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Study on Heavy Oil Viscosity Reduction by Ultrasound and Parameter Optimization Based on COMSOL Simulation

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Abstract. Heavy oil is very thick and flows badly. So it is hard to get heavy oil from the ground. This paper uses ultrasound to make heavy oil less thick. First, this paper studies how ultrasound works. Ultrasound can break the material inside heavy oil. Then, this paper uses COMSOL to build a model. It studies how frequency and voltage affect the sound field in heavy oil. The study shows that the best effect is at 20kHz. Sound pressure becomes higher when voltage is higher. Using right frequency and higher voltage can make ultrasound work better. This gives help for making better ultrasound equipment.

Keywords: ultrasound, viscosity reduction, cavitation, heavy oil

1. Introduction

Under the dual promotion of global energy transformation and national energy security strategy, heavy oil, as an important supplement to conventional oil and gas resources, has become a key topic for the high-quality development of China's petroleum industry. China has rich heavy oil resources. The onshore proven reserves of heavy oil are about 4 billion tons, mainly distributed in Liaohe, Xinjiang, Shengli and other major oil areas. The offshore proven reserves of heavy oil are about 4.2 billion tons, concentrated in the Bohai Sea area, with great development potential. However, heavy oil contains a lot of resin and asphaltene. It has high density, high viscosity, high resin and high wax. It flows very poorly at room temperature. Some extra heavy oil is like solid asphalt, called "oil field that cannot flow". It brings many problems to the process of exploitation, lifting and gathering, and seriously restricts the efficiency of reserve development [1].

At present, the gathering and transportation of heavy oil in China still mainly uses heating transportation. Heating can improve the temperature of crude oil to reduce viscosity and improve fluidity. But this method has high energy consumption, high loss and high emission. Take the heavy oil gathering and transportation system of Xinjiang Oilfield as an example. The average heat flow density of steam injection pipeline is 120 W/m^2, and the highest can reach 167 W/m^2. The heat loss is very big. In some heavy oil areas of Shengli Oilfield, the traditional water mixing and heating gathering mode uses 120 cubic meters of natural gas per day in a single area. It increases the cost and carbon emission. Under the "dual carbon" goal, low-carbon transformation of heavy oil gathering and transportation is very urgent. The disadvantages of traditional heating transportation are difficult to meet the new requirements of green development. We need new low-consumption,

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high-efficiency and green technology to reduce the viscosity of heavy oil. Ultrasonic viscosity reduction technology is a good way to meet this need. It can be directly installed outside the pipeline. It uses sound energy to work inside the fluid. It can be used when needed and adjusted with flow. It is especially suitable for heavy oil transportation in remote wells, small flow wells and submarine pipelines. It provides a new way to reduce the total cost of gathering and transportation system.

2. Mechanism of ultrasonic viscosity reduction

Ultrasonic viscosity reduction mainly depends on four effects: cavitation effect, mechanical effect, thermal effect and emulsification effect. These effects make heavy oil temperature rise and improve low-temperature fluidity, so as to reduce viscosity and flow resistance [2-4]. Through these effects, ultrasound destroys heavy oil colloid structure, breaks heavy molecules and improves flow state.

2.1. Cavitation effect

In ultrasonic viscosity reduction technology of heavy oil, cavitation effect is the core driving force. It means that when ultrasound travels in heavy oil, bubbles in the liquid form, grow, shake and break suddenly. The extreme energy released when bubbles break can directly destroy heavy components in heavy oil and reduce viscosity.

