Oil Displacement by the Magnetic Fluid Inside a Cylindrical Sand-Filled Sample: Experiments and Numerical Simulations

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ABSTRACT: Magnetic fluid is a new type of smart material, which holds implications for highly enhancing the oil displacement efficiency. In the present study, we perform a comprehensive investigation to probe the influence of a magnetic fluid on the displacement efficiency in porous media under the action of magnetic force. First, the displacement efficiency is measured by a self-developed setup, where factors such as the magnet thicknesses, the volume of the fluid injected, the fluid injection speed, and the porosity of the sample are surveyed as controllable variables. Moreover, the experimental results are well verified by the scaling laws according to the principle of dimensional balance. Next, a numerical simulation is performed to explore the detailed displacement process. First, the magnetic force generated by the ring magnet is calculated. Then, the function curves of the displacement efficiency with respect to the controlling variables are validated by the numerical simulation. In addition, the numerical simulation also demonstrates the volume phase distribution, the pressure field, and the velocity field of the mixed fluid during the displacement process. The simulation results are in excellent agreement with the experimental data. These findings are beneficial for us to better understand the oil displacement with the aid of external fields, which also provide inspiration for the areas of microfluidics, diffusion of pollutants, microsensors, etc.

1. INTRODUCTION

Oil- and gas-based energy sources are facing critical challenges because fewer new fields are being identified. The enhanced oil recovery of fields is an effective method to solve these challenges. At present, the remaining oils in the ultrahigh water-cut reservoirs are relatively dispersed. It is a heavy task to exploit oil and gas from the underground, as this process cannot be monitored in time, which is associated with complex geological structures and strong reservoir heterogeneity. Therefore, gaining a full understanding of the distribution law of the remaining oils and seeking new oil displacement techniques are two key points to enhancing oil recovery. Among others, a convenient and economical way to increase the sweeping area of the displacement fluid is using external energy, including the gravitational field, electrical field, chemical field, magnetic field, etc.

It has been known that the magnetic field has the advantages of no contact, low energy consumption, etc., and thus, it has potential application in many engineering areas. A magnetic field-controlled fluid, i.e., the magnetic fluid, is a smart material that has been widely used in the industry. The main property of the magnetic fluid is that it shows a good response to the action of magnetic field, i.e., it can freely move, spread, and flow under the action of magnetic field. Evidently, the motion of the magnetic fluid obeys fluid dynamics, and it is also governed by the magnetic field. Due to these performances, the magnetic fluid plays an important role in the fields of machinery, aerospace, chemical industry, electronics, metallurgy, energy, medical treatment, etc. Because of its low preparation cost, good permeability, and strong controllability, many scientists and engineers have tried to use the magnetic fluid as a new type of displacement fluid in the petroleum industry, aiming to improve the effectiveness of oil displacement.

In recent years, many efforts have been devoted to expanding the application of magnetic fluids by means of experimental studies and numerical simulation methods. For example, Moridis et al. found that the magnetic fluid can normally flow to an area with a high magnetic field strength by an experiment on two-phase flow including the magnetic fluid and water. They realized the control of the magnetic fluid via the applied field, which provides some inspiration for the application of the magnetic fluid in oil displacement. In succession, Borglin et al. did an experiment to study the flow of the magnetic fluid in two-dimensional porous media and found that the magnetic fluid, i.e., the ferrofluid can, overcome...
the effect of gravity and change its flow path under the action of a magnetic field. However, they paid attention to only flow behaviors and did not apply flow controllability to porous media reservoirs. Rahmani et al.\textsuperscript{15,16} proposed that the heterogeneity of the reservoir makes the displacement situation different in each direction, and they believed that timely adjustment of the magnetic fluid flow state has an important impact on the improvement of oil recovery. For the detailed observation of the flow process, Herb et al.\textsuperscript{17} fabricated a microfluidic chip as a visualized microscale porous medium. They claimed that the magnet can efficiently control the flow process of the magnetic fluid at the microscale, and the migration law of the magnetic fluid can be obtained in the pores. Moreover, Chai et al.\textsuperscript{18} utilized the ferrofluid slug in the microchannel as a kind of thruster to drive the front-end fluid flow when an external magnetic field was applied, and thus, a magnetically controlled micropump could be invented. These studies have provided support for the precise control of the magnetic fluid in the tiny pores, but the mechanism of the interaction between the magnetic fluid and oil has not been elucidated as yet. Based on these studies, Huang et al.\textsuperscript{19} conducted an experiment to probe the mechanism of magnetic fluid flooding to improve oil recovery through a two-dimensional heterogeneous and fractured sand-packed flat plate model. With the extensive development of computer technology, many experts have begun to explore the process of magnetic fluid flooding through numerical simulations. Oldenburg\textsuperscript{20} first introduced the magnetic volume force into the Darcy equation, and in their work, the EOS7M module was developed based on TOUGH2 software to simulate the two-phase flow of the ferrofluid in the porous media. However, due to the concentrated loads of the magnetic field close to the magnet, this algorithm easily leads to non-convergence in the calculation. From different routes, Zhang et al.\textsuperscript{21} used the lattice Boltzmann method to study the convection process of magnetic fluid in a square porous medium. They pointed out that this method is more suitable for the two-phase flow process of magnetic fluid flooding. Similarly, Hadavand et al.\textsuperscript{22} studied the flow process of the magnetic fluid in porous media at the microscopic scale, where the detailed information for the magnetic fluid displacing the original liquid phase is revealed.

