Numerical study on the desorption processes of oil droplets inside oil-contaminated sand under cavitation micro-jets

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A R T I C L E   I N F O

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A B S T R A C T

The removal of the adsorbed oil droplet is critical to deoiling treatment of oil-bearing solid waste. Ultrasonic cavitation is regarded as an extremely useful method to assist the oil droplets desorption in the deoiling treatment. In this paper, the effects of cavitation micro-jets on the oil droplets desorption were studied. The adsorbed states of oil droplets in the oil-contaminated sand were investigated using a microscope. Three representative absorbed states of the oil droplets can be summarized as: (1) the individual oil droplet adsorbed on the particle surface (2) the clustered oil droplets adsorbed on the particle surface; (3) the oil droplet adsorbed in a gap between particles. The micro-jet generation during the bubble collapse near a rigid wall under different acoustic pressure amplitudes at an ultrasonic frequency of 20 kHz was investigated numerically. The desorption processes of the oil droplets at the three representative absorbed states under micro-jets were also simulated subsequently. The results showed that the acoustic pressure has a great influence on the velocity of micro-jet, and the initial diameter of cavitation bubbles is significant for the cross-sectional area of micro-jets. The wall jet caused by a micro-jet impacting on the solid wall is the most important factor for the removal of the adsorbed oil droplets. The oil droplet is broken by the jet impinging, and then it breaks away from the solid wall due to the shear force generated by the wall jet. In addition to a higher sound pressure, the cavitation bubble at a larger initial diameter is more important for the desorption of the clustered oil droplets. Conversely, the micro-jet generated by the cavitation bubble at a smaller initial diameter (0.1 mm) is more appropriate for the desorption of the oil droplet in a narrow or sharp-angled gap.

1. Introduction

During the process of refining, storage and transportation of oil, the accidents of spilling and leaking oil will inevitably produce a large number of oily solid wastes, including oil-contaminated soils and oily sludge and so on. Therefore, the remediation of oil-contaminated soils becomes increasingly significant for environmental requirements. The deoiling treatment of oil-contaminated soils can not only reduce environmental pollution, but also effectively recycle and utilize the adsorbed oil, which is also an essential step in the solid waste treatment. The soil is usually considered as a porous media with a complicated pore network formed by the accumulation of particles. The pores inside the oily soil are filled with oil–water mixture which is in the oil-in-water (O/W) state generally. The oil droplets in the pores mainly exist in the forms of free and adsorbed states. The adsorbed oil is generally much more difficult to be removed than the free oil. Therefore, it is especially significant to change the adsorbed oil into the free oil for improving the deoiling efficiency of the oil-contaminated soil. It is crucial to remove the adsorbed oil droplets using effective methods.

In recent decades, the solid waste treatment assisted by ultrasound has attracted more attentions of investigators [1–6]. Ultrasound is regarded as one of the most promising techniques applied in the deoiling of oily solid wastes [7–14], owing to much less producing secondary pollution than the chemical desorption. Recently, many studies have been carried out to explore the influence factors on the ultrasound-assisted deoiling technology [9–14]. Ultrasonic cavitation is regarded as one of the most important effect mechanisms. The cavitation bubble alternately presents a series of behaviors such as expansion, shrink and collapse. A series of tiny and transient cavitation bubbles violently collide, and then the pressure and temperature within the bubbles increase rapidly in few microseconds. The cavitation bubble experiences several hundreds of microseconds from growing to collapsing, then the micro-jet is generated by the cavitation bubble collapsing in the final stage due to the huge pressure difference inside and outside the bubble.
The ultrasonic power is recognized as a critical parameter which has a great influence on cavitation jets generation. The ultrasonic frequency has relatively fewer influence on cavitation is lower, and then cavitation bubbles are larger in size but relatively smaller in number. The collapse of the individual bubble releases a pressure wave and micro-jet with relatively stronger energy [28, 29]. Okawa et al. experimentally investigated the extraction of bitumen from oil sand under different ultrasound frequencies of 28 and 200 kHz, it can be concluded that only sonication at 28 kHz showed the capacity to extract bitumen from oil sand at a low temperature solution (45 ℃) [30]. For this reason, the micro-jet generated by the cavitation bubble collapse close to a rigid wall at an ultrasonic frequency of 20 kHz will be investigated numerically in present study.

