Research on the Hydrodynamics of the Mechanism of Viscous-Elastic Fluids Displacing Residual Oil Droplets in Micro Pores

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Abstract. In order to analyze the microscopic stress field acting on residual oil droplets in micro pores, calculate its deformation, and explore the hydrodynamic mechanism of viscous-elastic fluids displacing oil droplets, the viscous-elastic fluid flow equations in micro pores are established by choosing the Upper Convected Maxwell constitutive equation; the numerical solutions of the flow field are obtained by volume control and Alternate Direction Implicit methods. From the above, the velocity field and microscopic stress field; the forces acting on residual oil droplets; the deformations of residual oil droplets by various viscous-elastic displacing fluids and at various Wiesenberg numbers are calculated and analyzed. The result demonstrated that both the normal stress and horizontal force acting on the residual oil droplets by viscous-elastic fluids are much larger compared to that of inelastic fluid; the distribution of normal stress changes abruptly; under the condition of the same pressure gradient in the system under investigation, the ratio of the horizontal forces acting on the residual oil droplets by different displacing fluids (which are water, a power-law fluid with a power law index of 0.6 and a viscous-elastic fluid with a Wiesenberg Number of 0.3 respectively) is about 1:8:20, which means that under the above conditions, the driving force on a oil droplet is 20 times higher for a viscous-elastic fluid compared to that of a Newtonian Fluid. This force must be considered when studying the mechanism of isolated oil droplets mobilization. Furthermore, the viscous-elastic fluids will cause the residual oil droplet to deform much more significantly, beneficial to the mobilization of residual oil droplets. The above results are very beneficial to understanding the mechanism of the mobilization of residual oil droplets by viscous-elastic fluids; the conclusions are supportive of the mechanism that viscous-elastic driving fluids can increase the Displacement Efficiency. This should be of help in designing new chemicals and selecting Enhanced Oil Recovery systems.

1. Introduction

The practice of Daqing Oilfield shows that using viscoelastic polymer solution after water flooding can further enhance the oil recovery, especially high-concentration polymer solution. In order to explore the displacement mechanism of the elasticity of polymer acting on the residual oil, scholars like Demin Wang [1], Chunze Liu [2], Huifen Xia [3], Hongjun Yin [4], Huh Chun [5], Lijuan Zhang [6] have separately analyzed influence on microscopic displacement about elasticity of polymer solution from different angles, and elaborated the creative cognition that viscoelastic fluid can enhance the microscopic displacement efficiency. In this paper, viscoelastic fluid flow equation in the micro pore is established by choosing upper convected Maxwell [7] constitutive equation, the velocity field and stress field are got by means of numerical calculation, and then the driving force of different fluids acting on the residual oil droplet in the micro pore is analyzed and compared, and the hydrodynamics mechanism of viscoelastic driving fluid acting on the residual oil droplet has been revealed further by analyzing the
influence factors of force and deformation.

2. Flow Equation

Figure 1 is a micrograph, which is the residual oil droplet in the two-dimension micro pore displaced by the polymer solution with viscoelasticity. The conventional and simple constitutive equations have not been used to describe its complicated rheological properties due to the viscoelastic property of polymer solution. Many years’ practice indicated that the upper convected Maxwell constitutive equation is suitable to describe the viscoelastic property of polymer solution. In the paper, momentum equation, continuity equation and constitutive equation are used as follows:

Continuity equation:
\[ \nabla \cdot \mathbf{u} = 0 \quad (1) \]
Where: \( \mathbf{u} \) is velocity vector.

Momentum equation:
\[ \frac{d\mathbf{u}}{dt} = \mathbf{F} + \frac{1}{\rho} \text{div}\mathbf{P} \quad (2) \]
Where: \( \mathbf{F} \) is mass force; \( \rho \) is density; \( \mathbf{P} \) is stress tensor.

\[ p = -\mathbf{P} \cdot \mathbf{I} + \mathbf{T} \quad (3) \]
Where: \( \mathbf{I} \) is unit tensor; \( -p \) is static pressure; \( \mathbf{T} \) is deviatoric stress tensor.

Constitutive equation:
\[ \mathbf{T} + \lambda \frac{\partial \mathbf{T}}{\partial t} = \eta \mathbf{A}_1 \quad (4) \]
Where: \( \lambda \) is relaxation time, which is the characterization of fluid elasticity; \( \eta \) is shearing viscosity; \( \mathbf{A}_1 \) is one order Rivlin-Ericksen tensor.

Fig.1. Micrograph of residual oil droplet.

3. Numerical Method of Flow Equation

Figure 2 shows the physical model of driving fluid flow in the micro pore, which is obtained by simplifying the microcosmic flow field (Fig.1). The nonlinear differential equations are composed by Equations (1~4), however, it is impossible to solve by analytic method, the reasons are as follows: first, there are driving fluid and residual oil droplet in the flow field; second, boundary conditions are extremely complicated, therefore, it is necessary to use the numerical calculation to solve.
Numerical method is mainly to solve flow equation, which has been developed with the computer known in the past century middle period. In the first place, flow field is discreted to many computing units according to certain regulation (Fig.3); The second place, flow equation is changed into algebraic equation concerning flow parameter of every node, i.e. discretization equation, in this paper, the control volume method [8] which was given by Patankar is applied to discreted the flow equation; at last, ADI method is used to solve discretization equation for getting the velocity distribution of flow field (Fig.4).