Although a plethora of work has been done on the flow of the magnetic fluid inside the porous media, there is still a lack of comprehensive studies on the oil displacement process by the magnetic fluid. The accurate experimental control and quantitative results remain a blank room. Henceforth, this situation would limit the wider application of magnetic fluids in the area of the petroleum industry. Therefore, the goal of the present work is directed toward full exploration on the oil displacement via magnetic fluids by way of experiments and numerical simulations. Introducing a magnetic field for coupling provides a driving force for the displacement flow process of the magnetic fluid, which effectively increases the swept area of the displacement fluid and promotes more oil to be displaced.

The outline of the article is structured as follows: In Section 2, we measure the displacement efficiency by the self-developed setup, where different factors, such as the magnet thicknesses, the volume of fluid injected, the fluid injection speed, and the porosity of the sample, are surveyed as controllable variables. Then, we verify the experimental results by the scaling laws according to the principle of dimensional balance. In Section 3, we probe the detailed displacement process by numerical simulations. The magnetic force due to the ring-shaped magnet is computed by solving the equations of the magnetic field, and its distribution law is given. We then analyze the function curves of the displacement efficiency with respect to the controlling variables, which have been compared with the experimental results. In addition, the numerical simulation is conducted to demonstrate the volume phase distribution of the fluid. The pressure field and velocity field of the mixed fluid during the displacement process are also given by the numerical simulation. The simulation results have been thoroughly compared with the experimental results. Section 4 presents the conclusions.

2. EXPERIMENTS

2.1. Experimental Setup and Method. We first perform an experiment to measure the displacement efficiency of the magnetic fluid in the sand-packed porous media. As shown in Figure 1a,b, a sand-filled porous medium sample is prepared by pressing silicon dioxide particles into a polypropylene tube, and the top end of the tube is encapsulated with epoxy resin. The radius of the cylindrical tube is denoted by \( R \), which is 4.25 mm, and its height \( h \) is 50 mm. A connecting pipe with an inner diameter of 1.5 mm is inserted at the center of the top surface of the tube to ensure the injection of the fluid without

![Figure 1](https://doi.org/10.1021/acsomega.2c02444) (a) Experimental diagram of the porous medium model; (b) schematic diagram of the experimental setup, where a porous media sample, a micropump, and a ring-shaped magnet are shown; (c) sand-packing models in the porous media; and (d) internal view of sand-packing pipe model during displacement.
resistance. The connecting pipe is linked with a microfluid pump to control the injection flow rate. There is a hole at the center of the bottom surface of the tube, with a diameter of 1.5 mm, which is directly open to the air and the fluid can flow into the reservoir. The glass glue is used to seal the joints of each connection part to prevent leakage. In the experiment, a ring-shaped magnet with an inner diameter of 20 mm, an outer diameter of 30 mm, and a thickness of \( d = 5 \) mm is placed coaxially with the sample. The material of the magnet is NS2 neodymium iron boron.

The oil in the experiment is selected as dimethyl silicone, which is purchased from Aladdin Biochemical Technology Co., Ltd., with a density of \( \rho_1 = 0.955 \) g/cm\(^3\), an API of 16.668, and a viscosity of \( \mu_1 = 360 \) mPa-s. The magnetic fluid is the SS-F10C water-based nanomagnetic fluid, which is purchased from Hangzhou Jikang New Materials Co., Ltd., with a density of \( \rho_2 = 1.450 \) g/cm\(^3\), a concentration of 33\%, and a viscosity of \( \mu_2 = 8.0 \) mPa-s. The water used in the experiment is ultrapure water, with a pH of 6.8 and salinity of 0.05\%. The reservoir temperature used in the experiment is nearly 18 °C.