Assume that the static pressure of liquid is P_0. When the pressure inside the bubble is the same as the static pressure of liquid, the bubble is stable and its radius does not change. When ultrasound with certain amplitude p_1 and frequency acts on heavy oil, the pressure of liquid changes between -p_1 and p_1. The external pressure of the bubble changes between $(-p_m+P_0)$ and (p_m+P_0). $(-p_m+P_0)$ is negative pressure area, so the pressure inside the bubble is higher than outside, and the bubble expands. (p_m+P_0) is positive pressure area, so the pressure inside the bubble is lower than outside, and the bubble is compressed. When the next ultrasound trough comes, the bubble expands again. When the peak comes, the bubble is compressed. Under continuous ultrasound, bubbles keep expanding and compressing. This process makes bubbles move and work, so temperature rises. When it reaches a critical value, cavitation bubbles break and release energy with high temperature and high pressure. This is the cause and process of ultrasonic cavitation. The high temperature and high pressure reduce the viscosity of heavy oil. The whole process includes oscillation, growth and collapse of cavitation bubbles. The sound pressure when cavitation happens is called cavitation threshold. Many researchers find that cavitation threshold is mainly affected by medium temperature and static pressure [5,6].

2.2. Mechanical effect

Ultrasound is a kind of longitudinal mechanical wave. Its essence is that medium particles vibrate back and forth periodically at the balance position, and the vibration direction is the same as the wave propagation direction. When ultrasound acts on heavy oil, vibration energy transfers through molecular collisions, forming periodic mechanical disturbance field in heavy oil. Shear force, impact force and directional flow produced by this disturbance are the core performance of mechanical effect. Different from the instantaneous extreme energy of cavitation effect, mechanical effect is continuous, gentle and global. It destroys heavy oil colloid structure mainly by physical dispersion instead of chemical cracking.

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2.3. Thermal effect

Ultrasound is a kind of energy carrier. When it travels in heavy oil, energy turns into heat mainly in two ways. The first way is heat from viscous loss. Heavy oil is high-viscosity non-Newtonian fluid with large internal friction between molecules. When ultrasound makes medium particles vibrate at high frequency, relative sliding between molecules produces a lot of viscous friction heat. The second way is heat assisted by cavitation. When ultrasonic power reaches cavitation threshold, transient cavitation bubbles collapse as adiabatic compression. Kinetic energy of gas molecules inside bubbles turns into heat instantly, forming local hot spots. Although this heat exists in a very small space and lasts a very short time, it can transfer to surrounding heavy oil through heat conduction and raise local temperature. The core function of thermal effect is to reduce heavy oil viscosity by increasing temperature. Higher temperature reduces heavy oil viscosity and viscous resistance of particle vibration, so it improves shear efficiency of mechanical effect. At the same time, higher temperature reduces cavitation threshold, makes bubbles form and collapse more easily, and enhances viscosity reduction effect of cavitation effect.

2.4. Emulsification effect

When heavy oil is treated by ultrasound, small bubbles inside vibrate. There is relative movement between bubbles and heavy oil, so heavy oil forms emulsion. When heavy oil contains water, the emulsion is mainly water-in-oil (W/O) and oil-in-water (O/W). Water-in-oil heavy oil emulsion has heavy oil outside, so friction between droplets is large and viscosity is high. Oil-in-water heavy oil emulsion has water outside, so friction between droplets is small and viscosity is low. Whether heavy oil forms water-in-oil or oil-in-water emulsion under ultrasound depends on water content of heavy oil. High water content easily forms oil-in-water emulsion, and low water content easily forms water-in-oil emulsion.

