Pressure Attenuation Law of Low-Frequency Pulse Pressure Flooding and Its Influence on Oil Recovery

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ABSTRACT: Pulse water injection is widely used in tertiary oil recovery. This study aims to reduce the pulse frequency, control the pulse frequency at 0.033∼0.1 Hz, simulate the pressure change in the formation at 0.1 Hz and 100 mD through COMSOL, and combine the core displacement experiment to determine the frequency. The effect of permeability change on the recovery factor of the water cut agent is summarized as follows: when the pulse frequency is 0.033∼0.066 Hz, the recovery factor of 100, 300, and 500 mD increases by 0.25, 0.34, and 0.39 percentage points, respectively, and these data can be of low frequency. The method proposed in this paper can provide certain theoretical basis and basic experimental data for tertiary oil recovery.

1. INTRODUCTION

The method of low-frequency pulse water injection originated from the theory of vibration oil production. The frequency below 1 Hz is called low frequency. From 1948 to 1989, Bodine et al.1 in the United States carried out a lot of research and design on the mechanism and equipment of vibration oil recovery. Berkeley et al. have studied the influence of different low-frequency fluctuations on the core and found that the pulse method can play a certain role in increasing production in oil field experiments.2−4 Canadian scholars also carried out research work on vibration oil recovery for heavy oil production. Nikolaevskiy et al.5 conducted a pressure pulse test in the Abuzy oil field of Krasnodar area in the North Caucasus with a frequency of 11−13 Hz and found that the water cut of the produced fluid decreased. In the former Soviet Union, the hydraulic pulse method was regarded as one of the most widely used methods to effectively treat the near-well zone of oil and water wells. Since 1957, researchers in the Soviet Union have devoted efforts to the research on the effect of hydraulic vibration on the formation model and have successfully conducted field experiments on the reservoirs with low production and low permeability.6 In 1967, the Soviet Union applied the near-well zone method of low-frequency wave elastic vibration treatment to field test and achieved a great production increase that was maintained for more than 1 year.7 The use of low-frequency pulsed water injection has little effect on high-permeability reservoirs. As a result, experts and scholars gradually focused on the low-frequency pressure pulse water injection method. Low-frequency pressure pulse water injection is a new method developed recently and its research began in the mid-1980s.8 The United States, Canada, and other countries are in the international leading level in the research of the low-frequency pulse water injection method. From 1985 to 1995, the Alberta University of Canada carried out theoretical research on the low-frequency pulse water injection method. In 2001, porous medium mechanics was successfully developed, and the pressure pulse method became a means of oil recovery quickly.9 Later except the above countries, China conducted research on pulse water injection. In May 1990, a field experiment with a hydraulic vibrator was carried out at the Dagang Oilfield, which verified the reliability of the field work. From June 1990 to May 1991, six water injection wells were tested in the Zaonan block of Dagang Oilfield, and the success rate was 100%.10 After 1990s, the hydraulic vibration oil recovery method in Russia (the former Soviet Union) gradually developed into an effective method, which was widely used to deal with the near-wellbore zones for production and injection wells.

Since then, many experiments of low-frequency pulse water injection have been carried out worldwide,11 and most of them have achieved a certain increase in production.12 In 2005, Ariadji et al.13 studied the seismic wave parameters of rock and fluid properties in the laboratory and found that the
The fundamental mechanism of this method is the increase of original porosity and absolute permeability, which improves the recovery rate. At the same time, in order to better study the method, Pu et al. first proposed to compare the impact of the low-frequency pulse wave on core permeability by using an artificial core and simulated the flow of oil and formation water. Zhang et al. established a mathematical model to estimate the average production of the oil field through physical calculation. Wang et al. deduced the prediction model of the attenuation coefficient of a low-frequency wave in the reservoir. He et al. established a mathematical model of low-frequency hydraulic vibration propagation in the reservoir in order to further study the mechanism of the low-frequency pulse water injection method in the reservoir. Based on the

