ENHANCEMENT OF OIL RECOVERY VIA DIRECT CURRENT

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ABSTRACT
Mathematical models were established to describe one-phase flow fluid in fractured-vuggy media under the influence of an electric field. The finite element equations of numerical models were derived. The fluid flow mechanism in fractured-vuggy media under the influence of electric field was systematically investigated using COMSOL Multiphysics software. The distributions of velocity, pressure, and potential in the fracture and vug were studied. The results show that the electric field effectively increases fluid flow. The distributions of isobar and equipotential line can be affected by the fracture and vug. Overall, the findings offer an important theoretical basis for the enhancement of the oil recovery of fractured-vuggy reservoir via direct current (DC) electric field methods. The 150 V-regulated DC power supply was initially designed according to the results of the simulation, and then MULTISIM simulation software was applied. waveform state and thereby meeting the requirements Inductance-capacitance was then utilized to filter the DC power, resulting in a smooth simulation of oil displacement and imposing electricity.

KEY WORDS
DC electric field; fractured-vuggy media; recovery factors; fluid flow; numerical simulation

1. Introduction

Direct current (DC) electric field is a new, enhanced oil recovery technique. Its influence ranges from the physical field to the rock saturation of fluid saturation, causing several kinds of electrochemical and electrodynamic effects, such as electroosmosis and electrophoresis in the stratum. As a result, changes in the regular influence pattern of oil-water appear. Several studies on the technology of improving recovery by imposing electricity on oil have been reported [1–3]. However, most of them mainly involved qualitative analysis. Previous research has established the fluid flow formula of electro dynamic and hydrodynamic forces based on the model of capillary electro dynamic and hydrodynamic forces; the unsteady one-dimensional leading displacement edge was based on the Buckley –Leverett model. The finite-difference method is commonly used in numerical reservoir simulations. However, adapting it on an arbitrarily shaped area and determining which is the priority of the gamma present in the area by simply using the orthogonal grid are difficult. By contrast, the finite difference method can be used to divide the area into any kind of grid, facilitates the free and regular arrangement of the grid points according to the demand of field functions, and has strong adaptability to the area and flow field patterns. The present study mainly focuses on the initial flowing fluid mechanism to establish a more refined mathematic mold. Finite element resolution method was used to solve the mathematic mold. For precision, computer software was also employed for all calculations [4–8]. Without consideration of the inertia item’s influence, the mathematical model of single-phase seepage influenced by the external electric field is as follows:

Motion equation:
\[
\frac{\partial}{\partial t}\left(1 \frac{\partial V}{\partial t}\right) = \frac{\partial}{\partial x} \left(\mu \frac{\partial V}{\partial x}\right) - \frac{\partial}{\partial y} \left(\mu \frac{\partial V}{\partial y}\right) = \frac{\partial}{\partial x} \left(\frac{\partial \phi}{\partial x}\right) - \frac{\partial}{\partial y} \left(\frac{\partial \phi}{\partial y}\right)
\]

Continuity equation:
\[
- \left[\frac{\partial V}{\partial x} + \frac{\partial V}{\partial y}\right] = 0
\]

The boundary condition of X is
\[
\begin{align*}
\left|P\right|_{x=0} &= P_1 \\
\left|P\right|_{x=L} &= P_2
\end{align*}
\]
The boundary condition of pressure.
\[
\begin{align*}
\left|\phi\right|_{x=0} &= \phi_1 \\
\left|\phi\right|_{x=L} &= \phi_2
\end{align*}
\]
The boundary condition of the electric potential.
The boundary condition of Y is
\[
\begin{align*}
q &= 0 \\
J &= 0
\end{align*}
\]
These are closed boundary and electric insulation boundaries.

2. Numerical Modeling

2.1 The Modeling
The ideas on and methods of seepage influenced by the external electric field were analyzed via COMSOL Multiphysics and finite element methods consisting of
three stages: (1) pre-processing and data entry; (2) finite element matrix calculation, assembling, and solving; and (3) data output and post-processing phase. The concrete procedure of modeling is as follows:
(1) In the inter phase of operating the software, the cuboid was cut to acquire a 0.5 m x 0.2 m x 0.2 m dimension.
(2) In the established place, a 0.01 m radius cylinder was taken in a horizontally open fracture (0.5 m in length) whose sectional view is shown in Figure 1.
(3) In the passage of the three-dimension model, a round hole with the same radius as the diameter of the spherical hole was taken. As a result, a round hole with 0.08 m radius was constructed in the well-established area.

![Figure 1 Structure of the single-fractured model of crack](image1)

(4) The fracture and hole established in the aforementioned procedures were combined into the entity; the inside boundary was removed.
(5) The generated part and the whole area were placed into the complete part. Figure 2 shows the sectional view of the single-fracture calculating model.

![Figure 2 Structural model of the single-slit hole](image2)

2.2 Imposing of the boundary condition
The boundary condition was imposed after the establishment of the model. The boundary was created to set the WASD boundary of the model in COMSOL Multiphysics.