The jetting dynamics of liquid plays an important role in the surface treatment and particles breakup [31, 32]. The velocity of the cavitation micro-jet mainly depends on the initial bubble radius and the original position of the bubble from the solid wall [17, 18, 25, 26]. The impact of the jet can induce a large pressure on the wall, which can produce a wall jet along the solid wall that is proved to play an important role in the surface treatment [32]. Similarly, the wall jet can also be used to remove the adsorbed oil droplets from the solid surface. Meanwhile, the oil droplets are broken and become smaller during the desorption process, and the smaller droplets are more easily to float up through pores inside the oily soil, which is significant to increase the desorbing efficiency of the oil-contaminants soil. However, less attention has been paid to that in previous studies. The influence of cavitation micro-jets on the desorption process of the oil droplet adsorbed on the solid surface is well worthy of being studied, which is of great significance for further exploring the mechanism on ultrasound enhancing the oil removal in porous media. In general, it is quite difficult to demonstrate clearly the behavior of the adsorbed oil droplet under a cavitation micro-jet on a microscopic scale using an experimental method. However, the simulation is a relatively appropriate means for the present investigation. The processes of the oil droplet breaking up, sliding on the solid wall and finally breaking away the wall under a micro-jet can be well described by the simulation results. In particular, the oil droplet motion can be better analyzed according to the velocity distribution of the fluid, which is significant to understand the effect of micro-jets on the oil droplet desorption process.

The objective of this study is to investigate the influences of micro-jets on the desorption processes of the oil droplets adsorbed on pore walls in porous media. Firstly, it is absolutely necessary to understand the distribution states of the adsorbed oil droplets in porous media, so the microscopic observation of the oil-contaminated sandy soil was taken by a stereoscopic microscope. Then the representative distribution states of the adsorbed oil droplets in the sandy soil were determined for numerical simulation. Secondly, the micro-jet formation during the cavitation bubbles collapse near a rigid wall at the ultrasonic frequency of 20 kHz and different acoustic pressure amplitudes was investigated numerically. Finally, the desorption processes of the oil droplets at different adsorption states under micro-jets were simulated numerically, and then the major factors influencing the oil desorption were also discussed. The present study provides a certain theoretical reference for revealing the mechanism of cavitation micro-jets enhancing the oil removal in porous solid wastes.

2. Distribution states of the adsorbed oil droplets in the oil-contaminated sand

The adsorbed states of the oil droplets inside porous media are varied and complicated, while it is crucial to the desorption behaviors of the oil droplets. So it is essential to understand the distribution states of the adsorbed oil droplets in porous media. A series of microscopic images of the oil-contaminated sand were taken by a stereoscopic microscope in our laboratory. Fig. 1 shows the distribution states of the oil droplets in the oil-contaminated sand under a microscope. The sandy soil can be considered as the porous media formed by the accumulation of particle matters. It can be seen that both water and oil droplets simultaneously exist in the pores formed by the accumulation of soil particles. As shown in Fig. 1, some oil droplets are adsorbed on the surface of sand grains, and others can freely move in the pore channels. In particular,
the relatively larger oil droplets are mostly adsorbed on the sand grains individually, and the smaller oil droplets are absorbed in groups. There are also some oil droplets trapped in the gaps and grooves between sand particles.

Three representative distribution states of the adsorbed oil droplets in the sandy soil were summarized as follows and shown in Fig. 2. (1) The large-size oil droplet is individually adsorbed on the particle surface (see Fig. 2 (a)); (2) the clustered small-size oil droplets are adsorbed on a particle together (see Fig. 2 (b)); (3) the oil droplets are adsorbed in the gaps between particles (see Fig. 2(c)). The subsequent simulations were mainly performed aiming at the three typical adsorbed states. The desorption processes of the oil droplets at different adsorbed states under micro-jets will be also contrastively analyzed based on the simulation results.

3. Mathematical model

3.1. Collapse of a cavitation bubble near a rigid wall

3.1.1. Governing equations

In this study, the final stage of the cavitation bubble collapse close to a rigid wall should be simulated numerically, which is crucial to the formation of micro-jets. The level set method was applied to trace the vapor–liquid two-phase interface. The level set method was introduced originally by Osher and Sethian [33], and it is a Eulerian computational technique for capturing moving boundaries or interfaces.

The assumptions were applied on the simulation of dynamic behaviors of cavitation bubbles as follows [27].

- The fluids are Newtonian.
- The gas phase is represented by perfect gas, and the compression process of bubbles is adiabatic.
- The phase changes such as evaporation and condensation are negligible.

The conservation equations of mass, momentum and energy considering the vapor–liquid two-phase flows are represented as follows.

The Navier–Stokes equation

\[
\frac{\partial (\rho u)}{\partial t} + \nabla \cdot (\rho uu) = -\nabla p + \nabla \cdot \left( \frac{\mu}{\rho} \nabla u + \frac{2}{3} \rho \nu \nabla u \right) + F_n + F_t
\]

The Continuity equation:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho u) = 0
\]

The energy equation:

\[
\frac{\partial (\rho c_p T)}{\partial t} + \nabla \cdot (\rho c_p u T) = \alpha_p T \left( \frac{\partial p_s}{\partial t} + u \cdot \nabla p_s \right) + \nabla \cdot (k \nabla T) + Q
\]

The ideal-gas Equation:

\[
\rho_s = \frac{p_s M_s}{k T}
\]

Where, the fluid involves in the water and vapor phases, \( u \) is the fluid velocity, \( \rho \) is the fluid density, \( p \) is the fluid pressure, \( \mu \) is the fluid viscosity of, \( I \) is the identity matrix, \( T \) is the temperature, \( c_p \) is the specific heat capacity at constant pressure, \( \alpha_p \) is the isobaric thermal expansivity, \( p_s \) is the absolute pressure, \( k \) is the thermal conductivity, \( Q \) is the heat source term. \( M_s \) is the mean molar mass of steam(0.01802 kg/mol), \( R \) is the universal gas constant(8.3145 J/mol-K).

