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Original article

The design and simulation of new downhole vibration device about acoustic oil recovery technology☆

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ABSTRACT

More and more oilfields are using acoustic technology to enhance oil recovery. In order to know the mechanism of acoustic oil recovery technology, the sound radiator of a new downhole vibration device is modeled and analyzed. Based on the theoretical background, this paper firstly analyzes the acoustic mechanism for the oil reservoir and then makes a acoustic response analysis on the sound radiator model for frequency and time-domain investigation by using professional acoustic simulation software—LMS Virtual.lab Acoustics, finally calculates the acoustic transmission loss in the downhole oil reservoir. The research reveals that firstly, acoustic waves have influences on the oil & water fluidity in the oil reservoir, the oil pressure gradient and the interfacial tension of capillary; secondly, the acoustic radiation power and sound pressure of field point attain a peak on the natural frequency of the sound radiator; thirdly, with the acoustic impact, the sound pressure of oil reservoir would fluctuate so as to improve the oil recovery ratio; the last but not the least one is both the sound pressure of oil reservoir point and the transmission loss of rock have a positive correlation with the vibration frequency. Therefore, it is of great importance for the research of vibration frequency and structure optimization of sound radiator.

1. Introduction

With oilfields development extending over time, the production and injectivity index of the oilfields will significantly decrease. The main reason is that the mud, paraffin gum, asphaltene deposits, dirt, emulsion and other mechanical impurities block the aisle of pore, which results in the oil permeability, production and recovery decrease. Compared with other types of physical and chemical methods, acoustic oil recovery technology [1–5], as a main physical recovery way, has distinct advantages in equipment investment, operation costs, working area and effects in case of stratum blockage.

The acoustic vibration oil recovery technology has great effect on enhancing oil recovery. As the application of acoustic oil recovery technology, there are various fluid acoustic transducers in practical oilfields use, such as Rotary-flute style, Hartman type and Perlman type etc [6,7]. These fluid acoustic transducers can produce sonic and ultrasound in the oil reservoir. With the progress of material science, and the piezoelectric material and giant magnetostrictive material becoming maturer, the new generation of acoustic transducers for oil recovery are the piezoelectric transducers [8]and giant magnetostrictive transducers [9]. They can produce acoustic waves and work better on the oil reservoir to improve the recovery. The shared character of all these acoustic transducers is that all of them can generate vibrations which form acoustic waves and work on oil reservoir. However, seldom research has been made on the theory and simulation of the acoustic waves propagation in oil-water mixed and the rock layer.

The various fluid acoustic transducers, the piezoelectric transducers and giant magnetostrictive transducers are used in

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the practical oilfields. In this paper, a new type of downhole vibration device is designed based on the above-mentioned vibration transducers, and this device is driven by a linear actuator which drives sound radiator [10] to generate acoustic waves in the oil reservoir.

Based on the theory and LMS Virtual.lab Acoustics [11], this paper mainly research on the mechanism of the acoustic waves to the oil reservoir, the production and propagation of acoustic waves. By the combination of theory and simulation, the article analyzes the effect of acoustic waves generated by the sound radiator of the new downhole vibration device which are drived by outside actuators in the oil reservoir.

2. The acoustic waves mechanism

2.1. The acoustic waves in porous media

The oil reservoir is assumed to Warren-Root model [12] and the article assumes that the pores in the rock of oil reservoir are composed of numerous parallel capillary bundles of constant diameter. Having worked on the oil reservoir, the acoustic waves is able to make the oil viscosity decrease by 25%–30% [13]. The wave action will cause the expansion and contraction of capillary walls in the oil reservoir, the diameter changes of capillary aperture, the reduction of surface tension within the pores and the change of capillary internal and external pressure as well. The surface tension φ and capillary forces υ:

$$\varphi = \frac{E_s - E_i}{\pi r^2}, \quad \upsilon = \frac{2(E_s - E_i)}{\pi r^3}\cos\theta \tag{1}$$

Eq. (1), the energy of two-phase boundary layer is E_s, the energy of same volume molecular layer in the phase is E_i, the wetting angle of the fluid to rock is θ. The diameter of capillary aperture is r.