2.3 Division of the grid
The boundary of the different materials was divided equally. In the single-fracture model, the holes make the model irregular in some way. Therefore, division through the triangle grid can be directly done, or a four-node quadrilateral can be used by adding lines. The division of the grid is shown in Figure 3. The figures followed the x- and y-axis graph model to facilitate observation.

![Figure 3 Fractured triangle mesh model](image3)

2.4 Setting of the parameter and the solution
The region parameters (viscosity, density, etc.) and boundary parameters (e.g., pressure and electric potential) of the fracture-hole model were defined in the software. A suitable optimizer was chosen for the computations. All necessary results and figures were recorded by a post-processor.

3. Results and discussion

3.1 Speed distribution in the fracture and hole under the influence of a DC electric field
The electric energies were 0, 3, and 5 V at 1000 Pa

![Figure 4 Equipotential line chart of velocity field at 0 V potential energy](image4)
entrance pressure. The speed distribution (in meters) is shown in Figures 4, 5, and 6.

The speed near the wall of the round cave is 0.003291 and 0.004891 ms⁻¹ under the absence and presence of an electric field, respectively (Figures 4 and 5). The presence of an electric field results in a much faster speed compared with that without electric field. Thus, electric field decreases the wallop of fluid to the wall, saves energy, and increases speed. Fluid speed increases with an increasing DC electric field energy (Figure 6), indicating that the electric field can significantly increase fluid speed.

![Figure 5](image5.png)

Figure 5 Equipotential line chart of the velocity field at 3 V potential energy

![Figure 6](image6.png)

Figure 6 Equipotential line chart of the velocity field at 5 V potential energy

Table 1 presents the different speeds in different electric potentials of the point (0.276622 and 0.129849). Figure 7 shows a chart based on the data in Table 1 and other results from the software (the x-coordinate is the electrical potential energy in volts, and the y-coordinate is the seepage speed in 10⁻³ ms⁻¹). The chart shows that the DC electric field can significantly increase the fluid speed, and the effects are very obvious at 150V electrical potential.

### Table 1

<table>
<thead>
<tr>
<th>Electric potential(V)</th>
<th>Seepage velocity of the point (0.276622 and 0.129849; 10⁻³ ms⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>2.962 859</td>
</tr>
<tr>
<td>1</td>
<td>3.439 585</td>
</tr>
<tr>
<td>3</td>
<td>4.158 801</td>
</tr>
<tr>
<td>5</td>
<td>5.017 988</td>
</tr>
</tbody>
</table>

![Figure 7](image7.png)

Figure 7 Seepage velocity function graph under different electric potentials of the point (0.276622 and 0.129849)

### 3.2 Pressure distribution in the fracture-hole

The electric potential energy is 5 V at 1000 Pa entrance pressure. The pressure distribution (in meters) is shown in Figure 8. The isobar in the fracture-hole model suddenly changes in the basement fracture and basement cave, indicating that the fracture and cave have a strong influence on the isobar.

![Figure 8](image8.png)

Figure 8 Pressure distribution

### 3.3 Electric potential distribution in the fracture-hole

The electric potential is 5 V at 1000 Pa entrance pressure. The electric potential distribution (in meters) is shown in Figure 9. Although no sudden change in equipotential line in the basement-fracture was observed, a sudden change...
in the basement-cave was noticed. This finding indicates that the cave, not the fracture, influences the potential.

3.4 Influence of applied DC electric field on different width-diameter ratio single-phase flow speeds
The width-diameter ratio \( \phi_{vf} \) is the ratio of the diameter in the fracture-hole to the open degree of the fracture.

3.4.1 Parameter of the different width diameter ratio fracture-hole model

Table 2

<table>
<thead>
<tr>
<th>No.</th>
<th>Open degree of fracture(m)</th>
<th>Diameter (m)</th>
<th>( \phi_{vf} )</th>
<th>Length (m)</th>
<th>Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>0.08</td>
<td>8</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.001</td>
<td>0.08</td>
<td>80</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.0004</td>
<td>0.08</td>
<td>200</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The different width-diameter consists of three models. Table 2 shows the basic model parameters.

3.4.2 Influence of the applied DC electric field on single-phase flow speed
Table 3 shows the seepage velocity of the different electric potentials and width diameter ratios in the fracture-cave model. A curve chart of the different width-diameter ratio seepage velocities (0.08 m radius) and electric field strengths is shown in Figure 10. The x-coordinate is the electric potential energy (in volts), and the y-coordinate is the seepage velocity (in 10-3ms-1).

Table 3

<table>
<thead>
<tr>
<th>No.</th>
<th>Open degree of fracture(m)</th>
<th>Diameter (m)</th>
<th>Number of holes</th>
<th>Length (m)</th>
<th>Width (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>0.08</td>
<td>1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>0.08</td>
<td>3</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>0.08</td>
<td>5</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

The seepage velocity in the fracture-hole model increases with an increasing electric field strength (Figure 10). Therefore, the electric field can increase the penetrance of the fracture-cave model. A larger width diameter ratio results in a larger seepage velocity. The significant influence of the electric field on the lower penetrance of the fracture-cave model is observed, and also the effects are very obvious at about 150V electrical potential.