In the level set method, the surface tension stress and gravitational force are considered as body force terms in the Navier–Stokes equation. In the Eq.(1), \( F_n \) is gravity, \( F_t \) is a singular surface force. This interfacial force indicates the hydrodynamic two-phase interaction, which can be expressed by [34]:

\[
F_n = \nabla \cdot \left[ \sigma [I - (nn^t)] \delta \right]
\]

Where, \( \sigma \) is the interface tension, \( n \) is the unit normal vector at the interface pointing from the steam phase to the water phase, which can be expressed as the normalized gradient of the level-set function:

\[
n = \frac{\nabla \phi}{|\nabla \phi|}_{|\phi|=0.5}
\]

The Dirac delta function \( \delta \) can be expressed as:

\[
\delta = \delta(1 - \phi) ||\nabla \phi ||
\]

The governing equation of interface represented by the level set function is expressed as:
3.2.1. Governing equations

Fig. 3. Physical model on the cavitation bubble collapse near a rigid wall.

\[
\frac{\partial \phi}{\partial t} + u \cdot \nabla \phi = \gamma \left( \rho \nabla \phi - \phi (1 - \phi) \right) \nabla \phi \nabla \phi
\]  

(8)

Where, \( \phi \) is the level set function, it is equal to 0.5 at the interface, less than 0.5 in the water phase and more than 0.5 in the vapor phase. The exact instantaneous interface position can be captured by locating the level set of \( \phi = 0.5 \). \( \gamma \) is the reinitializing parameter. \( \varepsilon \) is the controlled parameter of interface thickness.

In order to avoid the step changes of the physical parameters at the phase interface, and the smoothed Heaviside function \( H(\phi) \) are applied on the virtual interface [35,36]. The application of smoothed Heaviside functions \( H(\phi) \) can improve the problem of non-convergence in simulation.

\[
H(\phi) = \begin{cases} 
0, & \phi < -\varepsilon \\
\frac{1}{2} \left( 1 + \frac{\phi}{\varepsilon} + \sin(\pi \phi/\varepsilon) \right), & |\phi| \leq \varepsilon \\
1, & \phi > \varepsilon
\end{cases}
\]  

(9)

Then the physical property parameters can be written as:

\[
\rho = \rho_s + (\rho_o - \rho_s)H(\phi)
\]

(10)

\[
\mu = \mu_s + (\mu_o - \mu_s)H(\phi)
\]

(11)

Where, the subscripts of \( s \) and \( w \) denote the vapor phase and the water phase respectively.

3.2.2. Initial and boundary conditions

Figure 3 shows the physical model of the cavitation bubble collapse near a rigid wall. As shown in Fig. 3, The bottom boundary was set as a no-slip rigid wall, other boundaries were set as periodic pressure boundaries. The initial temperature was set as 293 K, and the initial pressure inside the bubble is set as the saturated vapor pressure of 2340 Pa at 293 K.

The periodic pressure wave condition was set at boundaries:

\[
p_t = p_o \cos(2\pi ft) + p_0
\]

(12)

Where, \( p_o \) is the acoustic pressure amplitude, \( f \) is the ultrasonic frequency, 20 kHz, \( p_0 \) is the ambient pressure.

3.2. Oil droplets desorption under cavitation micro-jets

3.2.1. Governing equations

In this study, the desorption process of the absorbed oil droplet inside the oily sand under a micro-jet involves in the oil–water two-phase flow, so the level set method was also applied to trace the two-phase interface. It is assumed that the fluid is immiscible and incompressible Newtonian fluid. The conservation equations of mass and momentum considering the liquid–liquid two-phase flow are represented as follows.

The Navier–Stokes equation coupled with the level set method:

\[
\rho \frac{du}{dt} + \rho (u \cdot \nabla) u = \nabla \left[ -p + \mu (\nabla u + (\nabla u)^T) \right] + F_u + F_s
\]

(13)

The Continuity equation:

\[
\rho \nabla u = 0
\]

(14)

Where, the fluid involves in the water and oil phases, \( u \) is the velocity of fluid, \( \rho \) is the density of fluid, \( \mu \) is the viscosity of fluid and \( p \) is the pressure of fluid. \( F_s \) is gravity, \( F_0 \) is a singular surface force, and it can be expressed by the equations (5)~(7).

The governing equation of interface represented by the level set function can also be expressed by equations (8), but \( \phi \) is the level set function of the oil–water interface in this model.

