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Study on removing calcium carbonate plug from near wellbore by high-power ultrasonic treatment

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Abstract: In this paper, the effects of ultrasonic wave on the removal of inorganic scaling and plugging in cores and the influence of the key wave field parameters, process parameters and core physical parameters on the plugging removal efficiency are systematically studied. The main dynamic mechanism of ultrasonic plugging removal is also systematically analyzed. Results show that the transducer frequency, transducer power, ultrasonic treatment time and initial permeability of core have great influence on the effect of ultrasonic scale removal. When the cumulative treatment time of ultrasonic wave exceeds 60min, the recovery rate of core permeability tends to be stable. Best effect can be achieved when processing for 80~120min cumulatively; the plugging removal effect is improved with the increase of ultrasonic transducer power and ultrasonic frequency, but the effect of plugging removal is not obvious with the further increasing of them. In addition, the micro dynamic mechanism of removing inorganic scale plug by high-power ultrasonic treatment is discussed in view of ultrasonic inorganic scale body crushing, ultrasonic cavitation, ultrasonic friction, ultrasonic peristaltic transport operation and ultrasonic fracture-making and permeability-increasing effect.

Key words: inorganic scaling and plugging; ultrasonic cavitation; ultrasonic friction

1. Introduction

Inorganic scale is a compact solid which grows gradually from small crystals and firmly adheres to the surface of the reservoir rock skeleton during oil production [1-3]. It is difficult to be removed that the pore hole of the wellbore formation of oil and water wells is once blocked by inorganic scale. The inorganic scaling plug in the near wellbore formation will make the water absorption capacity of many production wells and injection wells become worse and the injection pressure to be increased, resulting in a significant decline in oil output [4].

The types of scaling substances are mainly carbonates, such as $CaCO_3$, $FeCO_3$ and other acid soluble compounds, which account for more than 98% of the analyzed scale sample, besides, there are $CaSO_4$, $BaSO_4$ and other acid insoluble inorganic scale. Inorganic scale is caused by the change of temperature and pressure in

formation, and the solubility of salt in formation fluid changes in the process of oil well production [5-8].

It is a regular work in the process of oil field exploitation to remove inorganic scaling plug in the near wellbore formation. At present, the main measures to solve this problem are chemical measures such as bottom pit washing and deep acidizing of formation [9-15]. The effect of remove barium sulfate scaling plug using the conventional acidification method is usually poor, and it needs to be injected with a special super acid compound chemical liquid system with strong solubility. The chemical acidification method can not reach the expected plugging effect when inorganic scaling plug occurs in the larger range of formation [16-20]. Therefore, the hydraulic fracturing technique must be adopted to reconstruct the reservoir. The traditional acidizing fracturing technology is complex in construction, high in overall cost, high in pollutants content, difficult in processing and harmful to the environment [21-24].

Since the 1980s, ultrasonic near-well treatment technology has been highly valued for inorganic scaling plug removal by the petroleum engineering industry because of its strong adaptability, simple operation, low cost and no pollution [25,26]. When high-power ultrasonic waves act on the rock skeleton solid near the well reservoir, the solid will be elastically deformed, so that whole structure of the inorganic scale aggregates attached to the surface of the pore wall is damaged to varying degrees, which can make inorganic aggregate become broken and loose. At the same time, the fluctuation of the skeletal solids causes the internal fluid of the pores to be strongly squeezed, and the strong squeezed flow can effectively peel the loose inorganic fouling pieces and particles into the pore fluid [27,28-32].

The mechanism of power ultrasonic plugging removal has three main functions: mechanical vibration, thermal and cavitation. The mechanical vibration can reduce the cohesion between the blocking particles and the formation rock, and reduce the interfacial tension between the formation oil and water. Under the action of mechanical vibration, the interfacial friction can make the local temperature rise, thus reducing the viscosity of the crude oil and improving the oil permeation characteristic of the crude oil; cavitation can change the molecular structure of crude oil, reduce the relative molecular weight, eliminate the gas resistance, enhance the fluidity of the fluid, lift the liquid column of the oil well, and promote the oil well's induced injection; thermal action can reduce the concentration of crude oil and increase the percolation rate of crude oil.