Figure 1. Relationship between the bottom hole pressure and the vibration propagation distance.
theory of continuum mechanics, Qi et al.\textsuperscript{18} established a single-phase medium model that can describe the propagation law of the hydraulic oscillation wave in porous media and further explained that a low-frequency hydraulic wave is the key for the pulse water injection method. At the same time, many scholars have analyzed the internal mechanism of the low-frequency pulse effect on oil production. Li et al.\textsuperscript{19} analyzed the specific effect of low-frequency vibration on the profile control of microspheres and gel flooding. Ma et al.\textsuperscript{20} found that low-frequency wave excitation can increase the permeability of the matrix. Li et al.\textsuperscript{21} found that the improvement of the displacement effect of pore throat in the dead oil area contributes to low-frequency vibration. Wei et al.\textsuperscript{22} analyzed that the low-frequency wave excitation can increase the reservoir permeability. Chen et al.\textsuperscript{23} proved that pulse water injection can reduce the remaining crude oil amount compared with conventional water injection.

With the development of science and technology, the range of vibration intensity (increasing) and frequency (decreasing) of a hydraulic vibrator is gradually expanding and improving.\textsuperscript{24} At the same time, with the aid of automation technology, acidizing, hydraulic fracturing, and other enhanced stimulation measures, the near-well treatment effect of this method has been further strengthened.\textsuperscript{25}

Nowadays, improvement of crude oil production by pulse water injection has already been verified by many experiments, but the specific factors which affect the production are still relatively unknown. Mohebbi et al.\textsuperscript{26} proposed that the frequency parameter of the pulse wave affects the recovery rate by controlling the asphaltene deposition through the ultrasonic experiment. Agi et al.\textsuperscript{27} found that intermittent pulse water injection enhanced oil recovery better than the continuous pulse. Christian et al.\textsuperscript{28} established the axisymmetric finite element model of a liquid-filled pipeline and analyzed the

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{corePressureResponse}
\caption{Pressure response curve of the core with a permeability of 100 mD at different frequencies.}
\end{figure}
influence of different rigidity sediments on the oil production rate.

Although the low-frequency pulse water injection method has the advantages of improved permeability, oil recovery, water drive effect, oil washing efficiency, etc., some problems exist in this method such as high price, poor operability, and technical blockade in pulse generators, which make this method difficult to popularize and be applied in a large scale. In this study, through theoretical analysis, how to fabricate and configure a pulse generator is discussed in detail, and the effect of low-frequency pulse water injection method is verified by experiments, and the internal mechanisms of increasing production using this method are analyzed.

2. RESULTS AND DISCUSSION

2.1. Pulse Energy Propagation Law. Through calculation, taking a pulse frequency of 0.1 Hz, a permeability of 100 mD, and an initial formation pressure of 10 MPa as an example, the variation of the pressure in the simulated formation is shown in Figure 1. As shown in the figure, the bottom hole pressure gradually increases with the increase of the propagation distance and finally returns to the original formation pressure.

The simulation diagrams (Figure 1a–f) show that as the pulse pressure enters the reservoir framework, the formation pressure shows a sinusoidal change. The initial pressure is 0.03 MPa. With the increase of the holding time, the pulse pressure gradually transfers to the center of the formation, and the center pressure also gradually rises to 6 MPa. The transmission of pulse pressure waves will affect each other and cannot be isolated. When the central pressure is held up to 8 MPa, the pressure will accelerate to the inner formation, and the central pressure will have a negative pressure of −0.5 MPa; on the contrary, the inner formation pressure will increase and then decrease with periodic changes, and the maximum holding pressure of the formation center pressure can reach −2 MPa to promote the oil displacement effect of the formation center pressure.

In addition, since the magnitude of the amplitude determines the energy of the pulse wave, the greater the amplitude, the greater the energy of the pulse wave, and the slower the decay rate. That is, as the amplitude of the pulse wave increases and the frequency decreases, the greater the effect on the improvement of the oil phase and oil–water two-phase flow characteristics of the core.