After the acoustic waves working in the oil reservoir, the diameter of capillary aperture r becomes larger (it is shown as Fig. 5 and Fig. 5), and the surface tension φ decreases in the way of the square of radius r and capillary forces υ decreases in the way of the cube of radius r. At the same time, when the acoustic waves work in the oil reservoir, the E_s and E_i generate fluctuations (it is shown as Fig. 7) and cause the changes of surface tension φ and capillary forces υ, which improve the flow of oil.

2.2. The acoustic waves in oil reservoir

In this paper, Bingham fluid model [14] is used to research on the effect of the acoustic waves to fluid in the oil reservoir. The abnormally high viscosity crude oil have Bingham plasticity and pseudoplasticity, and some also have time-dependent non-Newtonian [15]. Such fluids are suitable for Bingham rheology. The simplified mathematical simulation model [16–18] of low-frequency acoustic waves to the nonlinear low permeability fluid is shown as:

$$|\Delta p| \le A_j \quad u = 0 \tag{2}$$

$$|\Delta p| > A_j \quad u = -\frac{K}{\mu_h}\Delta p\left(1 - \frac{A_j}{|\Delta p|}\right) \tag{3}$$

Eq. (2) and (3), the average velocity of ideal fluid along the axial direction of capillary is u; the permeability is K; the viscosity coefficient is μ_h; the external pressure gradient is Δp; the yield shear stress is τ_0. Unplugging threshold (the minimum pressure gradient for the crude oil to began to flow) is $A_j = 2\tau_0/R$, where R is capillary radius. Δp_s is the static external pressure gradient.

If the static external pressure gradient Δp_s is blow the unplugging threshold A_j and a longitudinal vibration of the wall parallel to the pore axis is applied, an inertial pressure gradient P_{osc} on the fluid will be induced with the amplitude of approximately $\overline{\rho}a$.

$$P_{osc} \approx \overline{\rho}a \tag{4}$$

where $\overline{\rho}$ is the average density of crude oil fluid and a is the acceleration amplitude of wall. The instantaneous total combined positive pressure gradient on the fluid then becomes $P_{osc} + \Delta p_s$.

$$\Delta p = P_{osc} + \Delta p_s \tag{5}$$

One cycle of this combined pressure is shown on a vertical scale in Eq. (5) for an acceleration amplitude large so that Δp exceeds A_j during part of the vibration cycle.

According to Eq. (3), when the acoustic waves work on the crude oil fluid, the viscosity coefficient of crude oil μ_h will decrease, the Δp will increase, the average velocity of ideal fluid $|u|$ will increase and then the crude oil production and recovery are enhanced in the same time.

When the vibration frequency of sound radiator is fixed, the increase of the acceleration amplitude of wall a (by increasing of displacement amplitude) will cause P_{osc} increases, which strengthen plugging effect.

2.3. The influence of acoustic waves to crude oil flow

There is the given vibration amplitude and frequency of acoustic waves, $s_t = \zeta e^{i\omega t}$ is the displacement of capillary walls. where ζ is the displacement amplitude of capillary walls, ω is the angular frequency of vibration. $V_r = u - \dot{s}_t$ is the relative speed of the crude oil to capillary walls, where u is the flow velocity of the crude oil along x direction (the axial direction of capillary). In the capillary walls, the momentum equation of crude oil [19] is shown as:

$$\rho\frac{\partial V_r}{\partial t} = \left(-\rho\zeta\omega^2 e^{i\omega t} - \frac{\partial p}{\partial x}\right) + \frac{1}{r}\frac{\partial(r\eta)}{\partial r} \tag{6}$$

where $\eta = \mu_h \partial u/\partial r$ is the viscosity vector, p is the pressure of crude oil in the capillary walls, ρ is the density of crude oil fluid. The relative speed V_r and viscosity vector η are together brought into the above Eq. (6), and the relative velocity of crude oil fluid of any one radius r in the radius R capillary is shown as:

$$V_r(r,t) = \frac{1}{4\mu_h}\left(r^2 - R^2\right)\left(-\rho\zeta\omega^2 e^{i\omega t} - \frac{\partial p}{\partial x}\right) \tag{7}$$