Then the physical property parameters can be written as:

\[
\rho = \rho_o + (\rho_s - \rho_o)H(\phi)
\]

(15)

\[
\mu = \mu_o + (\mu_s - \mu_o)H(\phi)
\]

(16)

Where, the subscripts of \( o \) and \( w \) denote the oil phase and the water phase respectively.

3.2.1. Initial and boundary conditions

Figure 4 shows the physical models at the three adsorbed states of oil droplets. As shown in Fig. 4, the oil droplet is absorbed by the solid wetted wall with the specified contact angle and a slip length which equals to the mesh size parameter. The inlet boundary is set as the initial micro-jet velocity, and the outflow is prescribed with the pressure and no viscous stress condition. The density and dynamic viscosity of the oil droplets is set as 887.59 kg/m³ and 0.1791 Pa-s.

The jet velocities are quite different ranged from 20 to 600 m/s according to the predecessors’ studies. In present investigation, the initial micro-jet velocities ranged from 150 to 300 m/s are applied according to the simulation results on micro-jets formation. In addition, the jet velocity will rapidly attenuate in tens of microseconds result from the pressure change of fluid during the collapse process of the cavitation bubble. According to the tendency of the pressure attenuation during the cavitation process in the literatures [25,26], the velocity of micro-jet is supposed to have a similar trend of decay in this paper, and the decay
Fig. 4. Physical models at the three adsorbed states of oil droplets (a) Individual absorbed oil droplet; (b) Clustered absorbed oil droplets; (c) Individual absorbed oil droplet in a gap.

Fig. 5. Attenuation curve of the micro-jet velocity.
Fig. 6. Temperature and pressure distributions of the collapse processes of the bubbles with different initial diameters at the acoustic pressure amplitude of 5 MPa. (a) Initial bubble diameter $D_0 = 0.1$ mm; (b) Initial bubble diameter $D_0 = 0.2$ mm; (c) Initial bubble diameter $D_0 = 0.4$ mm.
Fig. 7. Temperature and pressure distributions of the collapse processes of the bubbles with different initial diameters at the acoustic pressure amplitude of 8 MPa. 
(a) Initial bubble diameter $D_0 = 0.1$ mm; (b) Initial bubble diameter $D_0 = 0.2$ mm; (c) Initial bubble diameter $D_0 = 0.4$ mm.
3.3. Simulation methods

The two-phase flow module of COMSOL Multiphysics is applied to solve the governing equations. COMSOL can automatically detect the physical field of the required solution, as well as the size of the problem, and select the solver for the specific problem. In this simulation, the PARDISO (parallel sparse direct solver) were used for solving large sparse symmetric and unsymmetric linear systems of equations, which has good convergence and computational efficiency. The simulation procedure involves two consecutive computations, including to calculate a smooth initial solution for the level set variable and then start the time-dependent simulation of the fluid motion using this initial solution. An extremely refined grid was used in the oil droplet and bubble zone, and the mesh independence was also detected. In order to accurately resolve the interface, the adaptive meshing was used in order to keep the mesh refined in the interface region when the interface moves during the simulation.

4. Results and discussion

4.1. Micro-jets generation during the bubbles collapse process

In present simulation, the ultrasonic frequency remains constant at 20 kHz. The distance between the bottom of bubbles and the rigid wall is 0.1 mm. Fig. 6 shows the temperature and pressure distributions of the collapse processes of the bubbles with different initial diameters at the acoustic pressure amplitude of 5 MPa. As shown in Fig. 6, the bubble shrinks rapidly in the positive pressure stage. The pressure is asymmetrical in the areas above and below the bubble owing to the existence of the rigid wall. While the bubble shrinks as a whole, a sunken is formed on the top of the bubble due to the pressure increases rapidly above the bubble. Subsequently, the sunken is deepened gradually, and the bubble is penetrated and becomes a toroidal shape. The micro-jet is formed in the hollow channel of the toroidal bubble. The deformed shape of the bubble during the collapse process in the present simulation is similar with the simulation and experimental results in the documents [16,27].
but the bubble collapse time is shorter than that in the literatures. That is because some operation conditions used in this simulation were different from those in the literature [16], especially the acoustic pressure amplitude is obviously larger. Moreover, it also can be seen that the temperature inside the bubble rapidly increases during its shrinkage process. The smaller the initial bubble size is, the faster the internal temperature rises during the compression process, and the highest temperature can reach about 950 K inside the bubble. It is also verified that the bubble cavitation process is usually accompanied by the high temperature and pressure in local environment. The collapse processes of the bubbles at different initial diameters are similar except slight differences. The jet velocity is larger at the initial moment when the bubble is penetrated, and it decays rapidly later. When the initial bubble diameter is 0.1 mm, the bubble is broken at a faster rate than that at the larger diameters (0.2 mm and 0.4 mm). The sectional diameter of the jet is about 21 μm at the initial bubble diameter of 0.4 mm (see Fig. 6(c)), and it is just 5.7 μm at the initial bubble diameter of 0.1 mm (see Fig. 6(a)). The jet with a larger sectional area can produce a larger impact force on the solid wall, which is beneficial to the desorption of oil droplets absorbed on the solid wall. Fig. 7. Shows the temperature and pressure distributions of the collapse processes of the bubbles with different initial diameters at the acoustic pressure amplitude of 8 MPa. As shown in Fig. 7, When the acoustic pressure amplitude increases to 8 MPa, the bubble collapse time is obviously shortened compared with