2.2. Amplitude Response at Different Frequencies. The flow data of the core with a permeability of 100 mD at different frequencies are shown in Figure 2.

As shown in Figure 2, under the condition of fixed rock permeability, when the frequency is 0.033 Hz, the amplitude is 0.2 MPa, and when the frequency is 0.1 Hz, the amplitude decreases to 0.05 MPa. The upper left corner shows the simulated pulse pressure change. When the frequency increases, the speed of pressure recovery slows down and the amplitude decreases with the increase of frequency. When the parameters of the flow rate and the working chamber are fixed, the cores with different permeabilities should have an optimal frequency range.

2.3. Improvement of Core Permeability by Pulse Water Injection. 2.3.1. Influence of Frequency on Core Permeability. Figure 3 shows the change of the core permeability after the oil flooding experiment by using pulse water injection under different frequencies.

It can be seen from Figure 3 that the core permeability increases gradually with the increase of pulse frequency. However, it will not continue to increase after increasing to a certain extent. This indicates that the applied pulse frequency reaches the peak at 0.04~0.06 Hz, and the permeability is higher than that before the pulse. The pressure pulse increases the stress sensitivity of the rock, enlarges the pore throat radius, dredges the pore throat of the reservoir, and improves the pore connectivity. However, when the frequency increases to a certain extent, the amplitude decreases obviously and the pore space and permeability also decrease. Therefore, different permeability cores correspond to a reasonable frequency range. In order to ensure the development effect, the actual pulse water injection should be carried out in a reasonable pulse range.

2.3.2. Influence of Amplitude on Core Permeability. Figure 4 shows the change of core permeability after the oil displacement experiment using pulse water injection with different amplitudes.

As shown in Figure 4, with the increase of the vibration amplitude, the core permeability increases gradually. The larger the amplitude is, the larger the permeability increases. When the amplitude increases to a certain extent, the core permeability tends to be stable in a certain range.
permeability becomes smaller. With the increase of amplitude, the change range of pore pressure is increased, the flow space is improved, and the permeability is obviously improved.

It can be concluded from the experiment that the pressure pulse can reduce the adhesion of the rock surface to the liquid. This results in the relative movement of the pore surface and its boundary layer, which reduces the adhesion ability of the rock medium surface to the liquid. Therefore, the adsorption of the rock to the liquid will be destroyed, the surface energy between the liquid and the solid will be increased, and the interface adhesion will be reduced. Furthermore, the pressure pulses also cause the bridging clay mineral filled in the pore throat to loosen and migrate so as to remove the pore throat blockage, dredge the pore throat of the reservoir, expand the pore throat radius, and improve the pore connectivity. After the end of this experiment, the core permeability can be restored to the level close to that before the experiment.

2.4. Analysis of Factors Affecting Oil Displacement Efficiency. The core sample is a quartz sand epoxy resin-cemented artificial homogeneous core, with a dimension of Φ 2.5 cm × 10 cm. The core parameters are listed in Table 1.

| core number | length (cm) | effective sectional area (cm²) | permeability (mD) |
|-------------|-------------|--------------------------------|------------------|
| 171021A-4   | 10.17       | 4.19                           | 501              |
| 171021A-5   | 10.17       | 4.19                           | 502              |
| 171021A-6   | 10.17       | 4.19                           | 501              |
| 171021A-7   | 10.17       | 4.19                           | 500              |
| 171021A-8   | 10.17       | 4.19                           | 501              |
| 171021A-9   | 10.17       | 4.19                           | 503              |
| 181114B-1   | 9.06        | 4.19                           | 98               |
| 181114B-2   | 9.20        | 4.19                           | 102              |
| 181114B-3   | 9.02        | 4.19                           | 101              |
| 181114B-4   | 9.09        | 4.19                           | 100              |
| 181114B-5   | 9.01        | 4.19                           | 103              |
| 181114B-6   | 9.11        | 4.19                           | 102              |
| 130829D-1   | 10.22       | 4.19                           | 301              |
| 130829D-2   | 10.20       | 4.19                           | 302              |
| 130829D-3   | 10.21       | 4.19                           | 300              |
| 130829D-4   | 10.16       | 4.19                           | 301              |
| 130829D-5   | 10.18       | 4.19                           | 300              |
| 130829D-6   | 10.10       | 4.19                           | 296              |

2.4.1. Influence of Frequency on Pressure (Amplitude). Figure 5 shows the relationship between the injection pressure (amplitude) and time during the experiment when the core permeability is 100 mD. The red line indicates the main pressure fluctuation range.