Eq. (7) is integrated. The flow of crude oil in the each radius R capillary is shown as:

$$q(t) = \int_0^R V_r(r,t)2\pi r\mathrm{d}r = \frac{\pi R^4}{8\mu_h}\left(\rho\zeta\omega^2 e^{i\omega t} + \frac{\partial p}{\partial x}\right) \tag{8}$$

The wave action of transducers is that the acoustic waves generated by the transducers make the capillary walls form vibration which can have an effect on the oil reservoir. According to Eq. (8), the crude oil flow will increases with the increasing of displacement amplitude ζ and angular frequency of vibration ω.

The crude oil flow can also be calculated by the internal and external pressure in the oil reservoir, the formula of crude oil flow is:

$$Q = \frac{p_g - p_j}{\frac{\mu_s}{2\pi Kh}\ln\frac{R_g}{r_b} + \frac{\mu_y}{2\pi Kh}\ln\frac{r_b}{R_y}} \quad (9)$$

where p_g is the supply pressure in oil displacement process, p_j is bottom hole flow pressure, the permeability is K, h is the effective thickness of oil reservoir, R_g is the radius of supply edge, R_y is the drainage radius, r_b is the edge radius of area including the oil, μ_s is the dynamic viscosity coefficient of water and μ_y is the dynamic viscosity coefficient of oil.

Eq. (9), there are three factors affecting the oil production: the pressure gradient in the oil reservoir, the permeability K and the dynamic viscosity coefficient μ. Among them, the oil pressure gradient depends on the mechanical state of the inside and outside oil layer; the permeability K has a relationship with the geometric size of porosity and particle, etc. In general, the bigger the particles is and the more the cracks is, the permeability K is higher; μ has a relationship with the physical nature and state of the oil, and is inversely proportional to the percolation rate [20]. When the acoustic waves work in the oil reservoir, the internal pressure add a periodic disturbance force based on the original pressure, which also increases the pressure gradient between the internal pressure and the around of the sound source, and enhance oil recovery in the oil reservoir.

3. New downhole vibration device and its sound radiator

3.1. New downhole vibration device

A new downhole vibration device formed the acoustic waves is shown in Fig. 1.

