Time-varying Numerical Simulation Of Reservoir Physical Properties Based On Surface Flux

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Abstract—Most of the domestic oilfields are developed by water flooding. The long-term erosion of injected water will transform the reservoir and change the physical properties of the reservoir. These changes continue to progress slowly, but the cumulative change range cannot be ignored. The reservoir physical property changes will affect the oil-water movement ability, and have a great impact on the oilfield development influence and the distribution of remaining oil in the later period. However, the mainstream commercial numerical simulation software at present fails to fully consider the time-varying phenomenon of reservoir physical property. According to the literature review, the numerical simulation methods considering the time-varying reservoir physical properties have some defects in continuity representation, directional representation and stability of calculation results. To solve this problem, it is necessary to establish a numerical simulation method based on the time-varying reservoir parameters. In this paper, a useful attempt is made to solve this problem, and an Eclipse-based time-varying simulation program is developed. Through the verification of various examples, all functions meet the design requirements and can realize time-varying simulation under different conditions.

1. Introduction
Until now, many scholars have made more cutting-edge research results on the time-varying properties of reservoirs. Jin Zhongkang deduced the relationship between permeability variation multiple and grid node water saturation, so as to achieve the time-varying numerical simulation of reservoir permeability in the process of water flood development equivalently, and realized the time-varying
numerical simulation characterization of reservoir physical property and relative permeability [1]; Xu Qiang started from the practicality and universality of reservoir numerical simulation software. In the calculation process of the existing commercial reservoir numerical simulation software, a processing method to establish a dynamic change model is proposed by considering the relationship between the water ratio and the permeability and the relative permeability[2]; Liu Xiantai and others established a mathematical model of the continuity of all directional permeability and relative permeability curves over time by conducting coring data analysis, laboratory experimental research, traditional black oil model transformation, and compilation of reservoir simulation software. It is suitable for the time-varying numerical simulation technology of physical properties of medium and high permeability sandstone reservoirs [3]. However, they all have limitations, and none of them considers that for a specific reservoir, within a certain range, the difference in water flooding changes, the degree of change in surface flux, and the size of permeability are also different.

According to the characteristics of high argillaceous loose sandstone in E oilfield, the characterization method of reservoir dynamic time-varying is mainly studied, and the theoretical mathematical model and principle of the characterization content are refined. Based on the experimental data, the relationship between the physical property change and the overwater multiple and surface flux is taken as the basis, and the dynamic fitting rate is taken as the standard, the time-varying numerical simulation of physical property is realized by combining Eclipse reservoir numerical simulation software in the form of self-developed plug-in.

2. Time-varying characterization method of reservoir physical properties

Because the mathematical model and numerical simulation do not directly consider the microscopic parameters, the changes of macroscopic parameters such as permeability, porosity and phase permeability curve are commonly used to reflect the time-varying phenomena of reservoir physical properties. Through investigation, it is found that using permeability and phase permeability curve to quantitatively characterize reservoir time-varying phenomenon with surface flux changes is in line with oilfield practice and is a better characterization method at present.

2.1. Surface flux

Area flux is defined as the cumulative volume of the water phase passing through a unit area.

\[ M = \frac{Q}{A} = nL\phi \]  

(1)

In the formula: Q is the cumulative injection volume, m³; A is the cross-sectional area, m²; n is the displacement multiple; L is the length, m; \( \phi \) is the porosity, %.

\[ M = M_x + M_y + M_z \]  

(2)

For a grid in a given three-dimensional space, the fluid flows in three directions in the three-dimensional space, and the total surface flux \( M \) is calculated by the sum of the surface fluxes \( M_x, M_y, M_z \) in each direction.

\[ K = K_0 (a \ln M + b) \]  

(3)

\( M \) is the surface flux, m; \( K_0 \) is the air permeability; a and b are regression coefficients, that is, the coefficient of the curve fitting formula of the relationship between the surface flux and \( K/K_0 \) obtained in the experiment.

2.2. Change law of permeability

Reservoir permeability is the most basic parameter reflecting reservoir performance and percolation conditions. The permeability directly determines the ability of the reservoir to flow. As the surface flux increases, the permeability gradually increases, but the rate of increase decreases. When the surface flux is greater than 6 m³/m², the permeability tends to be stable.
Through the statistical analysis of the core physical property data of reservoir E: The average permeability was increased by 255.39%, the extra low permeability samples with permeability less than $10 \times 10^{-3}$ m$^2$ accounted for 7.7%, the extra high permeability samples with permeability higher than $2000 \times 10^{-3}$ m$^2$ accounted for 3.8%, the extra high permeability samples with permeability ranging from $500 \times 10^{-3}$ m$^2$ to $2000 \times 10^{-3}$ m$^2$ accounted for 11.5%, the low permeability samples with permeability ranging from $50 \times 10^{-3}$ m$^2$ to $500 \times 10^{-3}$ m$^2$ accounted for 50.00%, and the low permeability samples with permeability ranging from $10 \times 10^{-3}$ m$^2$ to $50 \times 10^{-3}$ m$^2$ accounted for 26.9%. Therefore, Reservoir E is a medium-low permeability reservoir.