It can be seen from Figure 5 that when the pulse pressure acts on the core with a permeability of 100 mD, the pressure pulse wave circulates repeatedly at the peak and trough at a low frequency. The pressure peak decreases continuously, but when the frequency increases to 0.1 Hz, the pressure response becomes unstable, and there are several peaks. Therefore, a frequency less than 0.066 Hz is the best frequency fluctuation curve.

Figure 6 shows the relationship between the injection pressure (amplitude) and time during the experiment when the core permeability is 300 mD. It can be seen from Figure 6 that when the pulse pressure acts on the core with a permeability of 300 mD, the pressure pulse wave has a short rising stage at the beginning with a low frequency. The pressure peak is basically stable, but when the frequency increases to 0.066 Hz, the pressure response starts to become unstable, and the pressure pulse wave starts to decrease continuously after reaching the maximum peak at the first time. When the frequency is less than 0.05 Hz, the best frequency fluctuation curve is obtained.

Figure 7 shows the relationship between the injection pressure (amplitude) and time during the experiment when the core permeability is 500 mD. It can be seen from Figure 7 that when the pulse pressure acts on the core with a permeability of 500 mD, the pressure wave has the maximum peak in the first half with the increase of frequency and then the peak and valley begin to decrease uniformly. When the frequency is less than 0.04 Hz, the best frequency fluctuation curve is obtained.

The cores with permeabilities of 100, 300, and 500 mD have been displaced by the pressure pulse with the injection flow of 0.3 mL/min. The relationship between the water content and the injected pore volume (PV) number at different frequencies has been tested. The results show that the influence of different frequency pulses on water cut is also different. Compared with constant speed displacement, the rising rate of water cut is slower. When the PV number is less than 0.6, the rising rate of water content slows down obviously, then gradually tends to be stable, and finally reaches 100%.

2.5. Analysis of Factors for Parallel Core Pulse Water Drive. In order to analyze the influence of different permeability levels on the effect of pulse water injection, parallel experiments of different permeability levels were carried out.

The experimental water is simulated formation water with a total salinity of 7241.5 mg/L. The experimental core is an artificial homogeneous core with quartz sand epoxy resin-cemented. The geometry size is Φ 2.5 cm × 10 cm, and the permeability is listed in Table 2.

Figures 8910 show the recovery and water cut curves of low-frequency pulse flooding under different permeabilities. The curves show that the cores with permeabilities of 100, 300, and 500 mD have been displaced by the pressure pulse with an injection flow of 0.3 mL/min. The relationship between the recovery rate and the injected PV number at different frequencies is tested. The results show that the pressure pulse can effectively improve the water drive recovery, and when the PV number is less than 1, recovery is most obvious, and the subsequent increase rate begins to slow down. However, compared with constant speed displacement, the recovery of pulse water flooding is increased.

Also, the relationship between the water content and the injected PV number at different amplitudes has been analyzed. The results show that the water content can be reduced and the water breakthrough time can be delayed by the pressure pulse. Furthermore, when the amplitude of the pulse is small, the water content rises faster. When the injection multiple is less than 0.6 PV, the increase of water content slows down and the effect is obvious.