For comparison of the displacement efficiency, water and the magnetic fluid are respectively chosen as the displacement fluids. Before the experiment, we perform the saturated oil treatment on the sand-filled sample. The initial mass of the sample before the oil is saturated is \( M_0 \), and that after the oil is saturated is designated as \( M_1 \). The displacement fluid is injected into the sample through the micropump, and then, the oil in the sample is squeezed out, this is really the nature of “displacement”. After the injection of fluid, the sample’s mass is defined as \( M_2 \). As a result, the oil displacement efficiency \( \eta \) is obtained as

\[
\eta = \frac{M_2 - M_1}{(M_1 - M_0)/(\rho_1/\rho_2 - 1)}
\]  

(1)

The magnetic fluid trapped in the reservoir for each total volume injected is obtained as

\[
V_M = V_0 \eta
\]  

(2)

We choose the magnet thickness \( d \), the volume of fluid injected \( V \), the fluid injection speed \( v_0 \), and the porosity \( K_p \) of the sand-filled sample as controlling variables. In the experiments, the effects of the above four variables on the oil displacement efficiency are quantitatively probed. In particular, the values of the displacement efficiency based on the magnetic fluid flooding and water flooding are compared. In addition, we also calculated the relative permeability curve, as shown in Figure 2.

First, when considering the influence of magnet thickness on the displacement efficiency, the other variables are kept unchanged, and the displacement efficiencies corresponding to five magnet thicknesses of \( d = 5, 10, 15, 20, \) and 25 mm are measured, respectively. To alter the thickness of the magnet, several identical magnets are overlapped coaxially, where each has a thickness of 5 mm. Next, with other variables unchanged, the influence of the volume of fluid injected \( V \) with five different values of 0.7, 1.7, 2.7, 3.7, and 4.7 mL on the displacement efficiency is studied respectively. Third, we explore the influence of the fluid injection speed \( v_0 \) on the displacement efficiency, where five values of injection speed, namely, 0.5, 1, 1.5, 2, and 2.5 mm/s, are considered. At last, we alter the value of the porosity by changing the diameter of the sands in the sample, where five values of porosity of 0.436, 0.448, 0.456, 0.463, and 0.472 are investigated.

2.2. Experimental Results and Discussion. In the sand-packed model, the magnetic fluid rapidly expands to the edge of the model under the action of magnetic field and then displaces oil toward the outlet under the combined action of the gravitational field and the magnetic field. As shown in Figure 1c,d, the remaining oil distribution in the area where the magnetic fluid flows is less, which means that the flow of the magnetic fluid greatly improves the oil displacement efficiency.

As mentioned above, the effect of each variable on the displacement efficiency is explored by way of controlling variables. First, we keep the injection flow rate \( v_0 = 1 \) mm/s, the injection volume \( V = 1.7 \) mL, and the porosity \( K_p = 0.436 \) unchanged. Thus, the relation between the thicknesses of magnet \( d \) and the displacement efficiency \( \eta \) is demonstrated in Figure 3. The curve shows that the displacement efficiency of the water drive remains constant, with a value of \( \eta = 11.8\% \). This indicates that the magnetic force has no impact on the flow of water inside the porous media. However, for the magnetic fluid, the case is very different. The first law is that the displacement efficiency by the magnetic fluid is larger than that of water in the whole process. Moreover, with an increase in magnet thickness, the displacement efficiency of the magnetic fluid first increases and then decreases; i.e., the curve is not monotonic. Obviously, with an increase in \( d \), more oil can be squeezed out of the medium because of the stronger action of magnetic force. The fact is that the curve is not monotonic indicates that there is an optimal value of the magnet thickness to enhance the displacement efficiency. For example, when \( d = 15 \) mm, the displacement efficiency reaches the maximum value of 24.8\%. This means that the magnetic field has a positive effect on the flow regulation of the magnetic fluid only within a certain range.
Moreover, we perform sensitivity analyses of every single parameter. First, for variable $d$ in Figure 3, we take $d = 9$ mm and $d = 11$ mm for verification, respectively, on two displacement processes. It is found that the value of $\eta$ is 22.9 ± 0.32% at $d = 9$ mm and the value is 24.3 ± 0.26% when $d = 11$ mm. For the process of water flooding, the change in $d$ has no effect on $\eta$. When $d = 9$ mm, the $\eta$ is 11.5 ± 0.23%, and the $\eta$ is 11.5 ± 0.29% when $d = 11$ mm.