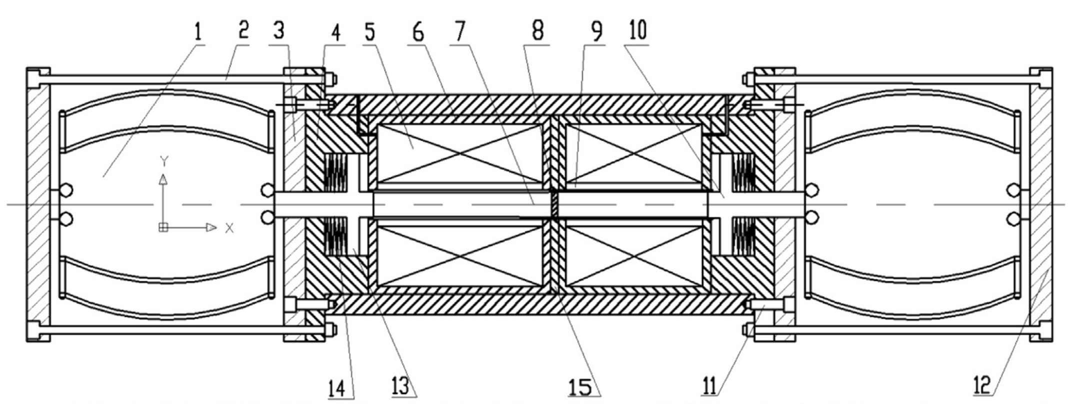
There is a linear actuator in the middle of Fig. 1, and it is a cylindrical structure and the power source of the sound radiator. The axial vibration displacement of linear actuator center pole is transmitted and amplified into the lateral vibration displacement by the sound radiator, and these lateral vibration displacement form acoustic waves and work on the oil reservoir. The linear actuator center pole is made of three sections and the three sections are linked into a whole by the threaded. The two ends of linear actuator center pole are made of a material with high magnetic permeability, and the short middle ends is made of the non-magnetic materials. The entire vibration device is vertically fixed in the wells by clamps. In the Fig. 1, the left and right two coils are respectively referred to as upper and lower coils. When this vibration device works, upper and lower coil are alternately energized and off. After the coil is energized, the magnetic field will form a closed magnetic circuit in the magnetic yoke and linear actuator center pole. The working theory of vibration device is magnetic reluctance minimization theory.

Since the top of the center pole does not exist the magnetic material, when the upper coil is energized and the lower coil off, according to the magnetic reluctance minimize theory, the upward electromagnetic force will work in the center pole and the center pole will have a upward displacement. Similarly, when the lower coil is energized and the upper coil off, the center pole will have a downward displacement. The upward and downward displacement are transmitted to the upper and lower mandrels, and the upper and lower mandrels put the axial displacement pass to the six-sided load plate of sound radiator.

The load plate of sound radiator accepts the axial displacement and the axial displacement is transmitted and amplified into the lateral vibration displacement forming the acoustic waves and working in the oil reservoir. The disc spring provide pre-pressure for the center pole, so that the axial displacement of center pole can be more effectively output. By adjusting the hexagon screws, the pre-pressure of disc spring is changed. The round sleeve and clapboard are used to prevent magnetic flux leakage. The links are used to link the linear actuator and sound radiator.

The novel of this new designed vibration device is that it has a special center pole structure and magnetic yoke structure. When the coils is energized, because of the magnetic part of center pole and the reluctance minimize theory, the center pole will move. The structure of sound radiator can enlarge the axial movement of center pole into the ateral vibration of the sound radiator, and generate the acoustic waves and work on the oil reservoir. When the coils is energized alternately, the upper and lower sound radiator form vibration alternately.

The power source for this device is the electricity, according to the reluctance minimize theory, this device generate vibration in the oil reservoir. Because of the popularity of electricity, this makes this device is more widely used in the oilfields applications, and this device is better than various fluid acoustic transducers at this point; because this device is installed in the



1. Sound radiator; 2.Links; 3. Panel of sound radiator; 4. Cover; 5. Upper coils; 6. Magnetic yoke; 7. Linear actuator center pole; 8. The short middle ends of center pole; 9. Bobbin; 10. Lower mandrels; 11. Hexagon screws; 12. The fixed disc bottom of sound radiator; 13.Upper mandrels; 14. Disc spring; 15. Clapboard

Fig. 1. The structure of a new downhole vibration device.

underground, the transfer efficiency is better than the ground artificial source. Because this device is made easily, has a low cost and a larger ateral amplitude than the piezoelectric transducers and giant magnetostrictive transducers, it can form better acoustic waves in the oil reservoir.

3.2. The sound radiator

In the article, the 3D models of sound radiator is established. Based on the practical constraints of sound radiator, the model constraints are established. The disc bottom of sound radiator has fixed constraint, another six-sided load plate only retains the translational freedom in the axial direction. One, second and third natural modes are shown in Fig. 2:

As is shown in Fig. 2, the third natural vibration modes of downhole sound radiator most favorably generates the acoustic waves.