3. Establishment and verification of COMSOL simulation model

3.1. Model establishment

This paper uses COMSOL Multiphysics software to build a multi-physics coupling model based on piezoelectric effect and fluid acoustics. A hemispherical medium domain with a radius of 60 mm, a brass film with a width of 10 mm and a height of 0.4 mm, and a piezoelectric ceramic model with a width of 7 mm and a height of 0.4 mm are built. The piezoelectric ceramic is attached to the brass film to form a composite structure. The piezoelectric ceramic can vibrate when electrified and radiate sound field for propagation. When the ceramic sheet stretches along the radial direction under the electric signal, due to the constraint of the brass film, the whole structure will produce bending vibration similar to a "drum surface". This bending mode can convert the small deformation of the ceramic into a large lateral displacement at the center of the brass film, which significantly improves the efficiency of sound energy radiation into the medium. The model is coupled by solid mechanics, pressure acoustics, electrostatics and thermoviscous acoustics interfaces in COMSOL. The material of the outer air domain is set to air, the material of the piezoelectric ceramic domain is PZT-5H, and the material of the brass film is brass. The custom heavy oil material parameters in the medium domain are density 0.95kg/m^3, sound velocity 1500 m/s, viscosity 1000 mPa·s, specific heat capacity 1.809 KJ/(kg·K) and so on. The model is meshed. To improve calculation accuracy, the mesh of the brass film and piezoelectric ceramic domain is refined. To accurately capture

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viscous dissipation, the boundary layer of the medium domain is refined with 8 boundary layers. The ultrasonic field simulation model is shown in Figure 3-1.

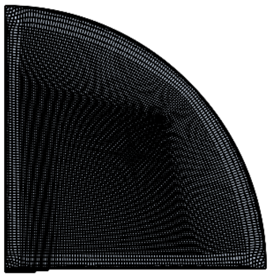

Figure 1. 2D view of the finite element model mesh for the ultrasonic field

To ensure reliable numerical simulation results, strict boundary conditions are set in the model, mainly including acoustic far-field conditions, electro-mechanical coupling boundaries and thermoviscous effect constraints. Based on the two-dimensional model, the corresponding three-dimensional computational domain is constructed by rotating around the model axis. After applying electric excitation to the lowermost piezoelectric ceramic region of the model, the corresponding magnetic field distribution can be generated in the computational domain. The model established in this paper involves the multi-field coupling of electricity, mechanics, acoustics and heat, and its physical process can be roughly divided into four stages. First, an alternating voltage V(t) is applied at both ends of the piezoelectric ceramic laminate through the electrostatic field interface. Under the piezoelectric relationship, the change of the electric field will make the electric dipoles inside the material align directionally, and then produce macroscopic structural deformation. In the solid mechanics governing equation, the piezoelectric coupling matrix is used to realize the correlation between the electric displacement field and the structural strain field. Second, the end face of the transducer horn produces high-frequency vibration, and transmits the vibration to the heavy oil area in the form of "acoustic-structure boundary". The normal motion of the horn surface drives the fluid particles to produce periodic compression and rarefaction, thus forming an outward-propagating sound field in the hemispherical fluid domain. Considering the high dynamic viscosity of heavy oil (about 1000 mPa·s), it is difficult to accurately describe the dissipation characteristics of sound energy in the near-wall region by using the ideal fluid assumption, so the thermoviscous acoustic governing equation is introduced into the model. This physical interface can simultaneously solve the shear stress generated by viscous friction and the temperature fluctuation during compression while considering the compressibility of the fluid. In the acoustic boundary layer near the transducer radiation surface, the viscous effect will consume part of the sound energy and convert it into heat, which directly affects the attenuation law of far-field sound pressure. Finally, monitoring points are selected in the fluid domain to extract the instantaneous sound pressure P(t) as the external driving pressure $P_\infty(t)$ of the Rayleigh-Plesset (RP) equation. Through the combination of macroscopic sound field and microscopic bubble dynamics, it can be judged whether the residual sound energy after thermoviscous loss can reach the cavitation threshold of heavy oil under different combinations of voltage and frequency, and then cause bubble collapse and produce strong mechanical shearing, which provides a basis for viscosity reduction.