Next, we keep $d = 5$ mm, $v_0 = 1$ mm/s, and $K_p = 0.436$, and different volumes of the displacement fluid are injected into the sample. Thus, the relation between the volume of the magnetic fluid $V$ and the displacement efficiency $\eta$ is displayed in Figure 4. The curve shows that, with an increase of $V$, the value of $\eta$ first increases rapidly and then increases slowly until it stabilizes at a value of 24.72%. This is because the process of oil displacement can be divided into two main stages. In the first stage, the displacement fluid quickly flows through the sample from the top to the bottom and displaces the crude oil. The flow direction of the displacement fluid is mainly vertical, and the crude oils displaced at this stage account for most of the stored oils in the entire displacement process. In the second stage, most of the fluids flow laterally. The latter-injected displacement fluids push those that previously occupied the pores, with greater pressure, and then displace the crude oils in these areas. In addition, the sweeping area of the magnetic fluid is limited; i.e., it is very difficult to occupy all of the pores, and thus, the displacement efficiency gradually stabilizes at a constant value. It is also found that the trend of water flooding is the same as that of the magnetic fluid, with the maximum displacement efficiency of $\eta = 14.5\%$. As shown in Figure 4, we take $V = 1.6$ and 1.8 mL to conduct sensitivity analysis on both two displacement processes. When $V = 1.6$ mL, the value of $\eta$ for the magnetic fluid is 20.9 ± 0.32% and for water is 11.2 ± 0.46%. When $V = 1.8$ mL, the value of $\eta$ for the magnetic fluid is 21.2 ± 0.35% and for water is 12.3 ± 0.23%.

Third, as shown in Figure 5, the displacement efficiency $\eta$ is also a function of the fluid injection speed $v_0$, where the other parameters are selected the same as those in Figure 4. It is easy to know that the displacement efficiencies of both water flooding and magnetic fluid flooding are significantly improved with an increase in injection rate. The curve shows that the highest displacement efficiency of water flooding can amount to the value of 15.0% and that of magnetic fluid flooding can arrive at 29.5%. Moreover, the difference between the two efficiency curves on water drive and magnetic fluid drive gradually increases with an increase in flow rate. This phenomenon can be explained as follows: the greater the initial velocity of the fluid, the more it can occupy the pores of the medium and then displace the oils and push them in the direction of the outlet. At the same time, the fluid flow is affected by the adhesion between the oil and the solid and its own viscosity. It can be seen that the magnetic fluid quickly gathers adjacent to the magnet after entering the porous media, and then, it starts to flow through the entire configuration from top to bottom; this would enhance the sweeping area. Very differently, the water will flow quickly to the exit direction under the action of gravity, and the route is nearly vertical. As a result, the displacement process of water only occurs in the area close to the sample center; i.e., the sweeping effect is quite weak. What is more, we set the inlet velocities to 1.99 and 2.01 mm/s by adjusting the microconsole, respectively. We found that when $v_0 = 1.99$ mm/s, the values of $\eta$ are 28.1 ± 0.26% for the magnetic fluid and 13.6 ± 0.33% for water. Moreover, when $v_0 = 2.01$ mm/s, the values of $\eta$ are 27.9 ± 0.23 and 13.8 ± 0.25%, respectively.
Finally, the relation between the displacement efficiency \( \eta \) and the porosity \( K_p \) is displayed in Figure 6, where the other parameters are taken the same as those in Figure 4. The curve shows that with an increase in porosity, the displacement efficiency gradually increases. Especially, when \( K_p = 0.472 \), the displacement efficiency arrives at a large value, \( \eta = 27.483\% \). As is well known, the variation of the porosity can significantly affect the permeability of porous media. That is to say, the bigger the porosity, the higher the permeability between the injection and production ends of the sample. When the permeability of the porous media is relatively low, some areas are basically not affected, and thus, the displacement efficiency is lower. When the magnetic fluid flows near the magnetic source, it can be drawn to flow along the radial direction of the sample, i.e., toward the low sweeping area of the sample; thereby, it can effectively displace more oils. As shown in Figure 6, we obtained two models with porosities of 0.445 and 0.450, respectively, by adjusting the mesh size of the sand. When \( K_p = 0.445 \), the value of \( \eta \) for the magnetic fluid is 21.2 \( \pm \) 0.22\% and for water is 12.0 \( \pm \) 0.26\%. When \( K_p = 0.450 \), the value of \( \eta \) for the magnetic fluid is 21.2 \( \pm \) 0.35\% and for water is 13.2 \( \pm \) 0.43\%.

In summary, the analysis data we selected fluctuate within the error range, the maximum error is 4.8\%, and the minimum error is 2.1\%. We can consider the experimental data to be credible.

