Academic Journal of Science and Technology
ISSN: 2771-3032 | Vol. 8, No. 1, 2023

Design and Structural Optimization of Electrically Controlled Throttle Valve Core for Stratified Injection

Zizhao Zhang, Haifeng Ma

Southwest Petroleum University, School of Mechanical and Electrical Engineering Chengdu 610500, China

Abstract: In order to solve the problems of poor regulation of throttling pressure drop and excessive viscous friction in electrically controlled throttle valves in stratified injection, a new valve core structure that can efficiently regulate pressure drop and reduce viscous friction is designed. An effective valve core simulation model is established, and the model is divided into grids for fluid dynamics simulation. The pressure drop and shear rate of three commonly used valve and throttle structures are compared comprehensively based on the simulation results. The optimal circular arc flow channel structure is selected, and the influence of the length of the circular arc structure on the shear rate is simulated. Compared with 20mm, 25mm and 30mm, the best effect was obtained when the valve joint length is 30mm.The experimental results show that the average viscosity of the optimized valve core is less than 11%, which reduces the viscosity loss.which provided theoretical support for the optimization of layered injection tool.

Keywords: Stratified injection; Valve core structure optimization; Loss of viscosity; Numerical simulation.

1. Introduction

In China, there are many difficult-to-exploit heavy crude oil or complex reservoir conditions. Traditional water flooding methods cannot meet the current oil extraction environment. Tertiary oil recovery techniques have gradually become an important part of China's petroleum technology revolution. Layered injection of polymer for oil displacement is an important method in tertiary oil recovery. However, during the extraction process, due to the variability of the polymer flow path structure, the polymer is subjected to significant shear forces, leading to mechanical shear degradation and irreversible viscosity loss. This weakens the oil displacement and oil recovery effectiveness. The viscosity loss of the polymer, especially the viscosity loss caused by mechanical shear, is one of the key problems that prevent current oil extraction from achieving the expected goals [1-3].

The electrically controlled layered injection barrel is an improved injector that can continuously adjust the injection flow rate based on the original layered injection barrel. The injection barrel adjusts the flow rate by changing the number of valve sections. However, an excessive number of valve sections will result in excessively long valve section lengths, which affects the design of downhole tools. Additionally, an unreasonable valve section structure can lead to significant viscosity loss. Therefore, this paper uses fluid dynamics simulations to analyze the shear rates of three common valve core structures and subsequently analyze the viscosity losses caused by these three different valve core structures. The influence of valve section length on shear rates is also analyzed to improve the valve core structure. Ultimately, a valve core structure that can change the flow channel opening is designed, aiming to improve the structure of the existing electrically controlled layered injection barrel and effectively reduce viscosity losses during the injection process [4-5].

2. Principle and Technology of Flow Control Mechanism in Electrically Controlled Layered Injection Barrel.

The working principle of the electrically controlled layered injection barrel is shown in Figure 1. The injection barrel has a central tube, and the electrical system and executive components are located in the annular area outside the central tube. The most important parts are the regulating mechanism and the driving system. The polymer flows from the central tube into the valve core of the regulating mechanism, and the valve core is axially moved by the driving system to change the number of valve core stages, thereby achieving pressure and flow regulation between different layers.

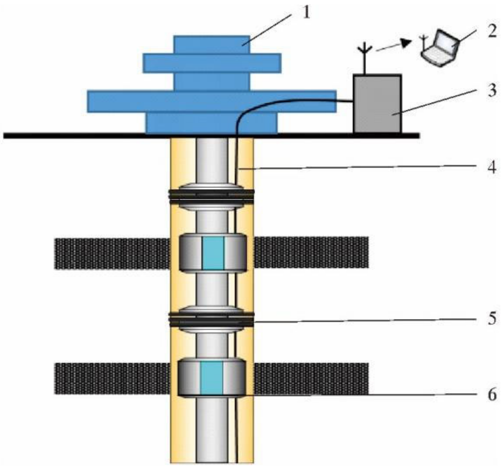


Figure 1. Diagram of the working principle of the electronically controlled eccentric injector

The throttling valve core in the regulating mechanism serves as a key component for controlling flow. This valve core structure typically consists of a periodically varying diameter valve stem, which utilizes the Venturi effect to accelerate fluid flow through the sudden contraction interface, thereby achieving pressure reduction. The driving system employs a high-torque driving motor to actuate the axial displacement of the valve core by driving the lead screw nut within the regulating mechanism, thereby adjusting the number of valve core stages to alter pressure drops and achieve flow regulation [6-8].