By the analysis of the natural frequency of sound radiator, their first ten step natural frequency are gotten at the same time. The results are shown in Table 1.

4. The acoustic response analysis of sound radiator under constant load

The article establishes the sound radiator and casing model, and sets the model materials. The sound radiator select the spring steel as the material and it is oil and water mixture between the sound radiator and casing, and the density of oil and water mixture is $\rho = 960$ kg/m^3.The speed of sound in the oil and water mixture is $c = 1330$ m/s.

When external load is certain and its frequency is 583HZ, SPL cloud of casing field point in the 583HZ is shown in Fig. 3.

When the constant load work in the sound radiator, with its vibration frequency, the curve of acoustic radiation power and the sound pressure of C, D which are arbitrarily selected in the casing model are shown in Fig. 4:

As is shown in Fig. 4, when the vibration frequency is the natural frequency of sound radiator, the acoustic radiation power and pressure of casing point reach the peak, and the sound pressure of casing point increases with the increase of the vibration frequency of sound radiator.

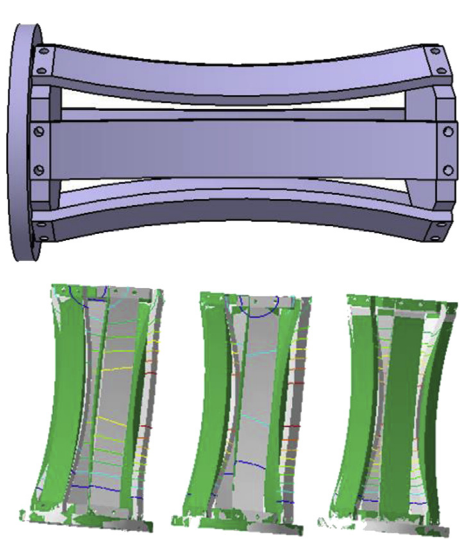


Fig. 2. The model and first three step natural modes of sound radiator.

Table 1
The natural frequency of sound radiator.

	Natural frequency/Hz		Natural frequency/Hz
1	552	6	824
2	561	7	1265
3	583	8	1276
4	757	9	1280
5	763	10	1316

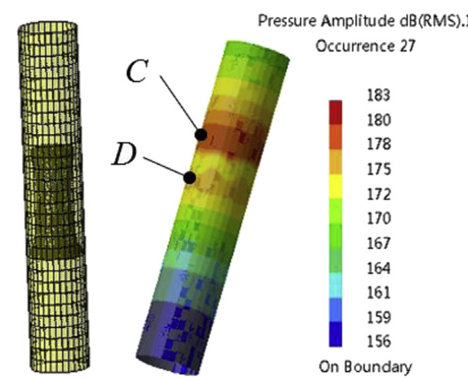


Fig. 3. SPL cloud of casing field point in the 583 HZ.

Similarly, the article establishes the sound radiator and rock models in order to explore the effect of the acoustic waves to the downhole rock. In the rock layer, $\rho = 5200$ kg/m^3, $c = 5000$ m/s.

Setting a certain magnifying deformation coefficient, the sound pressure cloud and magnifying deformation of rock in the 583HZ is shown in Fig. 5.

5. The time-domain analysis of sound radiator under the harmonic load

The sound radiator are driven by the time-domain response functions (the function is usually harmonic function) in practical

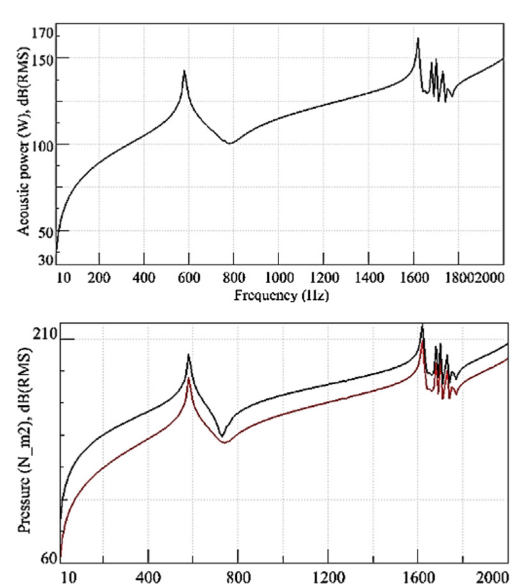


Fig. 4. The curve of acoustic radiation power and sound pressure in the C, D points.