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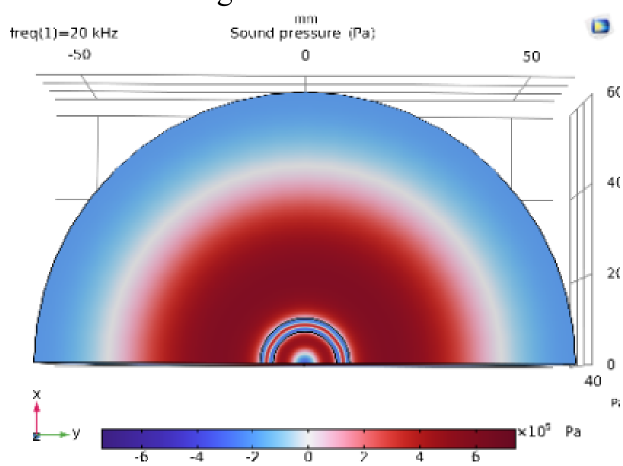
3.2. Parameter selection

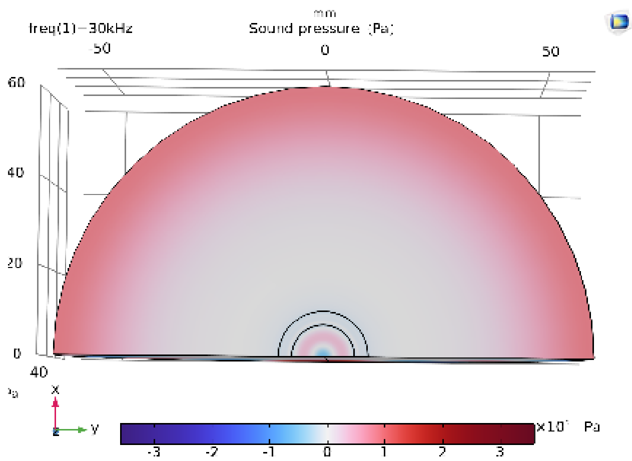
In the ultrasonic viscosity reduction process, the frequency directly determines the distribution characteristics and effective range of cavitation energy. This paper selects four frequencies of 20, 30, 40 and 50 kHz for research. The selection logic is based on the comprehensive consideration of physical mechanism and industrial actual situation. In the selection of excitation voltage, this paper sets five voltages of 20 V, 50 V, 100 V, 220 V and 380 V, aiming to reveal the complete evolution process and law from weak vibration to industrial strong cavitation. To improve the engineering reference value of the simulation results, this study does not use equally spaced voltage values, but selects two typical industrial voltage levels of 220 V and 380 V for analysis. The low-voltage groups of 20 V, 50 V and 100 V are selected to explore the "shielding effect" of high-viscosity medium on sound energy absorption. 220 V and 380 V correspond to the standard voltage levels of single-phase civil electricity and three-phase industrial electricity respectively. This setting is not based on random theoretical values, but comes from engineering practice, so that the simulation results can directly provide effective reference for the design of ultrasonic viscosity reduction equipment and power parameter matching in industrial sites. After determining the excitation voltage and frequency range, the waveform of ultrasonic wave needs to be further selected. This paper uses continuous sine wave as the excitation signal. The sound source continues to act with constant frequency and amplitude, focusing on analyzing the influence of sound energy on the temperature rise of heavy oil.

3.3. Simulation results and analysis

In this model, the system uses constant voltage drive mode. The excitation current is not a preset variable, but a dynamic feedback index of the electro-acoustic conversion performance of the transducer. Because the high viscosity of heavy oil forms a significant mechanical load, the complex impedance of the transducer changes with frequency and medium damping. First, numerical simulations at different frequencies are carried out. The frequencies of 20, 30, 40, 50 kHz are selected, and 220 V is chosen as the constant excitation voltage. This voltage is chosen because it is a standard single-phase working voltage and has the highest reference value for developing portable small and medium-sized experimental equipment. According to the model mentioned in the previous section and the above parameters, the finite element simulation and solution of the ultrasonic field are carried out. Figure 3-2 shows the simulation results.