Fig. 10. Desorption processes of the adsorbed oil droplets at different contact angles under micro-jets (The initial jet velocity $v_0 = 150$ m/s, the jet outlet diameter $d = 10$ μm, the oil droplet diameter $D = 100$ μm) (a) The droplet contact angle 70°; (b) The droplet contact angle of 100°.
that at the acoustic pressure amplitude of 5 MPa (see Fig. 6) under the same initial bubble diameter, but the sectional diameter of jets has no obvious change.

Figure 8 shows the velocity distributions of the collapse processes of the bubbles with different initial diameters at different acoustic pressure amplitudes of 5 MPa and 8 MPa. As shown in Fig. 8, the maximum jet velocity increases gradually with the initial bubble diameter under the same acoustic pressure amplitude. When the acoustic pressure amplitude is 5 MPa (see Fig. 8(a)), the maximum jet velocity is 124 m/s at the initial bubble diameter of 0.1 mm, and it increases to 140 m/s at the initial diameter of 0.4 mm. When the acoustic pressure amplitude increases to 8 MPa (see Fig. 8(b)), the maximum jet velocity arrives to 175 m/s at the initial diameter of 0.1 mm, and it is increased by 41.1%. The similar phenomenon can be found at the initial bubble diameters of 0.2 and 0.4 mm, and the increasing proportion is 47.6% and 55%, respectively. It can be concluded that the acoustic pressure amplitude has a great influence on the maximum jet velocity, and the initial diameter of bubbles is significant for the sectional diameter of jets. Fig. 9 shows the variation of the maximum jet velocity with the acoustic pressure amplitude. It can be seen that the maximum jet velocity has an obvious growth trend with the acoustic pressure amplitude. The appropriate jet velocity can be obtained according to operating the acoustic pressure amplitude. In the present simulation, the velocity and sectional diameter of the micro-jet generated by the cavitation bubble collapse near a rigid wall were analyzed. That is crucial to investigate the oil droplet desorption under the micro-jet subsequently.

4.2. Desorption process of the individual absorbed oil droplet under a micro-jet

Most large size droplets are individually adsorbed on the particle surface, which are usually difficult to be removed due to their strong adsorption capacities. So the removal of the large scale absorbed oil droplet is greatly significant for improving the deoiling efficiency of the oil-contaminated sandy soil. The adsorption capacity of oil droplets largely depends on its wettability on the solid wall, which is a basic property reflecting the relative size of three-phase interface energy. The surface of sand grains is originally hydrophilic and oleophobic. When the sand surface has been saturated with oil for a long time, its lipophilicity increases and some surfaces even become oleophilic. Therefore, the desorption processes of the oil droplets at different contact angles with the solid wall under micro-jets were investigated, and the
The simulated results are shown in Fig. 10. In this simulation, the fixed preconditions include the initial jet velocity $v_0 = 150$ m/s, the jet outlet diameter $d = 10$ μm, and oil droplet diameter $D = 100$ μm. It can be seen that the desorption process of an individual oil droplet can be clearly divided into three stages: collapse, desorption, and float. When the contact angle of the oil droplet is 70° (see Fig. 10 (a)), the micro-jet

![Fig. 13. Average velocities of the wall jets at different contact angles within the height of 5 μm from the adsorption wall (The initial jet velocity $v_0 = 150$ m/s, the jet outlet diameter $d = 10$ μm, the oil droplet diameter $D = 100$ μm, the jet time $t = 6$ μs).](image1)

![Fig. 14. Desorption processes of the oil droplets at different sizes under micro-jets (The initial jet velocity $v_0 = 200$ m/s, the jet outlet diameter $d = 10$ μm, the contact angle of oil droplets $\theta = 100^\circ$).](image2)

Fig. 15. Average velocities of the wall jets at different oil droplet sizes within the height of 5 μm from the adsorption wall (The initial jet velocity $v_0 = 200$ m/s, the jet outlet diameter $d = 10$ μm, the contact angle of oil droplets $\theta = 100^\circ$, the jet time $t = 6$ μs).
has penetrated the oil droplet at 4 μs and produces lateral wall jets on the solid wall. Then the annular oil droplet extends outwards from the center along the solid wall due to the wall jet, and its center hole becomes larger and larger. Meanwhile, the adsorption area of the oil droplet gradually decreases. Finally, the oil droplets have already separated from the solid wall at 6 μs under the action of shear flow and then the desorbed oil droplets gradually float up. In contrast, when the contact angle is 100°, the perforated oil droplet cannot be desorbed at 10 μs (see Fig. 10(b)). The reason can be obtained by analyzing the velocity distribution of the lateral wall jet, which is the most important factor for the oil droplet desorption.