3.5 Influence of the applied DC electric field on the different number of holes single-phase flow speed
Previous studies on the single-hole single-slit model have considered multi-hole single-slit model studies.

3.5.1 Parameter of the different numbers of fracture-holes model
The different numbers of holes have three models. The basic parameters of the model are shown in Table 4.

Table 4

<table>
<thead>
<tr>
<th>No.</th>
<th>Open degree of fracture [m]</th>
<th>Diameter [m]</th>
<th>Number of holes</th>
<th>Lenth [m]</th>
<th>Width [m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.01</td>
<td>0.08</td>
<td>1</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>2</td>
<td>0.01</td>
<td>0.08</td>
<td>3</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>3</td>
<td>0.01</td>
<td>0.08</td>
<td>5</td>
<td>0.5</td>
<td>0.2</td>
</tr>
</tbody>
</table>

3.5.2 Influence of the applied DC electric field on the different number of holes single-phase flow speed
Table 5 shows the seepage velocities of the different electric potentials and the number of holes in the fracture-cave model.

Table 5

<table>
<thead>
<tr>
<th>Electric potential [V]</th>
<th>Number of holes</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>0.00329</td>
<td>0.00395</td>
</tr>
<tr>
<td>0.00315</td>
<td>0.00328</td>
</tr>
<tr>
<td>0.00298</td>
<td>0.00314</td>
</tr>
</tbody>
</table>

The seepage velocity in the fracture-hole model increases with an increasing electric field strength (Figure 11). Therefore, the electric field can increase the penetrance of the fracture-cave model. A greater number of holes results in smaller seepage velocities. A significant influence of the electric field on the lower number of holes in the...
fracture-hole model is observed, and the effects are very obvious at about 150V electrical potential.

![Graph](image1.png)

Figure 11 Relationship curve between seepage velocity in different numbers of holes and electric field strength

4. Application and simulation

4.1 Circuit design of the regulated DC power supply

A significant effect can be observed at 150 V (voltage gradient) according to the simulation results above, so here the DC voltage is assumed to be 150 V, and the power supply is regulated DC 150 V.

A regulated DC power supply is an equipment that converts 220 V alternate current frequency to DC voltage output. The equipment consists of a transformer, rectifier, filter, and regulator to complete the four links.

Figure 12 shows the complete power circuit. LM317 is a floating regulator in series that adjusts its output voltage at 1.2–37 V (continuously adjustable). The limit of the LM317 voltage protection circuit must be added based on hundreds of volts of power supply.

Under normal operating conditions, the voltage difference between the input and output in LM317 ranges from 3 to 40 V. In the minimum voltage difference, the electric potential of F and E is 150 and 153 V, respectively; R3 drops to 5V at 100 mA current flow. Then considering the N2 pipe pressure decrease, the A electric potential is set to 160 V. The transformer rated output voltage is set to UN. The voltage UA, filtered via a capacitor filter, is estimated using the formula $UA = 1.2 \times 0.8 \text{ UN} \geq 160 \text{ V}$ (i.e., UN $\geq$ 166 V). UN was then set to 170 V.

The first limiting voltage circuit level is composed of N1, N2, Z1, R1, R2, and R3. The N1 base voltage-stabilizer circuit is composed of R1 and Z1, causing UBF to stabilize at approximately 6.2 V. The base-emitter voltage between N1 and N2 under normal operating conditions is approximately 0.6–0.7 V, limiting the magnitude of UDF and UEF. Therefore, the voltage difference in LM317 between the input and output can also be limited. This part of the circuit is the series regulator; the UDF is nearly stabilized at 4.8–5.0 V.

The second level of the voltage-stabilizer circuit is composed of LM317, E2, E3, D1, R4, and R5. R5 may be generated via a 10 KΩ resistor and a 5.1 KΩ potentiometer. The potentiometer was adjusted to obtain a 150 V regulated voltage output.

4.2 MULTISIM emulational models of electric circuit

Figure 12 shows the whole power circuit. Figure 13 shows the simulation circuit. They show the results of this simulation.

5. Conclusion

The current study used finite element numerical models to simulate single-phase seepage in different fracture-cave models under the influence of a DC electric field. The main achievements and conclusions are as follows:

1. Mathematical single-phase seepage models under the influence of electric field were established via the fluid...
equation of motion. The method for solving the finite element in mathematical single-phase seepage models on the influence of applied electric field was studied. Then the finite element equation of single-phase seepage under the influence of a DC electric field was deduced.

(2) Fracture-hole speed and pressure distributions were examined under the influence of an electric field. The DC electric field significantly increases fluid speed, and the effects are very obvious at 150V electrical potential.

(3) The whole circuit of the DC electric field was designed for practicability reasons. In addition, the requirements of the DC electric field were met using MULTISIM emulation software.

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References