Due to the positioning of the flow control mechanism within the eccentric channel of the layered injection barrel, the eccentric channel is relatively narrow. Therefore, a lead screw nut mechanism is chosen to implement the flow control mechanism. To enable the vertical movement of the valve core, a lead screw nut structure is utilized at the driving end, which is actuated by the motor and reducer, driving the lead screw nut to facilitate the upward and downward movement of the valve core. By controlling the vertical position of the valve core to adjust its opening degree, the injection flow can be precisely regulated to meet the flow requirements under different conditions. The schematic diagram of the system transmission is shown in Figure 2.

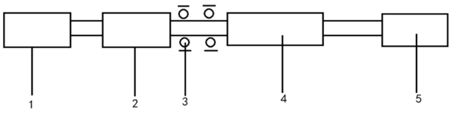


Figure 2. Schematic diagram of system transmission

2.1. The improvement of the valve core regulation scheme

In this structure, the pressure drop across a single-stage valve core is fixed, and achieving the predetermined flow control target requires adjusting the number of valve cores in the circuit. When regulating lower flow rates, a greater number of valve cores are needed in the circuit, resulting in longer valve cores. However, the limited space for tool placement underground makes longer valve cores unfavorable for tool arrangement. Therefore, an optimization design of the valve core in the traditional flow control mechanism aims to effectively regulate flow while reducing the length of the valve core [9-10].

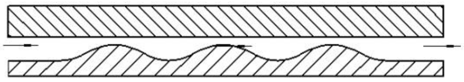


Figure 3. Traditional spool construction

A new type of valve core structure has been designed as shown in Figure 4. The newly designed valve core structure is illustrated in the diagram below, where the pressure drop across a single-stage valve core varies with the axial displacement of the valve core, thereby achieving the function of dynamically adjusting the flow rate. Compared to traditional valve cores, this valve core design alters the axial displacement distance of the valve core during the flow regulation process, enabling the adjustment of the flow passage from minimum to maximum opening within a single stroke.

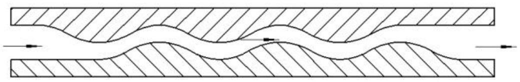


Figure 4. Optimized spool structure

3. Research and Numerical Analysis of Flow Control Valve Body Flow Channel Structure Scheme

In order to achieve reasonable pressure drop regulation and reduce viscosity loss during polymer flow, a structure with gradual cross-sectional changes should be adopted. To obtain the most suitable flow channel structure, three different shapes of flow channel structures with similar diameters and lengths were designed in this study: annular, parabolic, and shuttle-shaped. The geometric models of each shape at 100% opening are shown in the figure below. Numerical calculations and analysis are conducted for each model to select the optimal flow channel structure.

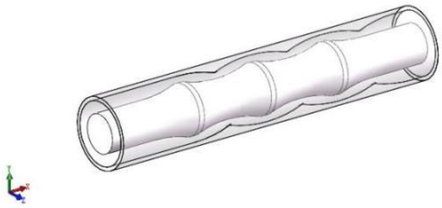


Figure 5. Circular arc runner

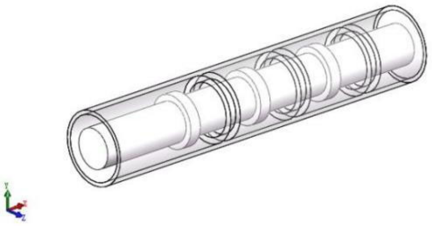


Figure 6. Rectangular runner

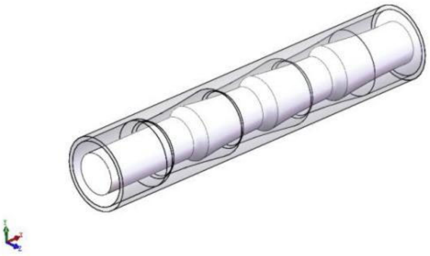


Figure 7. Spindle-shaped runners

3.1. Establishment of rheological model.

During the analysis of fluid characteristics, computational fluid dynamics (CFD) methods are used, which are based on the fundamental governing equations of fluid mechanics for modeling and research purposes. These fundamental governing equations include the continuity equation, momentum equation, and energy equation [11-12].

(1) Fundamental governing equations In this numerical analysis, the thermodynamic processes are not considered, so the energy equation is not included in the fundamental governing equations. It is assumed that the physical quantities in the flow channel of the flow control valve do not vary with time, representing steady, incompressible flow. The influence of gravity is neglected, and the following fundamental governing equation is established.

Continuity equation.

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

Momentum equation.