Ultrasonic deplugging is an advanced physical method for increasing production of oil wells in recent years. It acts on the formation with strong ultrasonic energy, which causes different physical and chemical changes in the reservoir and fluid, thus changing the seepage conditions of the reservoir, dredging the oil flow channel, and creating an environment conducive to the flow of crude oil. The production wells, injection wells and the near-well reservoir are treated by ultrasonic deplugging technique, so that the plugging of injection wells and wells is removed. It is of great significance to improve the production of oil wells and oil well recovery in the middle and late stages.

When the power ultrasonic wave is used to remove the plugging of production

wells, water injection wells and near-well reservoirs, the power ultrasonic controller will produce intermittent oscillatory pulse signals, which will be transported to the piezoelectric transducer downhole by high-frequency cable. Piezoelectric transducers convert electrical energy into sound energy and radiate ultrasonic waves.

Ultrasonic waves produce linear alternating vibration, alternating shock, orientation, cavitation and other effects on the reservoir, causing micro-cracks in the formation, changing the physical properties and fluidity of the fluid in the reservoir, reducing the viscosity of the fluid， improving the permeability of the oil layer and removing the plugging of the production well and the injection well, so as to achieve the purpose of improving crude oil production and oil well recovery.

2.The chemical principle of inorganic salt precipitation and the factors affecting the formation of inorganic precipitation.

2.1 The chemical principle of inorganic salt precipitation in near-wellbore of oil well

The inorganic salt precipitation in near-wellbore of oil well mainly consists of six kinds of precipitation: $CaCO_3$ precipitation, $SrCO_3$ precipitation, $FeCO_3$ precipitation, $BaSO_4$ precipitation, $CaSO_4$ precipitation and $SrSO_4$ precipitation.

The corresponding chemical principles are as (1)~(7) shows:

$HCO^{3-} = H^{+} + CO_3^{2-}$ (1)

$Ca^{2+} + CO_3^{2-} = CaCO_3$(precipitation) (2)

$Sr^{2+} + CO_3^{2-} = SrCO^3$(precipitation) (3)

$Fe^{2+} + CO3^{2-} = FeCO_3$ (precipitation) (4)

$Ca^{2+} + SO_4^{2-} = CaSO_4$ (precipitation) (5)

$Sr^{2+} + SO_4^{2-} = SrSO_4$ (precipitation) (6)

$Ba^{2+} + SO_4^{2-} = BaSO_4$ (precipitation) (7)

2.1 The factors affecting the formation of inorganic precipitation

The factors affecting the formation of inorganic precipitation main are PH value, temperature, pressure, contact time and total mineralization. The high pH value promotes $HCO^{3-} = H^{+} + CO_3^{2-}$ so that the concentration of CO_3^{2-} ions are increased, which is beneficial to the formation of carbonate and calcium hydroxide; The increase of temperature is beneficial to the reaction of endothermic precipitation, and the decrease of temperature is beneficial to the reaction of exothermic precipitation, which makes the precipitation increase; lower pressure can make the formation of CO_2 prolapse, PH value and CO_3^{2-} concentration increases, which is conducive to the formation of $CaCO_3$ precipitation; the formation damage becomes serious due to that the volume and number of the precipitated particles becomes larger and more and more with the increase of contact time; the increase of the total mineralization is beneficial to the dissolution of the precipitate.

3. Experimental device and materials

Experimental equipment is mainly composed of the following systems: high-voltage pulse servo system, acoustic-ultrasonic generation system, displacement system, model system, ring pressure automatic tracking system, process management system, oil and water metering system, back pressure system, temperature control system, pump down the components, steam generation system, data acquisition and computer monitoring and control systems. Flow chart of dynamic simulation system for ultrasonic oil recovery is as Fig.1 shows. Displacement system is shown in Figure 2.