In addition, the obtained experimental results can be compared with the existing results. For instance, Huang et al.\(^{19}\) used a two-dimensional heterogeneous sand-filled flat plate model to compare the effects of ferrofluid and water flooding. Their results show that the displacement efficiency on the water drive is 33\% and that on the ferrofluid drive is 73\%; the latter is more than twice of the water drive. In the present work, the displacement efficiency of the magnetic fluid is about 1.9 times that of water flooding, but the value of displacement efficiency is different from Huang’s result. The reason for this difference is that the oil used in Huang’s experiment is a kind of polymer with a viscosity of only 22.1 mPa·s and the oil in our experiment is silicone oil with a viscosity of 360 mPa·s, more than 10 times that of the former. It can be seen that although their materials and models are different from the present work, the tendency is the same.

The experimental results can be further investigated by the way of dimensional analysis, as there are too many factors working and the analytical solution is nearly impossible. The displacement efficiency \( \eta \) is correlated with many variables, which mainly include the magnet thickness \( d \), the volume of fluid injected \( V_i \), the fluid injection speed \( v_0 \), the sand filling model porosity \( K_p \), the viscosity of simethicone \( \mu_s \), the surface tension of simethicone \( \gamma \), the gravitational acceleration \( g \), the radius of the sample \( R \), and the depth of the sample \( h \). According to the principle of dimensional analysis, the scaling law for the \( \eta \) reads

\[
\eta \sim \left( \frac{\gamma d \mu_s}{\gamma} \right)^3 K_p
\]

(3)

The above relation can be definitely used to analyze the obtained experimental results. Herein, the gravitational acceleration \( g \) is taken as 9.8 N/kg, and the other parameters are taken at the same values as mentioned in the Experiments section. First, the dependence relation between the magnet thickness \( d \) and the displacement efficiency \( \eta \) is exhibited in Figure 3. When the parameters \( V_i \), \( v_0 \), and \( K_p \) are fixed, by fitting the experimental data, we get the relation that

\[
\eta \sim d^3
\]

(4)

It can be seen that the experimental result is consistent with that derived by the dimensional analysis in eq 4, and thus, the experiment is reliable. Among them, the coefficient in eq 4 can be further obtained by fitting the experimental data.

Similarly, the relations between the displacement efficiency \( \eta \) and the other controlling variables, i.e., the fluid injection \( V_i \), the fluid injection speed \( v_0 \), and the porosity \( K_p \), can be given according to eq 3. If the other parameters are fixed, one can respectively get

\[
\eta \sim V_i^2
\]

(5)

\[
\eta \sim v_0
\]

(6)

\[
\eta \sim K_p
\]

(7)

It can be seen that these relations in eqs 5, 6, and 7 are in accordance with the experimental data in Figures 4, 5, and 6, respectively. This fact partially indicates that the experimental results are reliable.

3. NUMERICAL SIMULATIONS

3.1. Formulation of the Mechanics Model. To get further information about oil displacement in the porous media, a convenient way is to adopt the numerical simulation, as the analytical solution is not at hand currently. For modeling, the porous media with the multiphase flow module and the magnetic field module in the commercial software COMSOL are utilized to simulate the process of magnetic fluid flooding inside the porous media. To reduce the computational cost, an axisymmetric configuration including oil and displacement fluid is chosen. The porous medium phase field model, Darcy’s law, and the magnetic field model are used to depict the displacement process.

To describe the effect of wettability on the experimental results, we added a surface tension term to the simulation. We have supplemented the wettability analysis in the displacement processes. In the experiment, we uniformly coated a layer of sand on a glass sheet, used a pendant drop method to drop
water droplets and oil droplets on the substrate, respectively, and employed a contact angle meter to measure the contact angle. It was found that the contact angle of water on a sand substrate was $115 \pm 3.6^\circ$ and that of oil was $20 \pm 4.2^\circ$. This means that the sand filling medium is hydrophobic. Based on this conclusion, we set the oil-water interfacial tension in the numerical simulation and introduced the effect of surface tension in the flow model.

Herein, the porous media phase field model is selected to formulate the flow of the mixed liquid, which is formed by two different liquids. The continuously changing phase parameters of the two liquids are introduced, and therefore, the model can accurately predict the behaviors of the considered two liquids in the confined room. The phase-transfer equations of the two liquids inside the porous media are expressed as

$$\frac{\partial}{\partial t}(K_i \rho_i s_i) + \nabla \cdot (\rho_i \mathbf{v}_i) = 0$$ \hspace{1cm} (8)

$$\frac{\partial (K_i \rho_i s_i)}{\partial t} + \nabla \cdot (\rho_i \mathbf{v}_i) = 0$$ \hspace{1cm} (9)

$$\mathbf{v}_1 = -\frac{e_{11}}{\mu_1} (\nabla \rho_1 - \rho_1 \mathbf{a}_1)$$ \hspace{1cm} (10)