From the above results, the following conclusions can be obtained:

Figure 11 shows the comparison of the recovery and water cut of the high permeability layer at pulse and constant velocity. It can be seen that there is little difference between pulse injection and constant velocity injection on the high permeability layer, which indicates that pulse injection has a limited effect on the high permeability layer in the high water cut stage. Under the condition of parallel connection, the
The recovery under constant speed injection is 29.6%, and the recovery under pulse injection is 4.1%. Before the end of water drive, the water cut of pulse injection is lower than that of constant speed injection. When the grade difference is 5, the pulse injection has a good effect of increasing production and good adaptability. When the frequency of pulse water injection is kept constant, the water content of high permeability rises faster. At the end of collection, the water cut of a single tube was 38.9% at 100 mD and 98% at 500 mD. When the grade difference is 5, both high permeability and low permeability can achieve good development results. The oil recovery of the high-permeability layer and the low-permeability layer is 53.2 and 20.9%, respectively, indicating that the development effect of the low permeability part can be increased by pulse injection.

Comparing the recovery and water cut of the low-permeability layer under pulse and a constant speed, it can be seen that the recovery of the low-permeability layer under pulse injection is 20.9%, that of constant speed injection is 17.5%, and that of pulse injection is increased by 3.4%. At the end of water drive, the water cut of pulse injection is lower than that of constant speed injection. As a whole, there is little difference between pulse injection and constant velocity injection on the high-permeability layer, which indicates that pulse injection has a limited effect on the production of the high-permeability layer during a high water cut stage.

Through the analysis of the above figures, it can be seen that the oil-phase permeability increases and the isotonic point shifts to the right. The residual oil saturation decreases, and the two-phase seepage range expands. When the amplitude increases, the relative permeability of oil increases, and the isotonic point shifts to the right obviously. It shows that pulse water injection can effectively displace remaining oil and improve the oil washing efficiency and the water drive development effect. At the same time, the pulse water injection method only has a good effect on the low-permeability area and limited influence on the high-permeability area.
3. CONCLUSIONS

According to this study, the following conclusions can be obtained:

(1) The designed generator is used to simulate the process of crude oil collection. By changing the parameters such as frequency, amplitude, and water injection speed, several parameters are tested to effectively displace the remaining oil, improve the efficiency of oil washing and the development effect of water drive, control the rising speed of water cut, and enhance the oil recovery.

(2) The 100\(\sim\)300 mD parallel model pulse water drive with the frequency between 0.04 and 0.06 Hz can achieve a good recovery effect for the low-permeability area.

(3) When the pulse frequency is 0.033\(\sim\)0.066 Hz, the recovery factors of 100, 300, and 500 mD increase by 0.25, 0.34, and 0.39% points, respectively, and the water cut decreases by 20.9, 26.9, and 50.4% points, respectively.

4. THEORETICAL MODEL

The study found that the pore structure of the formation is a very complex system. In the process of establishing the mathematical model and numerical simulation, in order to calculate the validity and research needs, the following assumptions are made:

(i) The wavelength of the low-frequency pulse wave is much larger than the macrovolume unit of the study, and the pore size is much smaller than that of the macrovolume unit of the study, that is, both the solid phase and the liquid phase are continuous;

(ii) Both fluids and solids satisfy linear elasticity, their displacements are small displacements, and their deformations are microdeformations;

(iii) Both the elastic modulus and permeability in the solid phase are isotropic, and the fluid is a slightly compressible fluid;

(iv) The pore framework of the oil layer is the main phase, and the fluid in the pores is the secondary phase. The fluid fills the entire pores and the fluid can flow in the pores.

4.1. Fluid Continuity Equation. Considering that the fluid density and the porosity of the rock will change, the fluid continuity equation can be written as:

\[
\frac{\partial (\rho \phi)}{\partial t} + \text{div}(\rho \nu) = 0
\]  

(1)

Expanding eq 1, we get:
According to the continuity equation of the fluid, the continuity equation of the reservoir pores is obtained in the same way:

$$\frac{\partial \rho}{\partial t} + \frac{\rho}{\rho_t} \frac{\partial \rho_t}{\partial t} + \frac{\rho}{\rho_i} \text{div}(\rho v) = 0$$

(2)