(a) 20kHz Sound pressure distribution



(b) 30kHz Sound pressure distribution

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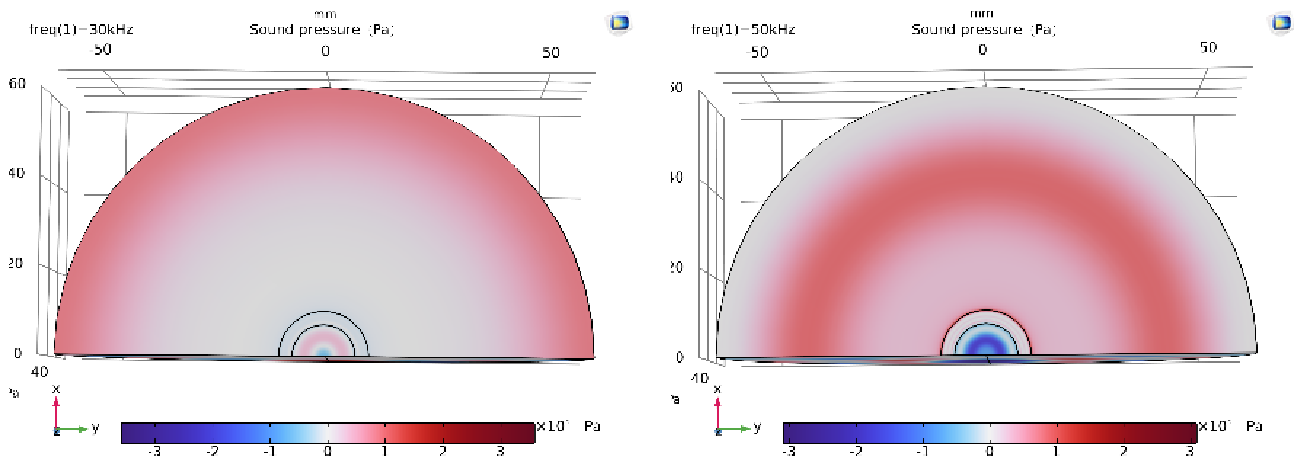

(c) 40kHz Sound pressure distribution

(d) 50kHz Sound pressure distribution

Figure 2. Sound pressure distribution at 220 V for various ultrasonic frequencies

Through simulation, the distribution law of sound pressure in heavy oil can be seen: the sound field from the center of the transducer radiates to the far field in a continuous ring shape with the center of the transducer radiation surface as the axis. Due to the radial constraint of the transducer and the fluid load, the sound pressure distribution shows obvious directivity. With the increase of propagation distance, sound energy is dissipated by the high viscosity of heavy oil, and the sound pressure amplitude decays exponentially from the near field to the surroundings.

From the simulation results, when the voltage is 220 V, the sound pressure peak at 20 kHz is 7.39×10^5 Pa; at 30 kHz it is 3.85×10^4 Pa; at 40 kHz it is 4.08×10^5 Pa; at 50 kHz it is 2.23×10^5 Pa. It is easy to find that the sound pressure amplitude changes non-monotonically with frequency, which is mainly due to the frequency response characteristics of the piezoelectric transducer. 20 kHz and 40 kHz are close to the resonance point of the system, producing strong mechanical resonance; while 30 kHz and 50 kHz are in a detuned state, resulting in a significant decrease in electro-acoustic conversion efficiency.

Based on the simulation results of the COMSOL multi-physics coupling model mentioned above, this study selects 20 kHz as the fixed ultrasonic frequency for follow-up research, mainly based on the following two key advantages verified by simulation:

20 kHz ultrasound can produce a high sound pressure amplitude and can effectively excite the cavitation effect. The simulation results show that when sound waves propagate in heavy oil at this frequency, the negative pressure stage can easily break through the cavitation threshold of the medium, thus stably generating cavitation bubbles. The collapse of cavitation bubbles is accompanied by local high temperature, high pressure and strong shock waves, which can destroy the spatial network structure formed by resin and asphaltene in heavy oil, which is the key mechanism to achieve viscosity reduction. Therefore, ensuring the full generation of cavitation effect is the primary condition for improving the effect of ultrasonic viscosity reduction.