| Rock sample | Displacement multiple | Irreducible water saturation | K/K$_0$ | Surface flux |
|-------------|-----------------------|-----------------------------|--------|-------------|
| 1           | 0                     | 30.40                       | 0.09   | 0.95        |
|             | 60                    | 69.90                       | 0.07   | 31.54       |
|             | 2000                  | 89.00                       | 0.07   | 27.56       |
| 2           | 0                     | 31.10                       | 0.07   | 0.96        |
|             | 70                    | 69.00                       | 0.07   | 27.56       |
|             | 2000                  | 92.40                       | 0.07   | 27.56       |
| 3           | 0                     | 39.90                       | 0.08   | 0.95        |
|             | 60                    | 68.10                       | 0.06   | 31.51       |
|             | 2000                  | 85.00                       | 0.06   | 31.51       |
| 4           | 0                     | 39.40                       | 0.07   | 0.98        |
|             | 70                    | 71.30                       | 0.07   | 28.03       |
|             | 2000                  | 90.50                       | 0.06   | 28.03       |
| 5           | 0                     | 23.90                       | 0.18   | 0.88        |
|             | 50                    | 48.70                       | 0.17   | 35.28       |
|             | 2000                  | 69.10                       | 0.17   | 35.28       |

2.3. Phase permeability change rule

With the development of water flooding, the pore structure and rock wettability change, which will lead to the change of relative permeability curve at different water-bearing stages. The oil-water relative permeability curve of rocks after long-term water flooding is significantly different from that before water flooding. The overall performance is that with the improvement of water washing degree, the hydrophilicity of reservoir rock samples increases, and the pore structure characteristics become better.

A large number of oil-water relative permeability curves were measured by selecting cores at different water-bearing stages. The experimental results show that the oil-water relative permeability curve shows obvious regular changes. With the increase of water content, the co-permeability point of the oil-water relative permeability curve moves to the right, the hydrophilicity is enhanced, the oil-water co-permeability range is increased, and the oil displacement efficiency is improved to some extent.

Water injection displacement multiple will lead to oil and water relative permeability changes. As the surface flux increases, the bound water saturation increases, the residual oil saturation decreases, and the water-phase permeability corresponding to the residual oil saturation decreases [4].

After a long period of water injection scouring action, the reservoir physical properties will change, generally permeability will increase with water flooding. For a specific reservoir, within a certain range, the magnitude of permeability may vary with surface flux, but when the permeability is lower than a certain value, the opposite may occur and the permeability may decline. However, from the beginning of reservoir input and development, the reservoir physical parameters are regarded as fixed values, which results in a certain discrepancy between the simulation results and the actual situation.
3. Software Implementation

3.1. The process of software program invocation
Based on the time-varying mathematical model of reservoir physical parameters, and mainstream commercial digital simulation software, the time-varying physical properties calculation module is added to develop a time-varying reservoir numerical simulation plug-in. Figure 1 below are the plug-in calling process.

![Program call flow chart](image)

3.2. Program call method
Equation (3), on the basis of using the method of mathematical regression formula to calculate the fitting, reflects the relative permeability with the relation between the surface flux change, which is equal to y represents the \(K/K_0\), x represents the \(\ln M\).

Based on the time-varying mathematical method of reservoir physical property parameters, a numerical simulator plug-in with independent intellectual property rights was developed. The plug-in utilizes the relevant mathematical formula of surface flux, adopts the mathematical regression method, and the module content of the physical property parameter change with time added to the simulator, and can effectively describe the time-varying law of the physical property of the reservoir.

| Rock sample | Mobility | regression coefficients a | regression coefficients b | Fitting formula |
|-------------|----------|---------------------------|---------------------------|----------------|
| 1           | 13.2     | -0.0007                   | 0.0918                    | \(y=-0.0007x+0.0918\) |
| 2           | 17.7     | -0.0002                   | 0.0721                    | \(y=-0.0002x+0.0721\) |
| 3           | 8.4      | -0.0004                   | 0.0758                    | \(y=-0.0004x+0.0758\) |
| 4           | 10.17    | -0.0004                   | 0.0749                    | \(y=-0.0004x+0.0749\) |
| 5           | 5.21     | -0.0004                   | 0.1798                    | \(y=-0.0004x+0.1798\) |

4. Example verification
To verify the accuracy and stability of the simulator, a fan-shaped model was cut out from the geological model of E oil field (as shown in Figure 2) to compare the permeability changes before and after the time-varying model. Here were 176 grids in the X direction, 138 grids in the Y direction, and 5 grids in the Z direction. The plane grid step is 25m and the longitudinal grid step is 4m.
Considering time-varying and doesn't consider time-varying of reservoir permeability distribution as shown in Figure.2 and Figure.3, simulation through plug-ins to time-varying correction of reservoir property, physical parameters time-varying, after considering the mainstream line near the production well regional permeability value, this is because the long-term injection water scour make the mainstream line area property is good, the permeability field shows well around the updated permeability distribution is more smaller and more uniform and concentrated, maximum permeability increased more than 200%, and the actual geological data after contrast, proof of permeability in the reservoir physical property and time-varying simulation closer to actual formation property after correction.

5. conclusion
1. In the process of oilfield water flooding development, long-term water flooding changes the physical properties of the reservoir, which affects the oilfield development influence and remaining oil distribution. A time-varying simulation program based on ECLIPSE was developed to establish a numerical simulation based on changes in reservoir parameters over time method.

2. The problem that the reservoir physical property time-varying phenomenon cannot be accurately simulated is solved. The time-varying correction of the reservoir physical property is carried out through the plug-in simulation, and the permeability distribution around the well is more refined. After the strength verification, it is proved that the permeability is closer to the actual formation physical property after the correction of the reservoir physical property time-varying simulation.

3. Generally, the permeability will continue to increase with the progress of water flooding. For a specific reservoir, within a certain range, the permeability and the degree of change with the surface flux may be different, but the permeability may be lower than a certain value, and the opposite situation may occur, and the permeability will decrease.
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