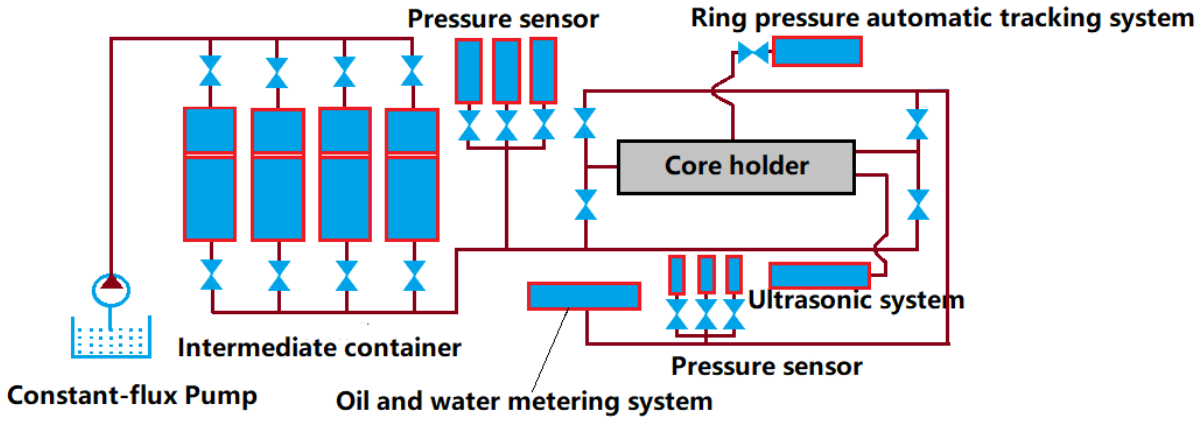

Fig.1. Flow chart of dynamic simulation system for ultrasonic oil recovery

Fig.2. Displacement system

Acoustic-ultrasonic generation system is shown in figure.3. It mainly consists of three parts: ultrasonic transducer, core gripper and core samples.

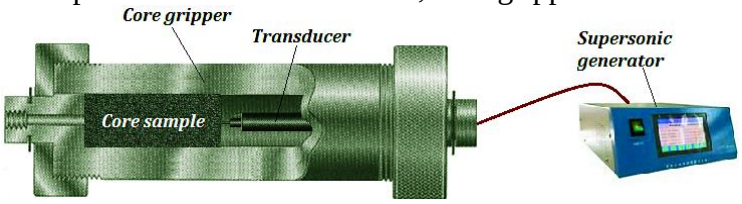

Fig.3. Experimental flow diagram of ultrasonic plug removal

Fig. 4. Three type artificial cores

Six transducers made of PZT are used to provided ultrasonic treatment. The frequency of the six ultrasonic transducers successively are 18kHz, 22kHz, 25kHz, 30kHz, 40kHz, and 50kHz respectively. The power of the six ultrasonic transducers successively are 1000W, 1000W,1000W, 100W, 100W, and 200W respectively. These transducers can bear a temperature of $110°C$and a pressure$35MPa$. Three type artificial core samples are shown in Figure 4.

The experimental materials include NaCl, KCl, $MgC1_2$, Na_2CO_3, $CaCl_2$, etc., all of which are of analytical grade; the artificial cores used in the experiments are 2.5 cm in

diameter and 7~8 cm in length. The artificial cores used in the experiments are composed of NaCl, $CaCl_2$ and $MgCl_2$, which can be divided into 3 categories according to the gas permeability values. Porosity of the artificial cores is 18.9% -21.9% and the standard salinity of the experiment is t/ L.

The diameter and length of the three core samples are all 2.5 cm and 7 cm respectively. Chemical constituents are quartz, feldspar, carbonate and clay, the contents of them are 54%, 39%, 2% and 5% respectively. The initial gas logging permeability of the three core samples are$30 \times 10^{-3}\mu m^2$, $50\times 10^{-3}\mu m^2$and $150 \times 10^{-3}\mu m^2$respectively. The chemical agent for removing near wellbore plugging caused by the chemical precipitation of inorganic salts is hydrochloric acid with a concentration of 10%, inject multiple is 2PV (PV refers to the multiple of the amount of polymer solution injected into the ground accounts for underground total pore volume).

4. Experimental results and discussion

The experimental results of removing calcium carbonate plug after ultrasonic treatment for 60 min are shown in Table1.