The frequency of 20 kHz corresponds to the longest wavelength, thus ensuring the largest action range. According to sound wave physics, the relationship between wavelength λ, frequency f and sound speed c is $\lambda = c / f$. When the sound speed is constant, the lower the frequency, the longer the wavelength. The simulation cloud chart clearly shows that each wave of 20 kHz ultrasound covers a larger area than each wave of other frequencies. This means that within the same propagation

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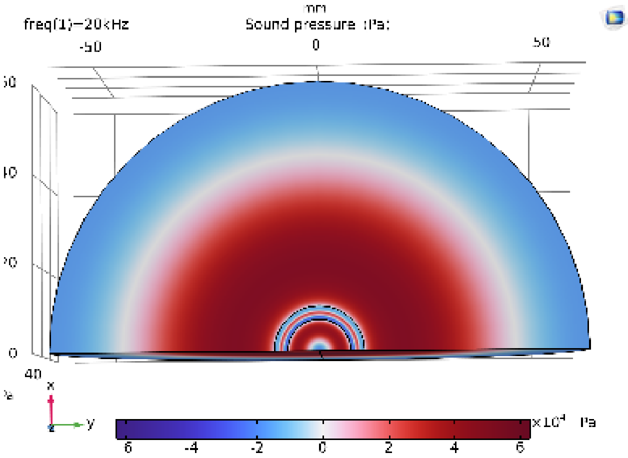
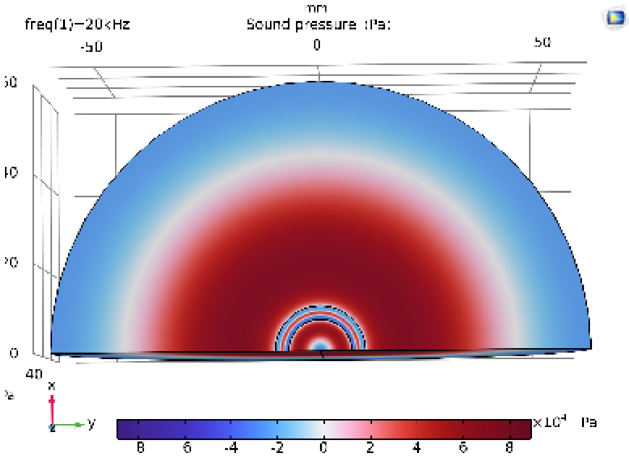
distance, 20 kHz ultrasound can reduce the viscosity of a larger volume of heavy oil, which is very important for industrial applications.

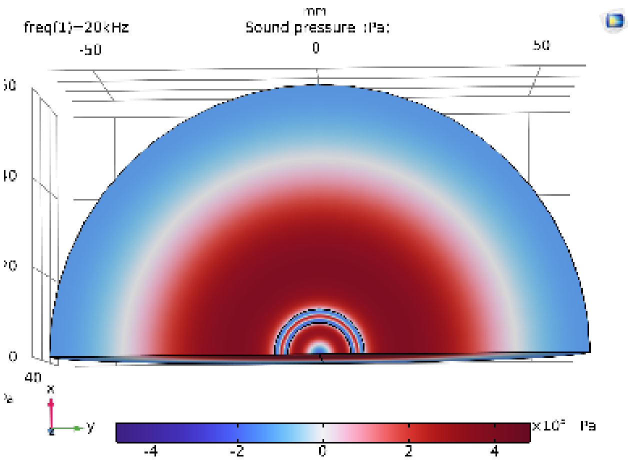
In summary, 20 kHz frequency achieves the best balance between "cavitation intensity" and "action range", the two key factors that determine viscosity reduction efficiency. Therefore, to further reveal the law and optimize parameters, this study will carry out systematic analysis around the central frequency of 20 kHz. Next, simulations are carried out at 20 kHz with voltages of 20 V, 50 V, 100 V, 380 V. Figure 3-3 shows the simulation results.