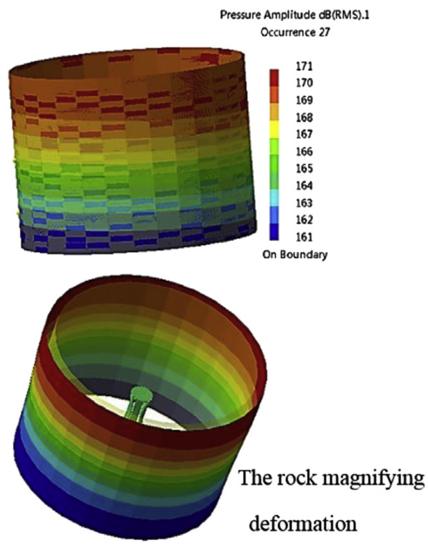


Fig. 5. The sound pressure cloud and magnifying deformation of rock in the 583 HZ.

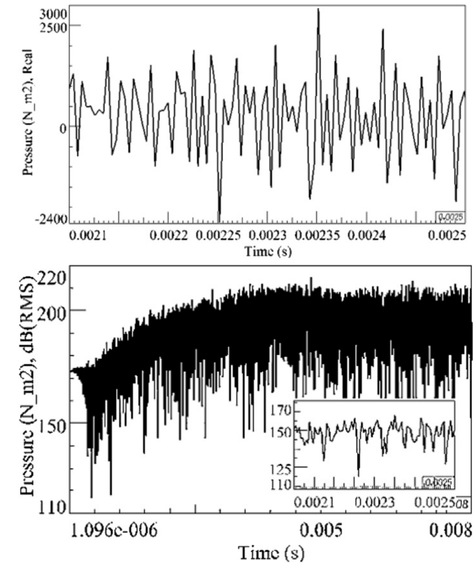


Fig. 7. The curve of sound pressure and sound pressure dB in the field point *C*.

oilfields use, we should adopt the time-domain view to analyze the problem.

By Ansys analysis, under the extraterritorial load, the calculation results of vibration displacement of each points in the sound radiator are received. The vibration displacement results of one of six radiant panels is considered as extrinsic motivation in the LMS Virtual.lab Acoustics. At the same time, under the time-domain load, the article analyzes the acoustic waves and the propagation of acoustic waves in the oil reservoir.

The same acoustic simulation models are established. Under the external time-domain excitation load, the time-domain cloud of sound pressure ($t = 0.0025, 0.003, 0.0035, 0.004$)and the time-domain cloud of magnifying casing deformation ($t = 0.0025, 0.005, 0.0075, 0.01$) in the perforation are shown in Fig. 6.

The curve of sound pressure and sound pressure dB in the field point *C* are shown in Fig. 7 (the partial magnifying view is shown in the right bottom corner).

As is shown in Fig. 7, the sound pressure fluctuates under the harmonic load. Because the acoustic waves occur reflection, diffraction and scattering in the oil reservoir, the change of sound pressure in one point is complicated.

The same method can be applied on the sound pressure cloud of acoustic waves in the rock, the time-domain cloud of magnifying deformation in the rock and the sound pressure chart of the rock point. These acoustic waves are both formed by sound radiator under the time-domain load.