Tab.1 Experimental results of removing calcium carbonate plug after ultrasonic treatment

Gas logging permeability/$10^{-3}\mu m^2$	Serial number	Transducer	K_i /$10^{-3}\mu m^2$	K_d /$10^{-3}\mu m^2$	K_t /$10^{-3}\mu m^2$	$[(K_t - K_d)/K_i]/\%$
35	35-1	1	20.87	12.01	19.01	33.54
	35-2	2	21.09	10.02	17.24	34.23
	35-3	3	19.89	11.60	18.20	33.21
	35-4	4	19.74	11.01	12.85	9.32
	35-5	5	20.90	10.69	12.40	8.12
	35-6	6	21.01	10.24	12.25	9.63
85	85-1	1	61.78	36.25	56.10	32.14
	85-2	2	57.03	32.40	54.01	37.92
	85-3	3	62.01	32.55	53.02	33.01
	85-4	4	66.82	35.50	42.01	9.72
	85-5	5	60.18	35.26	40.01	7.83
	85-6	6	65.01	34.50	40.89	9.82
160	160-1	1	109.01	60.78	95.01	31.42
	160-2	2	110.98	54.90	97.06	37.98
	160-3	3	110.89	63.01	101.56	34.73
	160-4	4	121.87	59.02	72.01	10.65
	160-5	5	125.70	63.28	77.01	11.12
	160-6	6	123.43	60.01	76.02	12.97

Where$K_i$is initial liquid permeability, $K_d$is core fluid permeability, K_t is the core fluid permeability after ultrasonic treatment, $[(K_t - K_d)/K_i]/\%$ is the permeability restoration rates of the cores used as the evaluation index of the effect of plug removal

Table 1 shows that the permeability of core is obviously increased after ultrasonic treatment, which indicates that ultrasonic wave is effective in removing calcium carbonate plugging. It can be seen that ultrasonic transducer No.2 has the best plugging removal effect for the core with different permeability. The recovery rate of core permeability is 34.23%, 37.92% and37.98% respectively. Due to the influence of physical properties of core and ultrasonic parameters, the effect of ultrasonic plugging is quite different.

5. The influence rules of core permeability on the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts

How core initial gas logging permeability influence the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts under the actions of six type transducers respectively are investigated in this section. Experiment results are as Fig.5 shows.

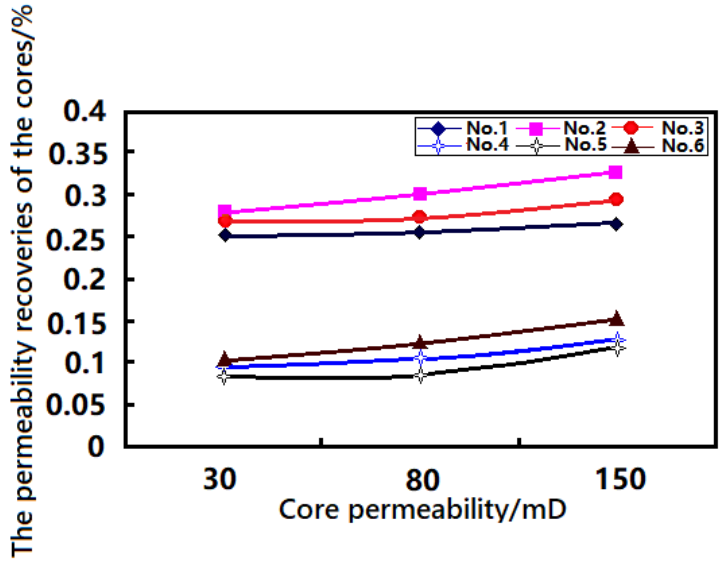

Fig.5. Experiment results of core permeability on removing near wellbore plugging caused by the chemical precipitation of inorganic salts using different transducers

It can be seen in Fig.5 that the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the cores after ultrasonic treatment get better with increase of core's initial permeability. inorganic scale plug, in fact, is belong to solid particles plug rather than fluid plug. Core pore size increases with the increase of its initial permeability. The adhesive forces among inorganic scale particles and between inorganic scale particles and core pore wall decrease with the increase of core pore size.

