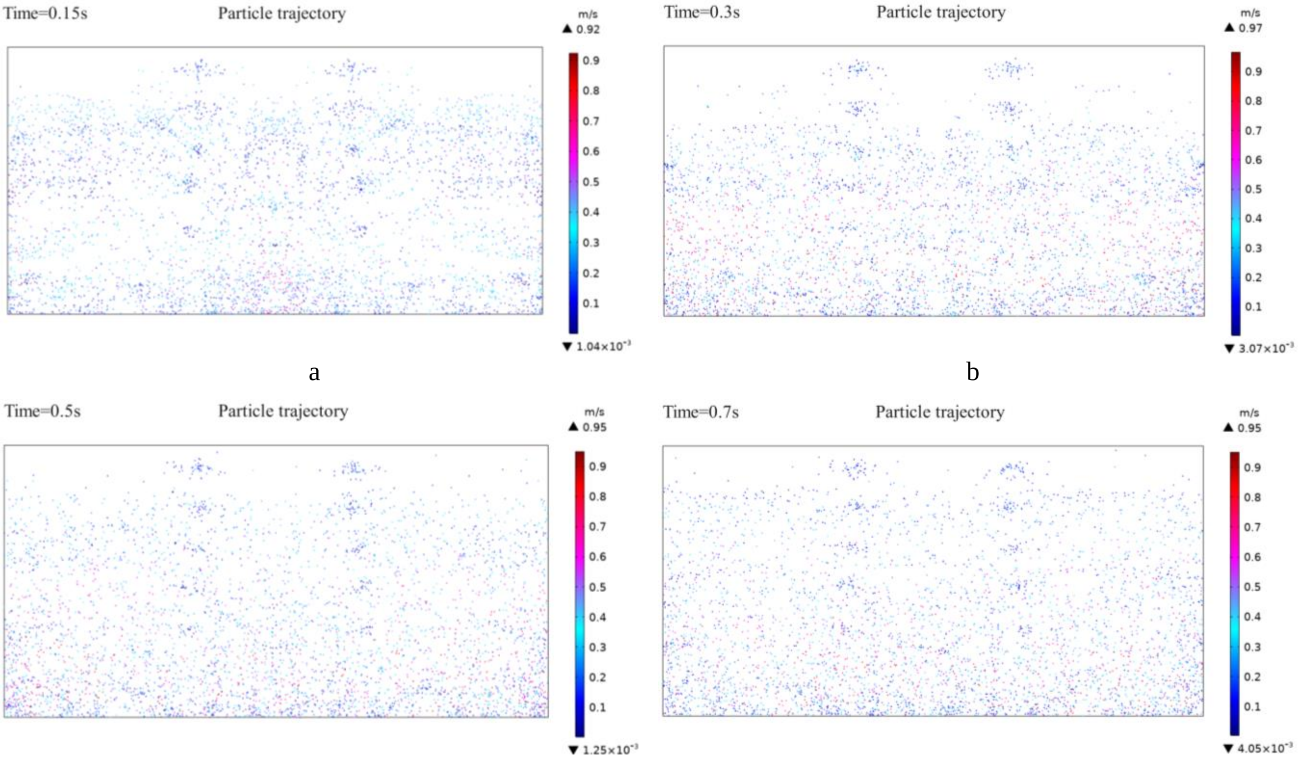


Fig. 8 Initial particle position and local magnification

After the simulations selected time points, it was found that the motion characteristics of the particles were different at different time points. As Fig. 9 shown, the figure shows the state diagram of the particle position presented by selecting different time points. Different time points were selected to analyze the macroscopic effect of ultrasound on the motion behavior of particles in water. By comparing the observation, it is found that in the initial stage of ultrasonic action, the bottom of the particles will be affected by ultrasonic waves first. With the further propagation of ultrasonic waves, the upper particles will also be affected by ultrasonic waves. In the initial stage, the particle motion state is dispersed and the particle dispersion state is obvious. Observing the time points shown in Fig. 9, it can be found that as time goes on, the particle instability will increase after the sound pressure acts on the particle surface. The aggregation effect of particles will become more and more obvious. The aggregation effect occurs not in the position where the sound pressure fluctuates greatly, but in the low sound pressure area.