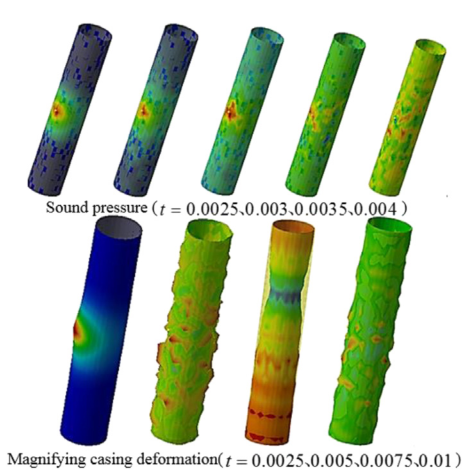


Fig. 6. The time-domain cloud of sound pressure and the magnifying casing deformation in the perforation.

6. The transmission loss of acoustic waves in the casing and oil reservoir

The transmission loss is usually used to measure acoustic performance. Transmission loss is the characteristics of structure itself, therefore we can use the LMS Virtual.lab acoustic finite element method to calculate the transmission loss of acoustic waves formed by sound radiator.

The transmission loss of acoustic waves includes medium loss and interface loss in the oil reservoir. Except for reflection and scattering, the interface loss also include the scattering attenuation of acoustic waves. In acoustics, the scattering attenuation coefficient is approximately direct ratio with the fourth power of acoustic waves frequency [21]. Due to the low frequency of acoustic waves and the tiny suspended scattering particles in the porous medium of oil reservoir, the particles have no significant influence on the propagation of acoustic waves. Compared to the medium loss, interface loss can be ignored.

When acoustic waves spread in the casing oil-water mixture, the cross-section of casing is usually not large and the cross-sectional area does not change, then we believe that the acoustic waves mainly spread in the way of plane waves in the casing.

When the acoustic waves spread, the formula of transmission loss is shown as:

$$TL(dB) = 10*\lg\left(\frac{W_{in}}{W_{out}}\right) = 10*\lg\left(\frac{p_2 \times \overline{p_2}}{p_1 \times \overline{p_1}}\right) \tag{10}$$

where p represents the sound pressure.

Eq. (10), p_{outlet} is the sound pressure of the outlet cross-section; p_{inlet} is the sound pressure of the inlet cross-section; $\overline{p}$ is the conjugate complex of sound pressure p.

The wavelength of acoustic waves, casing length and oil reservoir thickness are much larger than the geometrical size of sound source in the medium of oil reservoir, so the sound source can be seen as the point sound source. The propagation of the point sound source in the casing can be seen as the cylinder sound propagation, and the propagation in the rock can be approximately considered as the propagation of spherical wave. The cross-section of plumbing the casing axial direction and same radius sphere of rock have equal acoustic parameters.

The casing and rock layer models of acoustic waves propagation are established. The non-reflective boundary conditions in the outlet and inlet are defined, ρc is the acoustic impedance.

The simulation results are achieved in the condition of the ignorance of reflection, transmission in casing walls and scattering formed by the suspended particles in the fluid medium. The acoustic waves spread in the cylindrical way in the casing. Besides, its wavefront of propagation has not geometric expansion. As is shown in Fig. 8, when the acoustic waves spread in the casing, in a small range of frequency, the transmission loss of acoustic waves (due to the absorption of the medium to sound energy) has little change with the frequency. Therefore, the absorption coefficient of the medium to acoustic waves a can be considered as a constant.

Because of the absorption of the medium to acoustic waves energy, when the acoustic waves spread dl distance, the relationship between the sound pressure dp and the sound pressure p is shown as:

$$-\frac{\mathrm{d}p}{\mathrm{d}l} = ap \tag{11}$$

Eq. (11), negative sign indicates that the sound pressure reduced with the increasing of propagation distance. Eq. (11) is integrated and the initial condition is set as $l = 0$, $p = p_0$, there is $p = p_0 e^{-al}$, where p_0 is the initial sound pressure. When the sound pressure is replaced by the sound intensity during the propagation of plane waves, the formula of sound intensity because of the absorption of medium is shown as:

$$E = E_0 e^{-2al} \tag{12}$$

Eq. (12), E is the sound intensity of a point which has a l distance to the beginning point of the propagation.