The result is in accordance with the results obtained by Poesio P et al. [9]. In saturated fluid porous media, the tensile force produced by ultrasonic action to the particle is proportional to the radius of the particle. The greater the permeability of the core is, the larger the radius of the calcium carbonate particles formed in the pores of the core is , and therefore, the plugging removal effect becomes better with the increase of the tensile force generated by the corresponding ultrasonic wave. At the same time, the adhesion force between particle and pore wall and between particle and particle decreases with the increase of core radius, so that the stress state of particle is easy to change and particles fall off more easily. In addition, the larger the core channel is, the more difficult it is to form a secondary plugging in the process of the particles being discharged with the liquid.

6. The influence rules of ultrasonic frequency on the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts

How ultrasonic frequency influences the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the cores with different gas logging permeability is investigated in this section. Experiment results are as Fig. 6~8 shows.

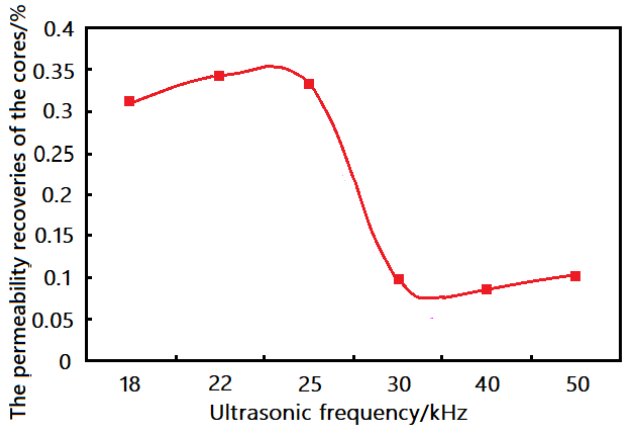

Fig. 6 The effect of ultrasonic frequency on removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the core with a gas logging permeability of $30 \times 10^{-3}\mu m^2$

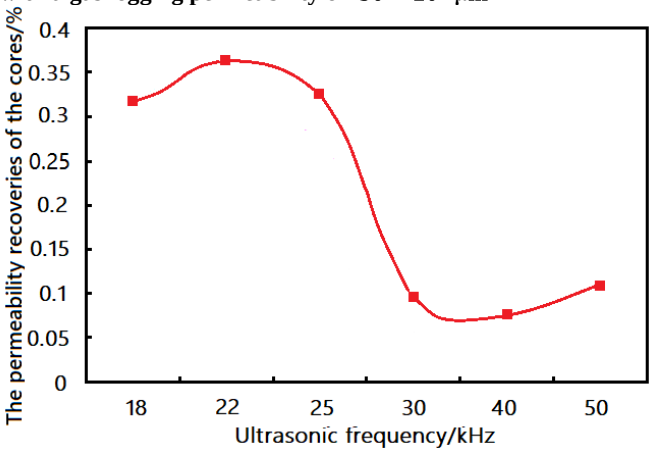

Fig. effect of ultrasonic frequency on removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the core with a gas logging permeability of $60 \times 10^{-3}\mu m^2$

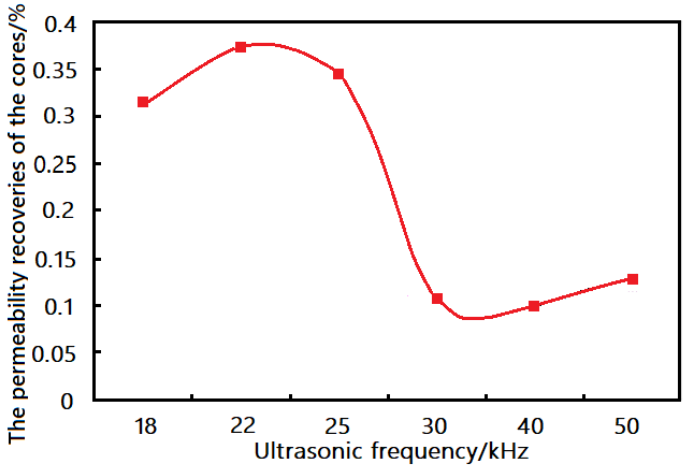

Fig. 8 The effect of ultrasonic frequency on removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the core with a gas logging permeability of $150 \times 10^{-3}\mu m^2$