Figure 11 shows the velocity distributions of the wall jets at a height of 2 μm from the adsorption wall (y = 2 μm) under different jet times. It can be seen that the maximum velocity of the wall jet decreases and its location moves outwards gradually with the jet time changing from 4 to 7 μs. The wall jet velocity at the contact angle of 70° is greater than that at 100° at the same moment. When the contact angle of the oil droplet is 70° (see Fig. 11(a)), the maximum velocities of the wall jet arrive to 69.7, 62.6, 52.1 and 44.39 m/s at the jet times of 4, 5, 6 and 7 μs, which appear at x = 12.2 μm, x = 18.2 μm, x = 23.2 μm and x = 20.2 μm respectively. However, when the contact angle increases to 100° (see Fig. 11(b)), the maximum velocities of the wall jet are just 22.7 (x = 8.2 μm), 49.9 (x = 11.2 μm), 46.1 (x = 17.2 μm) and 36.0 m/s (x = 19.2 μm) respectively at the same moment. That is because the wall jet can be produced only after the micro-jet penetrating the oil droplet and impinging on the solid wall. When the micro-jet penetrates the oil droplets with a larger contact angle, the jet velocity hitting on the wall decreases, and then the resultant wall jet becomes smaller, which is not beneficial to the droplet desorption.

Figure 12 shows the velocity distributions of the wall jets at different heights from the adsorption wall and a jet time of 6 μs. As shown in Fig. 12, the wall jet velocities are different at the heights of 1, 2, 3, 4 and 5 μm from the solid wall, and the velocity gradient forms a shear force which plays an important role in the droplet desorption. Fig. 13 shows the average velocity of the wall jets at different contact angles of 70° and 100° within the height of 5 μm from the adsorption wall. It can be seen that the average velocity of the shear flow at each position is larger at the droplet contact angle of 70° than that of 100°. It is beneficial for the oil droplet desorption due to the stronger shear force. Consequently, it can be explained that the oil droplet at the contact angle of 70° can be desorbed by the micro-jet at the velocity of 150 m/s, while the oil droplet at the contact angle of 100° fails to be desorbed.

Figure 14 shows the desorption processes of the oil droplets at different sizes under micro-jets. In this simulation, the initial velocity of the micro-jet is 200 m/s, the jet outlet diameter is 10 μm and the contact angle of the oil droplet remains 100°. As shown in Fig. 14(a), the oil droplet at a diameter of 100 μm can be desorbed at 6 μs. However, when the oil droplet diameter increases to 150 μm, the oil droplets has not been desorbed at 10 μs, and an annular oil droplet is still adsorbed on the solid wall (see Fig. 14(b)). Fig. 15 shows the average velocities of the wall jets at different oil droplet diameters of 100 and 150 μm within the height of 5 μm from the adsorption wall. When the oil droplet diameter is 150 μm, it can be seen that the average velocity of the wall jets is far less than that at the diameter of 100 μm at the same position. As shown in Fig. 15, the oil droplets at both the diameters of 100 and 150 μm have been penetrated at the jet time of 6 μs. The maximum average velocity of the wall jet is 94.4 m/s (x = 33.6 μm) at the diameter of 100 μm, but it decreases to 49.5 m/s (x = 28.6 μm) at the diameter of 150 μm, which is insufficient to finish the final desorption of the oil droplet. As a result, the micro-jet is more attenuated when the jet penetrates a larger oil droplet, and then the impact velocity on the wall surface reduces, so the wall jet decreases accordingly, which results in a weaker desorption effect.

Therefore, the size and contact angle of the oil droplet have great influences on the desorption process of the oil droplets. Fig. 16 shows critical velocities of the micro-jets for desorption of the oil droplets at different sizes and contact angles. The critical jet velocity represents the point at which the oil droplet can just break away from the solid wall. The oil droplet can be desorbed only when the initial jet velocity is greater than the critical velocity. As shown in Fig. 16, the critical velocity increases with the diameter and contact angle of the oil droplet increasing, and the influence of the contact angle is greater at a larger size droplet. According to the simulation results on the micro-jet formation above, the appropriate jet velocity is mainly determined by the acoustic pressure amplitude and the initial bubble diameters (see Fig. 9), and the cavitation bubble size is usually related to the ultrasonic frequency [14,28]. Therefore, the optimal desorption effect can be obtained by adjusting the ultrasonic parameters to acquire an appropriate micro-jet velocity according to the size and contact angle of the adsorbed oil droplets.