$$\mathbf{v}_2 = -\frac{e_{22}}{\mu_2} (\nabla \rho_2 - \rho_2 \mathbf{a}_2)$$ \hspace{1cm} (11)

where $s_i$, $\mathbf{v}_i$, $\mathbf{a}_i$, and $\rho_i$ are the volume fraction, velocity, acceleration, and pressure of the liquid; $i = 1$ corresponds to the simethicone; and $i = 2$ corresponds to the magnetic fluid. Symbol $t$ is the time of the displacement process, $e_{11}$ and $e_{22}$ are the relative permeabilities, and $\nabla$ is the gradient operator.

In the solution of the Darcy field, we treat the multiple fluids at each point in the porous medium as a mixed fluid with uniform physical parameters. It should be noted that these physical quantities of the mixed fluid at different points will vary according to the volume fraction of multiple fluids. The density, viscosity, acceleration, and velocity of the mixed liquid are respectively defined as follows

$$\rho = \rho_1 s_1 + \rho_2 s_2$$ \hspace{1cm} (12)

$$\mu = \mu_1 s_1 + \mu_2 s_2$$ \hspace{1cm} (13)

$$\mathbf{a} = \mathbf{a}_1 s_1 + \mathbf{a}_2 s_2$$ \hspace{1cm} (14)

$$\mathbf{v} = \mathbf{v}_1 s_1 + \mathbf{v}_2 s_2$$ \hspace{1cm} (15)

Therefore, Darcy’s equation is written as

$$\frac{\partial}{\partial t}(K_i \rho_i s_i) + \nabla \cdot (\rho \mathbf{v}) = N$$ \hspace{1cm} (16)

$$\mathbf{v} = -\frac{\mu}{\rho} (\nabla \rho - \rho \mathbf{a})$$ \hspace{1cm} (17)

where $N$ is the mass flux of liquid at the inlet, which is defined as the ratio of the mass of the injected liquid to the inlet surface and is calculated by experimental parameters. $N$ is calculated by experimental parameters, and the value is $N = 14$ kg/(m$^2$·s$^2$).

The magnetic field equations are

$$\mathbf{H} = -\nabla \varphi$$ \hspace{1cm} (18)

$$\nabla \cdot \mathbf{B} = 0$$ \hspace{1cm} (19)

where $\mathbf{H}$ is the magnetic field strength, $\varphi$ is the magnetic scalar potential, and $\mathbf{B}$ is the magnetic flux density. Evidently, the magnetic fluid is subjected to the force due to the external magnetic field, and its value per unit volume is expressed as

$$\mathbf{F} = \mu_0 (M \nabla) \mathbf{H}$$ \hspace{1cm} (20)

$$\mathbf{F} + \rho_i \mathbf{V}_g = \rho \mathbf{a}$$ \hspace{1cm} (21)

where $\mu_0$ is the vacuum permeability with a value of $4\pi \times 10^{-7}$ Tm/A, $M$ is the magnetization, and $\mathbf{H}$ is the magnetic field strength.

At the entrance of the sample, we use a fixed mass flux as the boundary condition and set the boundary conditions of the flow field and the phase field as

$$-n \cdot \rho_1 \mathbf{v}_1 = N_1$$ \hspace{1cm} (22)

$$-n \cdot \rho_2 \mathbf{v}_2 = N_2$$ \hspace{1cm} (23)

$$-n \cdot \mathbf{v} = N$$ \hspace{1cm} (24)

where $n$ is the outer normal vector on the interface, $N_1$ is the mass flux of the simethicone phase, and $N_2$ is the mass flux of the magnetic fluid. Quantities $N_1$ and $N_2$ are also calculated by experimental parameters, for which corresponding values are $N_1 = 0$ and $N_2 = 14$ kg/(m$^2$·s$^2$).

At the outlet of the sample, we use a fixed pressure as the boundary condition of the flow field and take the free outflow as the boundary condition of the phase field, i.e.,

$$p = p_0$$ \hspace{1cm} (25)

where $p_0$ is the atmospheric pressure.

For the other boundaries, the no-slip boundary conditions are adopted as follows:


\[-n \cdot \rho_1 v_1 = 0 \]  
\[-n \cdot \rho_2 v_2 = 0 \]  

\[n v 0 1 1 \cdot = \]
\[n v 0 2 2 \cdot = \]

3.2. Comparison with the Experiment. According to the above governing equations and boundary conditions, the oil displacement can be demonstrated in detail. Finite element software (Comsol Multiphysics 5.4a) is used to numerically simulate the fluid flow inside the porous media. In the simulation, the maximum element size of the grid in the calculation model is set to \(2.4 \times 10^{-3}\) m, the time step is selected to be \(10^{-2}\) s, and the tolerance factor is 1. We specify the convergence criterion to be 0.005 to control the iterative solution process and use the MUMPS solver for calculations.

