Numerical Simulation of Turbulent Flow for non-Newtonian Fluid in two kinds Complex Annulus Channel

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Abstract. During the polymer flooding multi-layered injection process, it is difficult to achieve large pressure drop and small viscosity loss at the same time in the injection allocators. To address this issue, two kinds of flow channel structures are designed. They are ring groove structure and spindle groove structure. CFD software FLUENT is used to simulate the flow characteristics of non-Newton fluid flowing in the above structures, which are complex annular channels. By comparing the pressure drop, velocity contours and turbulent kinetic energy, the spindle groove structure is preferred. It has large throttle depressurization and big solution viscosity retention rate within a limited length. The influence from different flow channels structure on pressure drop is limited, but the impact on viscosity loss is great.

1. Introduction

With the rapid development of the world industry and the growth of population, the demand and consumption of crude oil are also increasing year by year. Therefore, continuous exploration and discovery new oil fields and the use of new technologies to improve the recovery for old oil fields are the main work in today's oil field [1]. Many large oil fields in the world have entered the late stage of high water cut, and mining is getting harder every year. Polymer flooding is one of the main technologies to maintain the sustainable development of oil fields [2,3]. Through years of research and field trials, polymer flooding technology has made breakthroughs and entered large-scale industrial applications [4,5].

As for the design of allocator flow channel, if a variety of flow channel structures are manufactured and tested in the laboratory, it will consume both material and time, and many of flow characteristics from the laboratory test cannot be obtained. But it is possible to get much of flow characteristics by using numerical simulation which is economical and time saving [6]. The study presented here is focused on the non-Newtonian fluid turbulent flow in different complex annular flow channel structures and determine the most suitable structure that has enough pressure drop and lowest viscosity loss. The CFD software FLUENT was used in the simulation to study all the flow field characteristics in the flow channel structures.
2. Computational model

2.1. Governing equations
In this study, the flow field in the control unit is steady and isothermal turbulent flow. The corresponding governing equations are continuity equation, momentum equation and energy equation. For the turbulence simulation, the Reynolds-Averaged Navier–Stockes (RANS) method is usually used in engineering calculations currently. According to flow field characteristics, standard $k-\varepsilon$ model, which is widely used in engineering, is adopted in this paper [7, 8]. The $k-\varepsilon$ model is by far the most widely used and tested two-equation model, with many improvements incorporated over the years [9, 10]. This model is a semi-empirical model of two equations of the turbulent kinetic energy $k$ and the diffusion rate $\varepsilon$.

2.2. Computational domain and meshing
According to the labyrinth sealing principle and field situation, two kinds of throttling structures are designed. They are ring groove structure and spindle groove structure. Their schematic diagrams are shown in Figure 1 and Figure 2. The two flow channel structures are all 400 mm long. In each structure, each slot pitch unit has a length of 12 mm and a total of 30 slot pitches. To eliminate port effect, the channel inlet and outlet are 20 mm long respectively and to meet sufficient pressure drop, the annulus spacing is 1 mm.

![Figure 1. Ring groove schematic diagram.](image1)

![Figure 2. Spindle groove schematic diagram.](image2)

2.3. Physical properties of fluid and flow boundary conditions
The simulated fluid is incompressible non-Newtonian power-law fluid with large viscosity. According to the rheological properties of polymer solutions measured in oilfield sites, the consistency coefficient $K=0.335$ Pa•sn; flow behavior index $n=0.223$, dimensionless; and the solution density is set to 1020 kg/m$^3$.

The flow channel two-dimensional model adopts the velocity inlet and pressure outlet boundary conditions. According to the oil field operation, the inlet velocity values are set to 0.48 m/s, 2.87 m/s and 5.74 m/s, respectively (the corresponding injection rate are 100 m$^3$/d, 60 m$^3$/d, and 120 m$^3$/d, respectively). For near-wall treatment, there is no slip on the wall and the standard wall functions method is adopted. The flow is turbulent and SIMPLEC algorithm is selected to solve the pressure-velocity coupled field.

3. Simulation results and analysis
At different injection flow rate, the numerical simulation of the two designed flow channel structures was carried out, and the results of throttling pressure drop, velocity contours and turbulent kinetic energy were analyzed and compared. Based on them, the optimal flow channel structure was selected.

3.1. Pressure drop comparison
Figure 3 and Figure 4 shows the pressure reduction of different flow channel structures at the flow rate of 60 m$^3$/d. It can be found from the pressure drop curve that the pressure changes periodically with the periodic variation of the flow channel structure; the pressure decreases at the contraction of flow channel
in each cycle and gradually increases at the expansion place. Among the two kinds of throttling channel structures, the pressure drop in ring groove structure is larger.

Figure 3. Pressure drop in ring groove structure.  Figure 4. Pressure drop in spindle groove structure.

3.2. Pressure and velocity contours comparison
The contours of static pressure in the two throttling structures are shown in Figure 5 and Figure 6. It can be seen that the pressure gradually decreases from the inlet to the outlet. Each time a slot is passed, the pressure decreases accordingly.

Figure 5. Contours of static pressure in ring groove structure.

Figure 6. Contours of static pressure in spindle groove structure.

Figure 7 and Figure 8 are velocity contour plots for each flow channel structure that reflect the velocity distribution and variation. From velocity contours it can be found that eddy current is generated at the channel expansion, and the velocity gradient at the abrupt change of flow channel area is large. In the spindle groove structure, the velocity gradient is relatively uniform and the flow is relatively smooth.

Figure 7. Velocity contours in ring groove.  Figure 8. Velocity contours in spindle groove.

3.3. Turbulent kinetic energy comparison
The turbulent kinetic energy reflects violent state of flow. When it is big, the fluid flow changes complexly and violently, resulting in a great pressure loss and a big viscosity loss. Figure 9 and Figure 10 shows the contours of turbulent kinetic energy in each channel structure. It can be seen from the figure that the turbulent energy is large at the sharp corners, which adversely affects the retention of the solution viscosity [11,12]. In order to avoid high shearing action of the sharp corners on the fluid, the flow channels should be connected by arcs. Comparing each figure, the spindle groove structure has the least turbulent kinetic energy.
4. Conclusion
The flow field simulation of two kinds of throttling structures, ring groove and spindle groove were carried out. By comparison of pressure, velocity and turbulent kinetic energy in each flow channel structure, the spindle groove structure is preferred. Within a limited length, it can produce large depressurization and has high solution viscosity retention rate.

Different flow channel structures have limited influence on pressure drop, but have great impact on viscosity loss. The shear on fluid is serious where the area of flow channel changes sharply, resulting in great viscosity loss. For the preferred spindle groove structure, the structural optimization is also required, and arc-shaped connection should be adopted.

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