4.3. Desorption processes of the clustered oil droplets under a micro-jet

The small size oil droplets are more likely to gather together due to the surface tension, so clusters of adsorbed oil droplets are also not easy to be desorbed completely. Fig. 17 shows the desorption processes of six adjacent adsorbed oil droplets under the micro-jets at different initial jet velocities. In this simulation, the diameter and contact angle of the oil droplets are fixed at 50 μm and 100°. When the initial micro-jet velocity is 300 m/s and the outlet diameter of the micro-jet is 15 μm, it can be seen that the oil droplets undergo three processes: extrusion deformation, outward movement and detachment from the solid wall. The micro-jet impinges on the solid wall and forms a lateral wall jet spreading along the solid wall, and then the oil droplets are pushed outwards and extruded by the wall jet. The adsorption area of oil droplets decreases gradually, and finally the oil droplets completely break away from solid wall at 7 μs (see Fig. 17(b)). When the initial jet velocity is 200 m/s, the oil droplets fail to be desorbed at the same moment, although they move outwards under the wall jet (see Fig. 17(a)). The main reason also can be obtained by analyzing the velocity distributions of the wall jets.

Figure 18 shows the velocity distributions of the wall jets at different initial micro-jet velocities. As shown in Fig. 18(b), when the initial micro-jet velocity is 300 m/s, the maximum velocity of the wall jet is 108.2, 37.8 and 13.9 m/s at the jet time of 3, 5 and 7 μs. The adsorption area of the oil droplets become quite small at 5 μs and the adsorption oil droplets are completely removed at 7 μs. However, when the initial micro-jet velocity decreases to 200 m/s (see Fig. 18(a)), the maximum velocity of the wall jet is just 69.8 m/s at 3 μs, and it rapidly drops to 9.2 m/s at 7 μs. Although the adsorption area of the oil droplets decreased greatly, the oil droplets fail to be desorbed eventually, and the velocity
of the wall jet close to the undesorbed oil droplets is less than 4 m/s, which has no obvious influence on the subsequent desorption of the oil droplets.

In addition, the initial cross-sectional diameter of the micro-jet also has a great influence on the desorption process of the oil droplets. Fig. 19 shows the velocity distributions of the wall jets at different micro-jet outlet diameters of 15 and 20 μm. As shown in Fig. 19(a), when the initial velocity of the micro-jet is 200 m/s and its initial cross-sectional diameter is 15 μm, there are still adsorbed oil droplets on the solid wall at 10 μs, and the adsorption state of the oil droplets do not change significantly compared with that at 7 μs. When the jet cross-sectional diameter increases to 20 μm (see Fig. 19(b)), it can be seen that there are extremely small fractions of the oil droplets still sticking to the solid wall at the jet time of 8 μs, and the oil droplets are completely desorbed at 10 μs. It also can be concluded that the micro-jet at a larger cross-sectional diameter can produce a wall jet with a relatively larger velocity at the same jet time. Therefore, the increase of the micro-jet cross-sectional area has a positive effect on the removal of the clustered absorbed oil droplets.

According the simulation results on the micro-jet formation above, the cross-sectional area of a cavitation jet mainly depends on the center compressive curvature of a cavitation bubble before collapsing. The compressive deformation of a cavitation bubble is
Fig. 18. Velocity distributions of the wall jets at different initial jet velocities (The oil droplet diameter $D = 50 \, \mu m$, the jet outlet diameter $d = 15 \, \mu m$, the contact angle of oil droplets $\theta = 100^\circ$)(a) The initial jet velocity $v_0 = 200 \, m/s$; (b) The initial jet velocity $v_0 = 300 \, m/s$. 
usually largely affected by the initial size of the bubble and its surrounding pressure. The micro-jet generated by the collapse of the cavitation bubble at the initial diameter of 0.4 mm under the acoustic pressure amplitude of 8 MPa is appropriate for the desorption of the clustered oil droplet. Generally, a lower ultrasonic frequency is beneficial to generate the larger bubbles due to the relatively long expansion period [14,28].

4.4. Desorption process of the oil droplet adsorbed in a gap under a micro-jet

According to the microscopic observation, the accumulation of sand grains forms many small gaps and grooves. Some of the oil droplets fall into the gaps, which are more difficult to be desorbed. Fig. 20 shows the desorption processes of the oil droplets adsorbed in the gaps of different included angles under the micro-jet of outlet diameter of 10 μm. In this simulation, the initial micro-jet velocity is 250 m/s, and the oil droplet diameter is 100 μm. As shown in Fig. 20, the micro-jet breaks the oil droplet in the gap, and then forms the wall jets along the two slopes of the triangular gap, finally the oil droplets are pushed out the gap along the slopes by the wall jets, it can be seen that the oil droplet in the gap at the angle of 60° are not completely desorbed. Some parts of the oil droplet come out of the gap but stick to the outer horizontal wall, and there is also a part of the oil droplet still remaining on the bottom of the gap at 10 μs (see Fig. 20(a)). In contrast, when the include angle of gap is 90°, there are only some small parts of the oil droplet adsorbed on the solid wall outside the gap (see Fig. 20(b)). However, the desorption effect of the micro-jet on the oil droplet in the gap at the angle of 120° is significantly improved, and the oil droplet is almost entirely desorbed at 10 μs (see Fig. 20(c)). It can be concluded that the oil droplet in the gap with a steeper slope is more difficult to be desorbed. The larger cross-sectional area of the micro-jet is unfavorable to the removal of the oil droplet at the sharp corner of the gap bottom. In particular, the oil droplet in the gap is desorbed mainly due to the wall jet along the inclined wall, while the wall jet is greatly affected by the angle between the inclined walls. The larger the angle between the inclined walls is, the greater the velocity of the wall jet is.