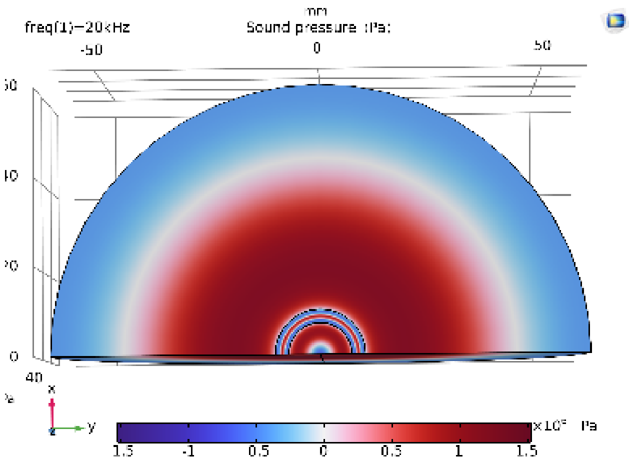
(a) Sound pressure distribution at a voltage of 20V



(b) Sound pressure distribution at a voltage of 50V



(c) Sound pressure distribution at a voltage of 100V



(d) Sound pressure distribution at a voltage of 380V

Figure 3. Sound pressure distribution at different voltages with a frequency of 20 kHz

The study found that at an ultrasonic frequency of 20 kHz, the sound pressure intensity in heavy oil is highly sensitive to the excitation voltage. As the driving voltage increases from 20 V to 380 V, the sound pressure peak increases from 10^4 Pa to 10^6 Pa, spanning two orders of magnitude. This proves that increasing the power supply can effectively overcome the high viscous damping of heavy oil and establish sufficient sound field energy inside the medium.

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Observing the sound pressure cloud charts at each voltage, the sound field shape remains highly consistent: sound energy radiates outward in a hemispherical wave centered on the transducer radiation surface, and the strong sound pressure area (red area) is concentrated in the axial near field of the transducer. This shows that increasing the voltage only changes the energy intensity, not the propagation mode of sound waves, which is conducive to accurate energy control in the viscosity reduction process. Especially under 380 V high voltage drive, the near-field instantaneous sound pressure peak is close to 0.71 MPa (about 7 atmospheres). According to the rheological properties of heavy oil, sound pressure disturbance of this magnitude is enough to induce cavitation effect or produce strong mechanical shear force, thus effectively breaking the molecular chain aggregates of asphaltene and resin in heavy oil, which is macroscopically manifested as a significant decrease in viscosity.

4. Conclusion and prospect

In this chapter, COMSOL Multiphysics finite element simulation software is used to establish a thermoviscous acoustic model of piezoelectric ultrasonic transducer in heavy oil. The influence of excitation frequency and driving voltage on sound field distribution and sound pressure intensity is systematically studied. The main conclusions are as follows:

(1) Spatial characteristics of heavy oil sound field distribution: The simulation results show that the propagation of ultrasound in heavy oil has obvious directivity. The sound field radiates to the far field continuously in a ring-shaped wave front with the center of the transducer radiation surface as the axis. Due to the high viscosity of heavy oil, sound energy dissipates strongly during propagation, and the sound pressure amplitude decays exponentially from the near field to the far field. This shows that the effective range of ultrasonic viscosity reduction is mainly concentrated in the near field area of the transducer.