First, based on eqs 18–20, we can obtain the force per unit volume of the magnetic fluid in the magnetic field via simulations. Take \(d = 5\) mm as an example for analysis, and the result is shown in Figure 7. The figure shows that the magnetic force exerted on the magnetic fluid in the sand-filled sample has an L-shaped distribution, which provides a good driving force for the movement of the magnetic fluid in the sand-filled sample. In the axial direction, the viscous oil can be squeezed by the magnetic fluid under the action of magnetic force and then it is further pushed to move toward the outlet. In the radial direction, the magnetic force promotes the lateral diffusion of the magnetic fluid, and this would increase the distribution area of the magnetic fluid and more oils can be driven out. In the experiment, when the magnet is applied, we also observe that in the radial direction the occupied area of the magnetic fluid increases, and thus, the magnetic fluid can contact more oils to produce the squeezing effect.

Next, the curve in Figure 3 is not monotonic, and this phenomenon can also be explained by the numerical simulation result. It can be imagined that when the magnetic field strength is sufficiently high, the magnetic forces in the radial direction can greatly increase and their effect becomes more predominant than that in the axial direction. This would limit the flow of the magnetic fluid along the axial direction, and thus, the displacement efficiency reduces.

In addition, the relationships between the displacement efficiency and the controlling variables mentioned above can also be given according to the numerical simulation. As shown in Figures 3–6, the simulation results are compared with the experimental results. The tendencies of these two results are the same, but the values have a slight difference. Especially, the maximum errors between the two results are 5.4, 4.5, 5.2, and 4.7%, corresponding to Figure 3, 4, 5 and 6; these errors are acceptable in engineering. The errors may be due to insufficient air tightness of the equipment, and certain errors in the measurement during the experiment cannot be avoided.

3.3. Phase Distribution of the Displacement Fluid. As mentioned above, it is impossible to directly observe the details of fluid flow because of the limitations of the experiment. Therefore, we get the fluid flow state and distribution by simulating the volume phase distribution of the fluid in the sample. In addition, the pressure field and velocity field distribution of the multiple fluids can also be displayed through numerical simulations.

The volume phase distribution of the fluids inside the sample can be clearly shown in Figure 8, where the magnetic fluid (Figure 8a–c) and water (Figure 8d–f) are analyzed. The initial state of the sample is shown in Figure 8a, where the displacement fluid has not been injected. From Figure 8b,c, it is noticed that the volume of the magnetic fluid at the entrance is relatively large, as the strength of the magnetic field is concentrated here. After the magnetic fluid enters the sample, under the action of magnetic force, part of the fluid flows toward the exit of the sample in the longitudinal direction and the other fluids spread out in the radial direction, i.e., trying to move toward the pipe wall. The case for water flooding is different, as less water is distributed in the vicinity of the pipe wall and most of the water directly penetrates toward the longitudinal direction under the action of gravity in the absence of the magnetic force. Altogether, the difference in the displacement efficiency for the two liquids is attributed to their different sweeping areas.

Moreover, the flow of the water drive is relatively fast. When \(t = 4\) s, the water has passed a long distance whose value amounts to \(3h/4\), while the magnetic fluid only passed a distance whose value is \(h/2\). This is also consistent with the flow state of the displacement fluid in the porous media as we observed previously. The magnetic field can effectively increase the contact area between the magnetic fluid and the oil, but it does not affect that between water and oil. After the oil is squeezed by the magnetic fluid, it will flow with the magnetic fluid through the outlet. In this process, the generated pressure urges the front oils to be de bonded from the rock surface and more oils are displaced. However, the water drive process is only affected by the gravity field and the water only squeezes the oils along the longitudinal axis of the configuration, resulting in a very low sweeping area.

3.4. Pressure and Velocity Fields in the Oil Displacement Process. The pressure and velocity fields of the fluids can also be given via the numerical simulation. As shown in Figure 9, the pressure variation at any position on the cross section of the sample with respect to the time evolution is demonstrated, where the results of water drive and magnetic fluid drive are compared. First, for the water drive, the pressure \(p\) increases linearly with an increase of \(h\), as the water is only under the action of gravity. From the figure, it is noted that for water flooding, when \(t = 4\) s and \(h = 37.5\) mm, the pressure of the mixed fluid arrives at 42.36 Pa. When \(t = 0\), the mixed fluid only includes the oil and its pressure is 43.1 Pa when \(h = 37.5\) mm. When \(h < 37.5\) mm, the pressure difference when \(t = 0\) and \(t = 4\) s is because the fluid components are different. When \(h > 37.5\) mm, the remaining area of the porous media is almost...
the same as the initial state when \( t = 0 \), which is consistent with the phase distribution in Figure 8e. The curve when \( t = 8 \) s has the same tendency as that when \( t = 4 \) s, but the values are different because the component fractions of the mixed fluid have changed with the evolution of time.