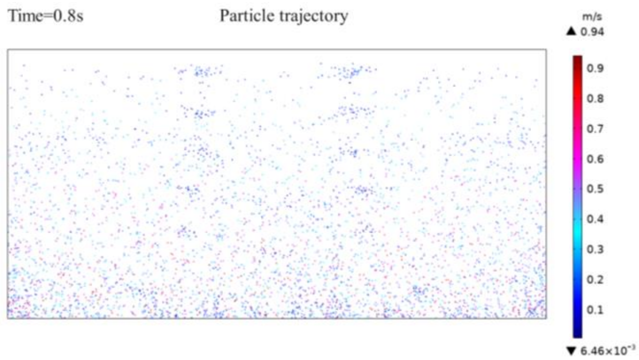


a

b

c

d



e

Fig. 9 Particle motion position at different time: a) t = 0.15 s; b) t = 0.3 s; c) t = 0.5 s; d) t = 0.7 s; e) t = 0.8 s

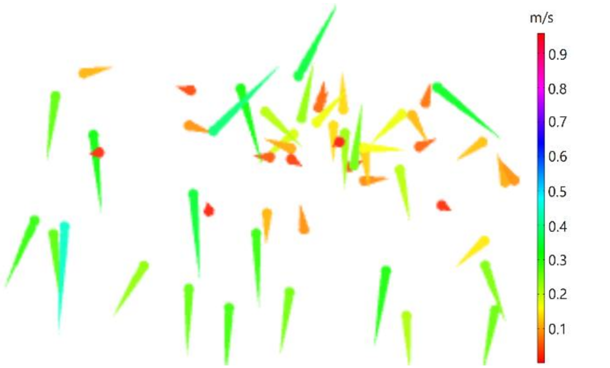


Fig. 10 Particle aggregation in the low sound pressure region

It can be seen from Fig. 9 that after the ultrasonic wave acts on the surface of the particles, acoustic aggregation occurs. In the area with large sound pressure, the particles fluctuate greatly and are difficult to gather. The particles gathered in the low sound pressure area have small velocity and small fluctuation. The particles in the high sound pressure region move to the low sound pressure region driven by the ultrasonic radiation force. Therefore, particle aggregation effect can be observed in the low sound pressure region.

Aggregation of particle motion in the low sound pressure region due to the limitation of acoustic radiation force. As shown in Fig. 10, it describes the aggregation of particles. It can be observed from the particle velocity in Fig. 10 that the particle velocity gradually changes after moving from the high sound pressure area to the low sound pressure area. The particles are limited in the low sound pressure area and aggregate.

5. Conclusion

In this paper, a two-dimensional sound field simulation model is established. The mathematical model of suspended particles in ultrasonic field is analyzed. The effect of ultrasound on particles and the motion characteristics of particles were studied. The effect of ultrasound on suspended particles in water is described theoretically and numerically, and the relationship of acoustic radiation pressure in ultrasonic field in water is given. The size of the acoustic radiation force on the surface of the particles in the ultrasonic field and the motion state of the particles are studied, and the time and position of the best ultrasonic cleaning effect are obtained. The results show that:

1. Array of ultrasound arrangement can produce positive (negative) sound pressure fluctuations in its propagation path as well as ultrasound focusing. The best ultrasonic cleaning effect is in these focusing areas, that is, the location of the larger vibration fluctuations.

2. According to the simulation results, it is found that for the horizontal position, the vibration amplitude of the suspended particles in the middle region is larger. For the vertical position, the region with larger vibration amplitude of the suspended particles is in the position 5~20 mm from the bottom surface.

3. Under the action of sound pressure generated by ultrasonic waves, the motion characteristics of the particles are observed. It is concluded that the aggregation region of the particles tends to be the low sound pressure region. The particles in the high sound pressure region are pushed to the aggregation region and thus confined to the low sound pressure region.

Acknowledgments

This work is supported by The Project of Sichuan University of Science & Engineering (No. 2020RC18) and The Key Project of Sichuan Provincial Key Lab of Process Equipment and Control (No. GK202007). We gratefully acknowledge the financial support received.