(2) Influence of frequency response on electro-acoustic conversion efficiency: The sound pressure amplitude changes non-monotonically with frequency, which is closely related to the frequency response characteristics of piezoelectric transducers. Near 20 kHz and 40 kHz, the transducer produces strong mechanical resonance due to being close to the resonance frequency of the system, and the sound pressure peak increases significantly (for example, it reaches 7.39×10^5 Pa at 20 kHz and 220 V). In detuned states such as 30 kHz and 50 kHz, the electro-acoustic conversion efficiency decreases greatly. Therefore, keeping the system operating at the resonance frequency is the premise to ensure effective sound energy output.

(3) Linear regulation of excitation voltage on sound pressure intensity: Under the fixed resonance frequency (20 kHz), the sound pressure amplitude increases significantly with the increase of excitation voltage. As the voltage increases from 20 V to 380 V, the sound pressure peak changes from 10^4 Pa to 10^6 Pa. Especially under 380 V high voltage drive, the near-field instantaneous sound pressure peak can reach 0.71 MPa. This proves that the sound field energy density can be accurately controlled by adjusting the input voltage.

(4) Collaborative optimization and engineering guiding significance: Comprehensive analysis of the influence of frequency and voltage shows that to achieve ideal heavy oil viscosity reduction effect, the driving frequency must be highly matched with the transducer resonance point, and on this basis, the sound field can be strengthened by increasing the excitation voltage. The strong sound pressure fluctuation generated at 380 V is enough to overcome the viscous damping of heavy oil and induce strong mechanical shearing effect, which provides a theoretical basis for the setting of power supply parameters in subsequent ultrasonic viscosity reduction experiments.

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Although this study reveals the good potential of 20 kHz ultrasound in heavy oil viscosity reduction through numerical simulation, there are still many challenges to push it to practical engineering application. Future research can be carried out in the following directions:

(1) Deepening and verification of multi-physics coupling model. This research model mainly considers sound-flow-thermal coupling. Next, the sonochemical reaction kinetic model can be introduced to quantify the cracking effect of free radicals generated by cavitation effect on heavy oil macromolecules. At the same time, considering the multi-component characteristics of heavy oil, a more accurate multiphase flow model can be established to study complex phenomena such as asphaltene deposition in the viscosity reduction process. In addition, carrying out indoor loop experiments strictly corresponding to the simulation conditions to fully verify the flow field, temperature field and viscosity reduction efficiency predicted by the model is a key step for the model from theory to engineering application.

(2) Research on device optimization and system integration for gathering and transportation conditions. The focus of future research should shift from mechanism exploration to engineering implementation. This includes: designing efficient high-power ultrasonic transducer arrays suitable for different pipe diameters to solve the problems of uniform sound energy distribution and energy efficiency; studying the cooperative operation strategy of ultrasonic viscosity reduction and existing gathering and transportation systems (such as heating furnaces and pumping equipment) to build a new composite energy-saving gathering and transportation process with ultrasound as the main and heat as the auxiliary; and conducting a life-cycle techno-economic evaluation of the whole system to clarify its economic feasibility.

(3) Adaptability research under extreme conditions and long-term operation. In view of the complexity of oilfield gathering and transportation environment, it is necessary to explore the viscosity reduction performance and equipment reliability of ultrasonic technology under harsh conditions such as high pressure and high salinity produced fluid. In particular, it is necessary to investigate the problems such as scaling and corrosion on the transducer surface, as well as the stability and maintenance cycle of the device under long-term ultrasonic action, so as to provide a basis for the durability design of industrial application.

(4) Development of intelligent control strategy. To achieve accurate and intelligent viscosity reduction, a feedback control system based on online viscometer or pressure sensor can be explored. By real-time monitoring of pipeline pressure drop or fluid viscosity, the power and action time of ultrasound can be dynamically adjusted to adapt to changes in flow and water content, and finally achieve the goal of minimizing energy consumption on the premise of ensuring transportation safety.

Through continuous exploration in the above directions, ultrasonic heavy oil viscosity reduction technology is expected to move from the laboratory to the field, providing an efficient and green innovative solution to the key bottleneck of heavy oil gathering and transportation.

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