As can be seen in Fig.6~8 that transducer No.2 has the beset effect for removing near wellbore plugging caused by the chemical precipitation of inorganic salts than other five transducers no matter what initial gas logging permeability the core is. Permeability recoveries of the three samples reach up to 34.3 %, 36.5 % and 35.6 % respectively after ultrasonic treatment using transducer No.2. On the whole, it can be seen in the above three figures that the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts using transducer No.1~3 respectively are better that using transducer No. 4~6 respectively. The optimum ultrasonic frequency range for removing near wellbore plugging caused by the chemical precipitation of inorganic salts is within 20~25Khz. The results indicate that the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the three type cores get poor with the increase of ultrasonic frequency.

However, from the perspective of classical acoustics theory, when the wave propagates in a liquid medium (taking into account the viscous and thermal conduction effects of the liquid medium), the ultrasonic energy dissipation becomes severe as the frequency increases the attenuation coefficient. In other words, the actual energy obtained by the core is reduced, and the deblocking effect should be slightly worse. Therefore, the experimental results of this paper are not consistent with the interpretation of the results from classical acoustics. This may be related to many factors such as experimental conditions, type of blockage, etc.

7. The influence rules of ultrasonic power on the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts

The effect of ultrasonic deblocking is related to the amount of energy acting on the core, and the energy acting on the core is directly related to the power of the ultrasonic transducer.

As can be seen from Fig.6~8, plug removal effect of transducers 1, 2 and 3 is significantly better than that of transducers 4, 5 and 6. This is affected by the power of the transducer: the power of the 1-3 transducers is 1000 W, the power of the transducers No. 4 and 5 is only 60 W, and the transducer of the No. 6 is 200 W. When the transducer power is small, the ultrasonic energy that acts on the core is less, and the deplugging effect is poor.

Therefore, one way to improve the efficiency of removing near wellbore plugging caused by the chemical precipitation of inorganic salts using ultrasonic treatment is to increase the power of transducers.

8. The influence rules of ultrasonic treatment time on the effect of removing near wellbore plugging caused by the chemical precipitation of inorganic salts

Whether the longer the ultrasonic treatment time is, the better effect of ultrasonic inorganic scale plug will be? This question is investigated in this section. It has been proved form section 5 that transducer No.2 has the best inorganic scale plug removal effect than other five type transducers. Therefore, transducer No.2 is selected as the ultrasonic source to investigate the proposed question in this section. Experiment results are as Fig. 9~11 shows.

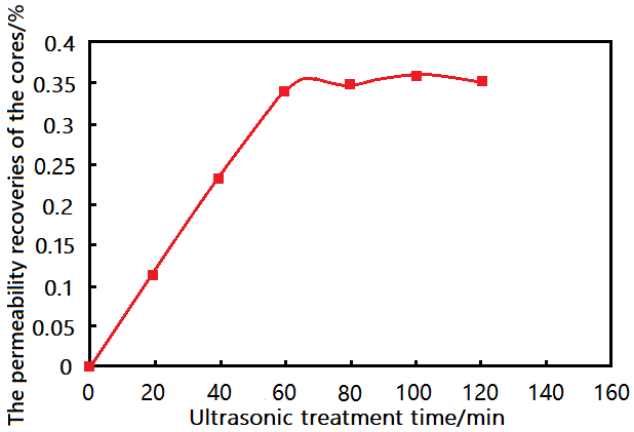

Fig.9.The effect of ultrasonic treatment time on removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the core with a gas logging permeability of $30 \times 10^{-3}\mu m^2$