Combining eq 2 and 3 gives the continuity equation of porous media:

$$\frac{\partial (1 - \varphi)}{\partial t} + \frac{1 - \varphi}{\rho_t} \frac{\partial \rho_t}{\partial t} + \frac{1 - \varphi}{\rho_i} \text{div}(\rho' v') = 0$$

(3)

### Table 2. Core Parameters

| core number   | length (cm) | effective sectional area (cm²) | permeability (mD) |
|---------------|-------------|---------------------------------|-------------------|
| 17032A-2      | 10.06       | 4.91                            | 98                |
| 17032A-3      | 10.12       | 4.91                            | 103               |
| 17032A-4      | 10.01       | 4.91                            | 99                |
| 17032A-5      | 9.98        | 4.19                            | 101               |
| 17032B-1      | 10.02       | 4.19                            | 302               |
| 17032B-2      | 10.12       | 4.19                            | 306               |
| 17032B-3      | 10.03       | 4.19                            | 296               |
| 17032B-4      | 10.12       | 4.19                            | 298               |
| 16033A-10     | 9.99        | 4.19                            | 502               |
| 16033A-11     | 10.13       | 4.19                            | 498               |
| 19012A-5      | 9.99        | 4.19                            | 1002              |

**Figure 7.** Relationship between the injection pressure (amplitude) and time at 500 mD permeability.

**Figure 8.** Recovery and water cut versus injected water volume for 100 and 300 mD permeability cores in parallel.
Assuming that the reservoir framework is an incompressible rigid structure, eq 4 can be simplified to:

\[
\frac{\varphi}{\rho_i} \frac{\partial \rho_i}{\partial t} + \frac{\varphi}{\rho_i} \text{div}(\rho_i \mathbf{v}) + \frac{1 - \varphi}{\rho_i} \frac{\partial \rho_i}{\partial t} + \frac{1 - \varphi}{\rho_i} \text{div}(\rho_i \mathbf{v}') = 0
\]  

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\[
\frac{\varphi}{\rho_i} \frac{\partial \rho_i}{\partial t} + \frac{\varphi}{\rho_i} \text{div}(\rho_i \mathbf{v}) + \frac{1 - \varphi}{\rho_i} \text{div}(\rho_i \mathbf{v}') = 0
\]  

4.2. Fluid Motion Equation. The total mass per unit volume of the fluid and the reservoir framework is:

\[
\rho = \rho_i + \varphi(\rho_i - \rho_f)
\]  

Assuming that there is no relative movement between the solid skeleton and the fluid, the pressure difference in the fluid per unit length is given by:

\[
\frac{\partial p}{\partial x} = \varphi \rho_i \frac{\partial^2 \mathbf{v}}{\partial t^2}
\]  

4.3. Fluid Property Equation of State. Under the action of a low-frequency pulse pressure, the medium will produce deformations such as compression and elongation, and the density and the pressure of the medium will change. Therefore, the physical property equation of the fluid can be written as:

\[
p = \sum_{n=0}^{\infty} \frac{1}{n!} \left( \frac{\partial p}{\partial \Delta \rho^n} \right)_{\rho = \rho_i} \Delta \rho^n
\]  

Using Taylor’s formula to expand, we obtain:

\[
p = p_0 + \frac{1}{C_i} \frac{\rho_i - \rho_0}{\rho_0} + \frac{n - 1}{2C_i} \left( \frac{\rho_i - \rho_0}{\rho_0} \right)^2
\]  

Based on the fluid motion equation, continuity equation, and state equation, the propagation model equation of the low-frequency pulse pressure wave in one-dimensional symmetrical dimension can be obtained as:
\[\begin{align*}
\frac{\partial p}{\partial x} + \frac{4}{3} \frac{\mu^2}{\rho_0 K p_0 g} \frac{\partial^2 v_y}{\partial x^2} - \frac{\rho_0 K p_0}{\rho_0 K p_0} v_y &= \frac{\mu f}{P_0} \frac{\partial v_x}{\partial t} \\
\frac{\partial v_x}{\partial x} &= -\frac{p_0 C_o \rho_0 f K}{\mu} \frac{\partial p}{\partial t} 
\end{align*}\]