Due to the influence of the external magnetic force, the pressure distribution for the magnetic fluid differs greatly from the water. At the initial moment when \( t = 0 \) s, the pressure curve for the magnetic fluid is the same as that of water. For magnetic fluid flooding, the pressure of the mixed fluid is almost 0 when \( t = 4 \) s and \( h = 28 \) mm, which is consistent with the case in Figure 8b. When \( h > 28 \) mm, the remaining area of the porous media is almost the same as the initial state when \( t = 0 \). However, one abnormal phenomenon is that, when \( t = 4 \) s and \( h < 15 \) mm, the pressure value has a significant jump due to the effect of the magnetic field. When it is far away from this area, the pressure gradually returns to the state that it is linear with the depth of the fluid. When \( t = 8 \) s, the mixed fluid includes the magnetic fluid and oil and its pressure curve is never crossed with that when \( t = 0 \) s, where there is only oil distributed, and this property can be shown in Figure 9.

Next, the velocity curve during the displacement process is shown in Figure 10. It is observed that the velocity of the mixed fluid during water flooding does not change much with an increase of \( h \), and its average value is nearly 1.2 mm/s.

When the magnetic fluid enters the sample, the velocity value changes significantly. Especially, the velocity of the mixed fluid inside the sample generally shows a trend that it first increases and then decreases. When \( h > 12 \) mm, the velocity comes to a stable value for magnetic fluid flooding, almost the same as that of water flooding. This phenomenon can be explained by the velocity streamline distribution in Figure 11.

4. CONCLUSIONS

In conclusion, the oil displacement by the magnetic fluid inside the sand-packed sample is comprehensively explored in the present work, aiming to find a useful strategy to enhance oil recovery. First, the displacement efficiency is measured by the self-developed setup. The experimental results can be well verified by the scaling laws according to the principle of
dimensional balance. Next, the numerical simulation is performed to probe the detailed displacement process. The function curves of the displacement efficiency with respect to the controlling variables can also be validated by the numerical simulation. In addition, the numerical simulation also demonstrates the volume phase distribution of the fluid. The pressure field and velocity field of the mixed fluid during the displacement process can also be displayed by the numerical simulation. Altogether, the simulation results are in excellent agreement with the experimental results.

It should be mentioned that further work can be done in the near future, including the analytical solution of the permeation fluid mechanics, and more engineering applications should be extended. All of the same, the current findings are beneficial for us to better understand the oil displacement with the aid of external fields, which also provide inspiration for the areas of microfluidics, diffusion of pollutants, microsensors, etc.

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Notes
The authors declare no competing financial interest. The data that support the findings of this study are available within the article.

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■ NOMENCLATURE

- $R$: radius of the cylindrical tube (mm)
- $h$: height of the cylindrical tube (mm)
- $d$: thickness of the magnet (mm)
- $\rho_1$: density of the oil (g/cm$^3$)
- $\mu_1$: viscosity of the oil (mPa·s)
- $\rho_2$: density of the magnetic fluid (g/cm$^3$)
- $\mu_s$: viscosity of the magnetic fluid (mPa·s)
- $M_s$: mass of the sample (g)
- $M_i$: mass of the oil and sample (g)
- $M_{i+1}$: mass of the sample after the injection of fluid (g)
- $V$: volume of fluid injected (mL)
- $v_0$: speed of the fluid (mm/s)
- $K_p$: porosity
- $\eta$: displacement efficiency
- $g$: gravitational acceleration (m/s$^2$)
- $s_i$: volume fraction
- $a_i$: acceleration
- $p_i$: pressure
- $t$: time of the displacement process
- $\varepsilon$: permeability
- $V$: gradient operator
- $N$: mass flux
- $H$: magnetic field strength
- $\varphi$: magnetic scalar potential
- $B$: magnetic flux density
- $\mu_0$: vacuum permeability
- $M$: magnetization
- $H$: magnetic field strength (mm)
- $\mathbf{n}$: normal vector
- $N_1$: mass flux of the simethicone phase
- $N_2$: mass flux of the magnetic fluid
- $p_0$: atmospheric pressure

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