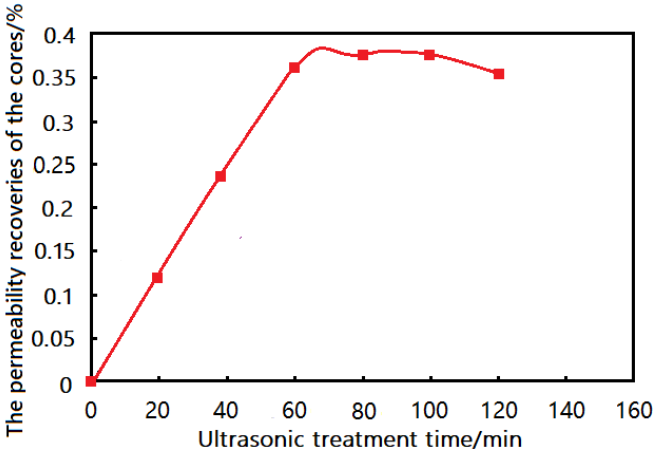

Fig.10. The effect of ultrasonic treatment time on removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the core with a gas logging permeability of $60 \times 10^{-3}\mu m^2$

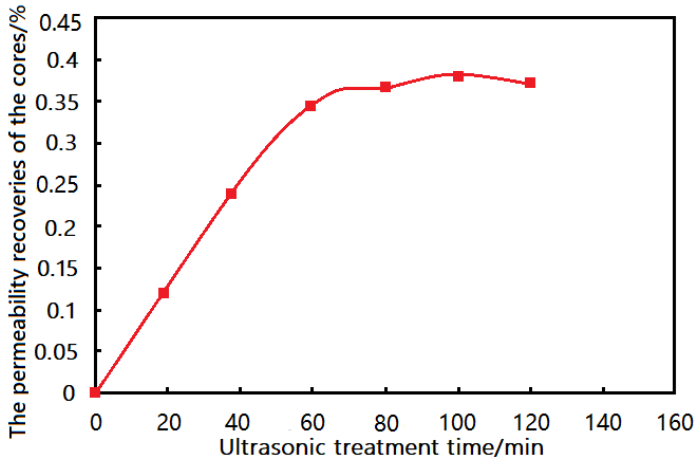

Fig.11. The effect of ultrasonic treatment time on removing near wellbore plugging caused by the chemical precipitation of inorganic salts for the core with a gas logging permeability of $150 \times 10^{-3}\mu m^2$

In the initial stage of ultrasonic treatment (0~60min), the recovery rate of core permeability is increased significantly. When the cumulative treatment time reaches 60min, the recovery rate of core permeability begins to stabilize, and the recovery rate of each core permeability reaches the maximum when the cumulative treatment time is within 80 ~ 120min. That is, the best effect of ultrasonic plugging is achieved. the experimental results of the core with a gas logging permeability of $30 \times 10^{-3}\mu m^2$show that the recovery rate of permeability is 1.2% lower than that of 100 min when the cumulative ultrasonic treatment time reaches 120 min. This is due to the fact that as the time goes by, a strong cavitation will occur in the liquid column of the transducer to the core, resulting in a large dissipation of ultrasonic energy, which will reduce the energy actually acting on the core; In addition, the shock wave generated by the cavitation phenomenon and the high pressure generated by the bursting of bubbles added back pressure to the displacement device, resulting in the obstruction of liquid flow in the core, which has a great influence on the core with relatively low permeability($30 \times 10^{-3}\mu m^2$). This results in the decrease of the measured permeability.

9. Research on the theory of ultrasound-assisted plugging removal

Under the action of high-power ultrasonic waves, tiny nuclei in the fluid inside the pores are activated. When the sound pressure is large enough, the bubble nucleus expands under the negative pressure of the sound wave, and the bubble nucleus is compressed under the positive pressure of the sound wave. This effect alternates rapidly with ultrasonic vibration, which is characterized by a series of dynamic processes, such as sharp oscillation, growth, contraction and rupture of the vesicular nucleus. When cavitation nucleus collapses, local temperature and instantaneous pressure generated in the extremely small space around it are very large in a very short period of time, accompanied by strong shock waves and jets with a speed of up to 400 km/s. This is the cavitation phenomenon. This intense cavitation also contributes to the shedding of inorganic scale fragments and particles from the pore surface.