In addition, the cross-sectional area of a micro-jet also has a great effect on the oil droplet removal in the cracks. Fig. 21 shows the desorption processes of the oil droplets in the gaps of different included angles under the micro-jet at the outlet diameter of 6 μm. As shown in Fig. 21(a), when the initial velocity of the micro-jet is maintained at 250
m/s, the oil droplet in the gap at the angle of 60° is almost completely desorbed at 10 μs, and the desorption effect is obviously better than that at the jet outlet diameter of 10 μm (see Fig. 20(a)). However, the oil droplet in the gap at the angle of 90° just breaks away from the solid wall at 10 μs (see Fig. 21(b)), but in fact the oil droplets cannot be desorbed in the end. The change of the jet cross-sectional diameter has no obvious effect on the desorption process of the oil droplet in the gap at the angle of 120° (see Fig. 21(c)). Therefore, it is concluded that the micro-jet at a small cross-sectional area has a better desorption effect on the oil droplet in the narrow or sharp-angled gap. The cross-sectional area of a cavitation jet mainly depends on the size of the cavitation bubble and its surrounding pressure. The collapse of a small-scale bubble generally produces a micro-jet with a relatively small sectional area. According to the previous simulation results on the micro-jet formation, the micro-jet generated by the collapse of the cavitation bubble at the initial diameter of 0.1 mm under the acoustic pressure amplitude of 11 MPa is appropriate for this case. Generally, a higher ultrasonic frequency is more conducive to the formation of the smaller bubbles due to the relatively short expansion period [14,28].

5. Conclusions

The adsorbed states of the oil droplets in the oil-contaminated sand were investigated using a microscope. Three representative adsorbed states can be summarized as: (1) the oil droplet is adsorbed individually on the particle surface; (2) the clustered oil droplets are adsorbed on a particle together; (3) the oil droplet is adsorbed in a gap between the particles.
The micro-jet formation during the cavitation bubbles collapse near a rigid wall at the ultrasonic frequency of 20 kHz and different acoustic pressure amplitudes of 5 ~ 11 MPa was investigated numerically, and the velocity and sectional diameter of the micro-jet were analyzed. Subsequently, the desorption processes of the oil droplets at the three representative absorbed states under micro-jets were simulated. It can be concluded that the wall jet is the most important factor for the removal of the absorbed oil droplets. The wall jet is produced by the impact of the micro-jet on the solid wall, and the oil droplet can be desorbed mainly due to the shear force generated by the wall jet.

For a single large size adsorbed oil droplet, the micro-jet penetrates the oil droplet firstly, and then generates a wall jet to peel the oil droplet from the solid wall. The size and contact angle of the oil droplets have great influences on the desorption process. When the micro-jet penetrates an oil droplet with a larger size or contact angle, the jet velocity of hitting the wall will reduce, and then the wall jets decrease accordingly. So the desorption effect of the micro-jet weakens gradually with the increase of the droplet size and contact angle. The critical micro-jet velocities for desorption of the individual oil droplet at different sizes and contact angles were also obtained by the simulated results.

The clustered oil droplets are usually more difficult to be desorbed than the single large size oil droplets. In addition to a higher micro-jet velocity, a larger jet cross-sectional area is needed. The micro-jet generated by the collapse of the cavitation bubble at the initial diameter of 0.4 mm under the acoustic pressure amplitude of 8 MPa is appropriate for this case.

In addition, the oil droplets in the gaps between the particles are also more difficult to be removed than that on the flat wall surface. A higher velocity of the micro-jet is also required, and the oil droplet in the gap at a larger angle is easier to be desorbed generally. The micro-jet generated by the cavitation bubble at the initial diameter of 0.1 mm has a better desorption effect on the oil droplet in a narrow or sharp-angled gap.

The suitable velocity and cross-sectional diameter of the micro-jet for the oil droplets desorption were present in present study, aiming at different sizes and adsorption states of the oil droplets inside the oily sand. The optimal desorption effect can be achieved by adjusting the cavitation parameters to produce an appropriate micro-jet according to the size and adsorbed state of oil droplets.

CRediT authorship contribution statement

Fang Zhao: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Visualization. Qianqian Yan: Software, Validation, Investigation, Formal analysis, Data curation. Daolai Cheng: Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence

![Fig. 21. Desorption processes of the oil droplets in the gaps of different included angles under the micro-jet at the outlet diameter of 6 μm. (The initial jet velocity $v_0 = 250$ m/s, the oil droplet diameter $D = 100$ μm) (a) The gap angle of 60°; (b) The gap angle of 90°; (c) The gap angle of 120°.](image-url)
the work reported in this paper.

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