Initial conditions: \(p_D(x,0) = 0\) \\
Left boundary condition: \(p_D(0, t) = p_0 \sin (2\pi t)\) \\
Right boundary condition: \(p_D(\infty, t) = 0\)

5. EXPERIMENTAL PROCEDURE

5.1. Design of the Pulse Water Injection Device. Based on the hydraulic vibration principle of pulse water injection and the technical working parameters of an indoor advection pump, a microflow pulse wave-generating device was established, which can automatically control the solenoid valve using a single-chip microcomputer. Before starting the experiment, the required frequency control information was loaded into the single-chip microcomputer through a program. Then, it was connected to the power supply. The frequency was adjusted through the switch. At the outlet of the solenoid valve, we can obtain the water flow with a pulse wave as shown in Figure 12. This device can control the holding time, that is, the frequency of pulse water injection. The upper left corner of the figure shows the control circuit diagram of the pulser.

The indoor oil displacement pump uses a parallel flow pump (2PB-1040). The main technical parameters are as follows: the flow rate range is 0.01~10 mL/min and the working pressure range is 0~40 MPa. The design of the pulse wave generator includes four aspects: the selection of the working cavity material, the selection of the working cavity volume, the selection of injection speed, and the selection of the frequency range. Considering the elastic modulus of the working cavity with different materials, different elastic modulus values have an influence on the amplitude and frequency of the pulse, and
the working cavity with different materials were selected for experiments to study the influence of different elastic modulus values on the amplitude and frequency.

5.2. Experimental Apparatus and Measurement System. 5.2.1. Materials. The experimental water is simulated formation water with a total salinity of 7241.5 mg/L, and the composition is listed in Table 3. The core parameters are listed in Table 4. An artificial homogeneous core is shown in Figure 13.

5.2.2. Equipment. The experimental equipment is divided into three systems. The first is the pulse pressure drive system: the low-frequency pulse pressure generator injects the pulse pressure into the core and adjusts the size of the water injection pressure in the core. The second is the water injection core displacement system: it uses the pressure of the pulser to flood the saturated oil core to simulate the oil displacement process in the formation, and the measuring cylinder (range 50 mL) measures the content of the displacement oil and water. The third is the data acquisition system: it consists of pressure sensors (RS-845 and HSTL-802) and electromagnetic flow meters (accuracy level ± 0.5%) to transfer the collected data to the data acquisition system and draw data curves. This experiment uses a screw pump (model: G40-1 screw pump), which provides high pressure (maximum 12 MPa) and high flow (200 L/min) to meet the experimental requirements. A low-frequency pulse water injection oil-driven physical connection map is shown in Figure 14.

5.2.3. Field Application and Economic Evaluation. The low-frequency pulse device in this study can be placed at the wellhead and pressure can be pumped through the pump room. The low-frequency pulse device is connected with the pump to control the intermittent control time of the pumping pressure. The method in this research has been tested in the first oil production plant of Daqing Oilfield. It was found that the low-frequency pulse water injection technology can effectively improve the recovery factor, which is 5% higher than that of conventional water flooding. Compared with the conventional continuous water injection volume, the pulse water injection can effectively control the amount of water injection so as to save investment.

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Notes
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**NOMENCLATURE**

- $P_0$: tabformation pressure under vibration (MPa)
- $P_{i0}$: tabinitial pressure of the formation under vibration (MPa)
- $K_{tab}$: permeability (mD)
- $\rho_{tab}$: density of the formation fluid (g/cm$^3$)
- $\mu_{tab}$: viscosity of the formation fluid (mPa·s)
- $q_{tab}$: porosity under the local formation pressure (%)
- $C_{tab}$: the elastic compressibility (1/MPa)

**Greek Symbols**

- $\tau$: vibration time (s)
- $f$: vibration frequency (Hz)

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