4. Analysis of the Force and Deformation Computation of Residual Oil Droplet
Constitutive equation is used to calculate the stress distribution of flow field after working out the velocity distribution. The stress $p_n$, which is pointed on the any curved surface in the flow field, is got by following equation:

$$ p_n = n \cdot \mathbf{P} $$  \hspace{1cm} (5)

Where: $\mathbf{p}_n$ is stress vector on the force face using $n$ as outward normal direction (Fig.5). Figure 6 shows stress of two points on the frontal portion and the opposite direction of residual oil droplet along the flow direction, in the figure 6, $p_{nt}$ is tangential stress; $p_{nm}$ is normal stress; $p_{nv}$ is vertical stress and $p_{nh}$ is horizontal stress.
In order to analyze the force on the residual oil droplet from fluid having various rheological properties, stress field is calculated when fluid flows the residual oil droplet under the different conditions as follows, micro pore is 6μm, pressure gradient is 0.02MPa/m; viscosity of Newtonian fluid (water) is 1mPa·s; viscosity of power-law fluid is 30mPa·s and liquidity index is 0.6; viscosity of viscoelastic fluid is 30mPa·s, in addition, according to the two decomposition ways from Figure 5 and Equation 5, tangential stress \( \tau_n \), normal deviatoric stress \( \tau_{nn} \), differential between horizontal deviatoric stress \( \tau_{nh} \) and horizontal stress \( p_{nh} \) on the residual oil droplet surface are calculated respectively (Fig.7), in which pressure is positive and tension is negative. However, water is pure viscous fluid, the elasticity is almost 0 and power-law fluid has only lower elasticity, but polymer solution has larger elasticity. Therefore, Wiesenberger number \( We \) is used to show the effect of elasticity of fluid in the flow process. The expression of Wiesenberger number is as follows:

\[
We = \frac{\lambda u}{D}
\]

Where \( u \) is characteristic velocity; \( D \) is characteristic length of micro pore, here the width is taken.

As shown in Figure 7, when water is used as driving fluid, normal stress is so low, moreover, the value of which is antisymmetric, in other words, the front half of residual oil droplet are all pressurized and the latter half are all in tension; when power-law fluid is used as driving fluid, the characteristic is the same as above; however, when polymer solution is used as driving fluid, normal stress is larger than inelasticity, and the distribution of normal stress has the abrupt change, the normal stress of the front half of residual oil droplet surface is obviously larger than the latter part. Thus, the viscoelasticity of polymer solution can make force (especially normal stress) of residual oil larger obviously. In order to describe the force on the residual oil droplet from various fluids more vividly, composition of stress vector diagram concerning viscoelastic fluids acting on the residual oil droplet is given in Fig.8.
Fig. 7. Normal deviatoric stress $\tau_{nn}$ on the oil droplet surface when $We=0.3$.

Fig. 8. Stress $p_n$ vector diagram of the oil droplet when $We=0.3$.

The results of microcosmic visual flooding \cite{1} and theoretical research \cite{4} all show that viscoelastic polymer solution has larger horizontal force on residual oil droplet, stress differential, which is produced by the asymmetry of normal stress on residual oil droplet surface, is the main reason for residual oil droplet deformation. Therefore, it is necessary to further analyze the value of horizontal force when using different fluids, i.e. horizontal stress differential, when pressure gradient is 0.02 and 0.005MPa/m respectively, horizontal stress differential is shown in Fig. 9 and Fig. 10. The results show that the ratio of horizontal stress differential among water, power-law fluid and visco-elastic polymer ($We=0.3$) is about 1:8:20, in other words, the driving force of polymer flooding is approximately 20 times than that of water flooding under the condition of the same pressure gradient.

Fig. 9. Horizontal stress differential when pressure gradient is 0.02MPa/m.

Fig. 10. Horizontal stress differential when pressure gradient is 0.005MPa/m.
Laplace equation can be used to calculate deformation of residual oil droplet after analyzing the force. Under the same condition, calculations of residual oil droplet deformation on the oil wet and water wet rock surface are shown in Fig.11. It can be seen from the diagram that the deformation of residual oil droplet will be larger with the elasticity of driving fluid enhanced. If the distance from injection well is different, pressure gradient of every point is also different in practical oilfields.

For this reason we also give the results that residual oil droplet deformation on the oil wet rock surface according to different pressure gradient (Fig.12), it is seen that the elastic driving fluid can make residual oil droplet deformation larger obviously than that of water flooding on the area where a little far from injection well. Shape of actual flow channel is so complicated in the oil reservoir, thus the residual oil droplet deformation displaced by different elastic fluids in the complicated water wet micro pore is calculated, the calculations of residual oil droplet deformation under the different elasticity are given as shown in Fig.12., the results show that the displacement effect of elastic driving fluid is evidently better than that of inelastic driving fluid.

Fig.11. Residual oil droplet deformation with different elastic fluids displacement on water wet and oil wet rock surface.

Fig.12. Residual oil droplet deformation comparison diagram on oil wet rock surface under different pressure gradient.
5. Conclusions
Based on the above analysis and calculation, some conclusions can be got as follows:

(1) Compared with inelastic driving fluid, normal stress of elastic driving fluid acting on the residual oil droplet is larger and the distribution of stress also has abrupt change. The stronger elasticity of driving fluid is, the larger horizontal driving force on residual oil droplet is.

(2) Under this calculation of this paper, the ratio of horizontal driving force on residual oil droplet among water, power-law fluid and viscoelastic polymer is about 1:8:20, in other words, driving force on the residual droplet of polymer flooding is approximately 20 times more than that of water flooding under the condition of the same pressure gradient.

(3) Deformation of residual oil droplet is more obvious using elastic driving fluid, the displacement effect will be better.

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