The acoustic waves propagation in the casing is benefit for cleaning blockage which attaches to the casing walls so as to increase the fluidity of crude oil and enhance oil recovery.

When the acoustic waves spread in the rock layer, the way of propagation is spherical waves. During the process of propagation, the wavefront of acoustic waves has a geometrical expansion, and the cross-section of acoustic waves in the inlet and outlet is different. As is shown in Fig. 8, when the acoustic waves generated by sound radiator spread in the rock layer, the greater frequency the acoustic waves has, the greater the transmission loss is and the closer the propagation distance will be in the rock layer. The low-frequency acoustic waves can spread further in the medium, but it has little sound power and sound pressure. In order to let the low-frequency acoustic waves produce greater sound power, the lateral displacement amplitude of radiant panels of sound radiator should be added. The pre-curved radiant panels structure can increase the lateral displacement amplitude of radiant panels very well.

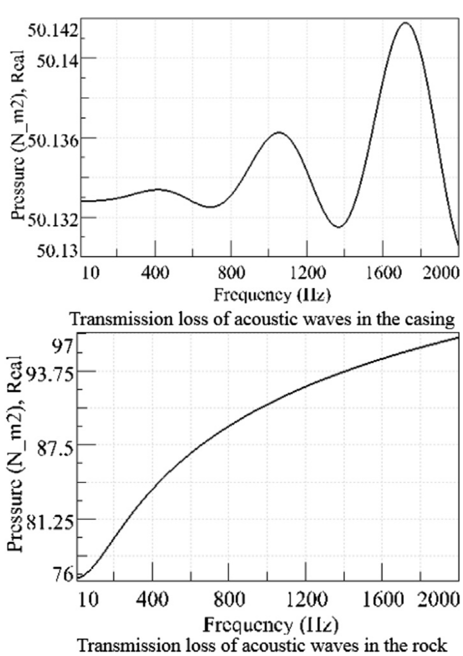


Fig. 8. The curve of transmission loss when the acoustic waves deliver in the casing and rock.

7. Conclusions

(1) The working process of acoustic waves generated by sound radiator is a dynamic propagation process of acoustic waves in the multiphase fluid and oil reservoir medium. The acoustic waves energy improves the flowing characteristics of oil and water in the oil reservoir and reduces the interfacial tension of capillary. Under alternating loads, the porous medium and the fluid have a constant alternate change of expansion and contraction, which can clean the sewage plugging, improve the permeability, reduce the oil viscosity and surface tension of fluid. Therefore, the oil production and recovery are improved at last.

(2) Under constant external loads, the sound power of sound radiator increases with the rise of the sound radiator vibration frequency. When the vibration frequency of sound radiator is on its natural frequency, the acoustic radiation power reaches a peak. The sound pressure of casing point increases with the rise of sound radiator vibration frequency and reaches peak on its natural frequency.

(3) When the harmonic time-domain loads work on the sound radiator, the acoustic waves produced by sound radiator will make a periodic fluctuating deformation in the casing perforation and the sound pressure fluctuate with time around the casing perforation. This sound pressure fluctuations make the mechanical state of the inner and outer oil reservoir have better changes, which then increase the pressure gradient of oil reservoir and enhance oil recovery.

(4) Acoustic waves generated by the sound radiator spreading in the casing, the absorption coefficient of the oil and water mixture to acoustic waves a can be used as a constant, and the sound pressure and sound power of acoustic waves in the crude oil reduce with the distance of acoustic waves propagation in the index way. When the acoustic waves spread in the rock layer, the transmission loss of acoustic waves have a positive correlation with the frequency.

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