When high-power ultrasonic waves act on rock skeleton solids in the near-wellbore reservoir, the solids can be elastically deformed. The integral structure of the inorganic scale aggregates attached to the surface of the hole wall will be damaged to

varying degrees, which is conducive to the inorganic scale aggregate becoming broken and loose. At the same time, the fluctuating deformation of the skeleton solid causes the internal fluid in the pore to be squeezed strongly, which makes the fluid in the pore produce a strong extrusion and jet flow mechanism. This intense extrusion flow will remove the loose inorganic scale fragments and particles from the pore wall effectively and make them into the pore fluid.

The mechanical properties of solid skeleton of reservoir rock and fluid in pore and the characteristics of energy absorption, transfer and reaction of ultrasonic dynamic field are very different, and the velocity and slowness of microscopic elastic movement caused by fluctuation of solid and fluid are not consistent. As a result of these differences, the solid/liquid system will occur a strong staggered flow phenomenon under the action of ultrasonic wave.

Under the action of high-power ultrasound for a long time, ultrasonic wave will produce a large additional force on the formation. When the additional force exceeds the ultimate shear and tensile strength of the rock, the rock will break up. When the ultrasound generated by the bottomhole generator continuously acts at the crack tip, stress concentration can be achieved, so a random distribution micro crack area is established in the near-wellbore zone. Micro cracks can effectively improve the percolation capacity of the reservoir in the near well. In addition, when the high-power ultrasonic wave acts on the porous medium of the near-wellbore reservoir and causes it to undergo elastic deformation, the pores of the reservoir will shrink and change, and the pore throats will alternately increase, which will result in an additional ultrasonic peristaltic transport phenomenon in the pore fluid. This kind of ultrasonic peristalsis operation also helps to recover the percolation ability of the near well reservoir by removing the inorganic scale debris and particles from the pore wall with the pore fluid.

10. Conclusion

It can be obtained from this paper that transducer frequency, transducer power, ultrasonic treatment time and initial permeability of core have great influence on the effect of ultrasonic scale removal. When ultrasonic cumulative treatment is 60min, the recovery rate of the three type cores permeability can reach 34.23%, 37.92% and 37.98% respectively. When cumulative treatment time of ultrasonic wave exceeds 60min, the recovery rate of core permeability tends to be stable. Best effect can be achieved when processing for 80~120min cumulatively.

In addition, plugging removal effect is improved with the increase of ultrasonic transducer power, and removal effect is improved with the increase of ultrasonic transducer frequency, but with the increasing of frequency and power, the effect of plugging removal is not obvious.

Through discussion and analysis, it can be known that the micro dynamic mechanism of removing inorganic scale plug by high-power ultrasonic treatment includes inorganic scale body crushing, ultrasonic cavitation, ultrasonic friction, ultrasonic peristaltic transport operation and ultrasonic fracture-making and permeability increasing effect.

Ultrasonic plugging is a kind of physical oil recovery, which does not inject chemical substances to drive oil, does not destroy the ground and produce secondary pollution and has no damage to casing, which is beneficial to continuous production and environmental protection.

(1) Under normal conditions, this technology can directly deal with water injection wells and wells (without moving string operation), the operation technology is simple,

the operation is convenient, the working period is shorter, usually the vehicular type is used to deal with the reservoir, which can be reused;

(2) The method can be combined with the traditional oil field stimulation technology, such as: sonic water injection, sonic acidification, etc., to better exert the oil recovery effect and improve the oil recovery rate;

(3) It has rapid effect, low equipment cost, long effective period of increasing production, high input-output ratio and good safety and reliability;

(4) Compared with the acidizing method, this method has the advantages of lower cost, longer validity period and higher average injection rate;

(5) The method has strong directivity, cluster emission and process selectivity, and can handle any layer of any section;

(6) It has good controllability and can adjust a series of technical parameters such as downhole power, sound field strength and processing time according to the condition of the oil layer in the well to achieve the optimal parameter design of ultrasonic treatment.

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Highlights

- **Plugging removal effect is improved with the increase of ultrasonic power**
- **Plugging removal effect is improved with the increase of ultrasonic frequency**
- **Plugging removal is not obvious with the further increasing of ultrasonic frequency**