References

1. **Peng, H.; Mao, L.; Qian, X.; Lu, X.; Jiang, L.; Sun, Y.; Zhou, Q.** 2020. Acoustic energy controlled nanoparticle aggregation for nanotherapy, IEEE Transactions on Ultrasonics, Ferroelectrics, and Frequency Control 67(4): 735-744. http://doi.org/10.1109/TUFFC.2019.2956043.
2. **Chen, D.; Qiu, M.; Lin, Z.; Liu, Q.; Zhang, G.; Zhu, Z.** 2021. Experimental study on the interaction of a cavitation bubble flanked by two particles, Acta Mechanica 232(12). http://doi.org/https://doi.org/10.1007/s00707-021-03093-3.
3. **Liu, Z.; Ji, C.; Wang, B.; Sun, S.** 2019. Role of a nanoparticle on ultrasonic cavitation in nanofluids, Micro & Nano Letters 14(10). http://doi.org/10.1049/mnl.2019.0033.
4. **Kenji, K.; Koki, K.; Yusuke, S.; Masashi, H.** 2022. Promotion effect of particle fluidization with ultrasonic vibration, Powder Technology 400. http://doi.org/10.1016/j.powtec.2022.117265.
5. **Tangsopa, W.; Thongsri, J.** 2020. A novel ultrasonic cleaning tank developed by harmonic response analysis and computational fluid dynamics, Metals 10(3). http://doi.org/10.3390/met10030335.
6. **Gao, S.; Guo, S.; Dong, G.; Wang, H.** 2021. Numerical simulation and experiment for the ultrasonic field characteristics of ultrasonic standing wave atomization. Journal of the Brazilian Society of Mechanical Sciences and Engineering 43(6): 318. http://doi.org/10.1007/s40430-021-03041-1.
7. **Zhang, J.; Dong, Y.; Wang, S.; Liu, X.; Lv, L.; Zhang, G.; Ren, Z.** 2023. Comparison of ultrasonic treatment of primary and secondary sludges: Physical properties and chemical properties, Separation and Purification Technology 308: 122892. http://doi.org/10.1016/j.seppur.2022.122892.
8. **Firstbrook, D.; Worrall, K.; Timoney, R.; Suñol, F.; Gao, Y.; Harkness, P.** 2017. An experimental study of ultrasonic vibration and the penetration of granular material, Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 473(2198): 20160673. http://doi.org/10.1098/rspa.2016.0673.
9. **Sumitomo, S.; Koizumi, H.; Uddin, M. A.; Kato, Y.** 2018. Comparison of dispersion behavior of agglomerated particles in liquid between ultrasonic irradiation and mechanical stirring, Ultrasonics Sonochemistry 40: 822-831. http://doi.org/10.1016/j.ultsonch.2017.08.023.
10. **Feng, K.; Wang, C.; Mo, R.; Hu, J.; Li, S.** 2020. Interaction between particles and bubbles driven by ultrasound: Acoustic radiation force on an elastic particle immersed in the ideal fluid near a bubble, Ultrasonics Sonochemistry 67: 105166. http://doi.org/10.1016/j.ultsonch.2020.105166.
11. **Tianquan, T.; Lixi, H.** 2021. Acoustic radiation force for multiple particles over a wide size-scale by multiple ultrasound sources, Journal of Sound and Vibration 509. http://doi.org/10.1016/j.jsv.2021.116256.
12. **Doinikov, A. A.; Thibault, P.; Marmottant, P.** 2018. Acoustic streaming induced by two orthogonal ultrasound standing waves in a microfluidic channel, Ultrasonics 87: 7-19. http://doi.org/10.1016/j.ultras.2018.02.002.
13. **Papež, P.; Praprotnik, M.** 2022. Dissipative Particle dynamics simulation of ultrasound propagation through liquid water, Journal of Chemical Theory and Computation 18(2): 1227-1240. http://doi.org/10.1021/acs.jctc.1c01020.
14. **Kyoden, T.; Yoshioka, H.; Momose, N.; Hachiga, T.** 2021. Array formation by ultrasound standing waves with solidification of liquid-suspended micro-particles, Journal of Applied Physics 130(19): 195109. http://doi.org/10.1063/5.0068551.
15. **Zhai, W.; Liu, H. M.; Hong, Z. Y.; Xie, W. J.; Wei, B.** 2017. A numerical simulation of acoustic field within liquids subject to three orthogonal ultrasounds, Ultrasonics Sonochemistry 34: 130-135. http://doi.org/10.1016/j.ultsonch.2016.05.025.
16. **Felisberto, P.; Santos, P.; Jesus, S. M.** 2019. Acoustic pressure and particle velocity for spatial filtering of bottom arrivals, IEEE Journal of Oceanic Engineering 44(1): 179-192. http://doi.org/10.1109/JOE.2018.2807898.

P. Liu, Y. Zhan, K. Quan, Z. Tang

STUDY ON MOTION MECHANISM OF SUSPENDED PARTICLES IN WATER UNDER ULTRASONIC

S u m m a r y

Particles in the ultrasonic field by the influence of acoustic radiation force, its motion characteristics will be changed. Based on the simplified ultrasonic cleaning assumption, numerical simulation is used to construct a simulation model of suspended particles in the ultrasonic field in liquid water environment, and to study the law of ultrasonic waves on the motion characteristics of suspended particles in water. The research results show that the ultrasonic arrangement of the array makes the ultrasonic waves produce ultrasonic focusing on the propagation path. The alternating fluctuations of ultrasonic positive and negative sound pressure are in the horizontal line parallel to the bottom, and the vibration amplitude of suspended particles in the middle region is the largest. For the vertical position perpendicular to the bottom, the region with larger vibration amplitude of suspended particles is at 1/5 from the bottom. The particles in the high sound pressure area are pushed to the gathering area, and the particle vibration amplitude in the low sound pressure area is small, which proves that the gathering area of the particles is often the low sound pressure area. The research results will contribute to the study of particle motion in the ultrasonic field.

Keywords: ultrasonic; simulation; particle; sound pressure.

Received March 23, 2023
Accepted October 9, 2023