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

Turbulence Model Considering the small overall size of the pressure reduction tool and the occurrence of throttling effects during liquid flow, as well as the significant turbulence dissipation effects, it is crucial to select an appropriate turbulence model for accurate simulation results. Based on extensive literature research and accumulated experience, the RNG k-ε model has been chosen for simulation [14].

(3) Carreau-Yasuda Model The polymer used in the injection well is a non-Newtonian fluid, where the viscosity of the fluid varies with shear rate. Therefore, the Carreau-Yasuda model is adopted to represent the viscosity variation of the model.

$$\mu = \mu_\infty + \frac{\mu_0 - \mu_\infty}{[1 + (\lambda \dot{\gamma})^\alpha]^{\frac{1-n}{\alpha}}} \tag{3}$$

The equation includes:

μ_0 ——Low shear viscosity, $\text{Pa} \cdot \text{s}$;

μ_∞ ——High shear viscosity, $\text{Pa} \cdot \text{s}$;

λ ——Time constant;

$\dot{\gamma}$ ——Strain Rate, s^{-1};

n ——Power-law exponents;

α ——Yasuda Index.

Table 1. Rheological property parameters of the simulated fluid

Power-law exponents n	Yasuda Index α	Low shear viscosity μ_0	High shear viscosity μ_∞	Time constant λ
0.36	2	0.3 $\text{Pa} \cdot \text{s}$	0.003 $\text{Pa} \cdot \text{s}$	1

3.2. Establishment of flow channel model.

This article uses the FLUENT software for computational fluid dynamics (CFD) simulation analysis. In order to emphasize the reflection of the geometric shape of the flow channel on the flow field, this article focuses on modeling and analyzing the flow channel of the control valve. The flow channel is a centrally symmetrical structure, so the flow channel model is simplified to a two-dimensional model, and a cross-section of one side is taken for analysis. The two-dimensional model depicted in the figure.

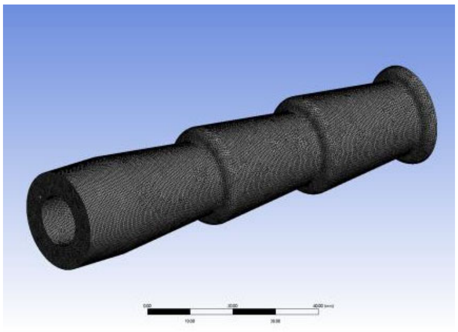


Figure 8. Shuttle runner grid diagram

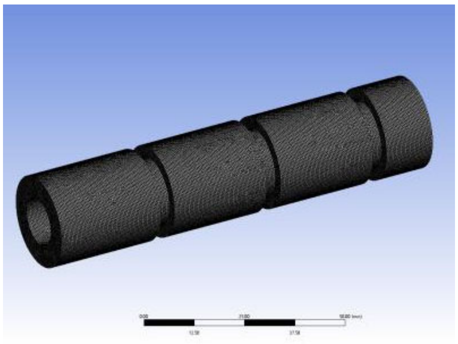


Figure 9. Rectangular runner grid diagram

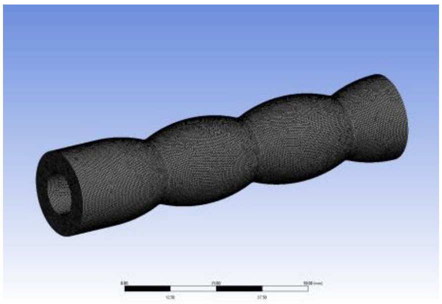


Figure 10. Circular arc channel grid diagram

3.3. Numerical calculation and analysis of flow control valve body flow channel

Boundary conditions setting: Outlet condition: The outlet is selected as a pressure outlet with a pressure of 0 MPa; hydraulic diameter is 27 mm, and turbulence intensity is set to 5%. Inlet condition: The inlet is selected as a mass inlet with flow rates of 5 m3/h, 10 m3/h, and 15 m3/h.

Numerical simulations are conducted for the three different structures of the control valve flow channel with varying inlet flow rates. The simulation results are shown below.

3.3.1. The shear-induced viscosity loss mechanism and shear rate distribution law of the flow channel of the regulating valve

The significant shear effect during the formulation, injection, and displacement processes is the main cause of polymer viscosity loss. Lower shear can reduce the breakage of polymer chains, thus minimizing viscosity loss resulting from mechanical degradation. Therefore, analyzing the shear strain rate in the flow channel of the control valve can assess the viscosity loss of the polymer within the channel and optimize the flow channel accordingly.

Figure 11 shows the shear rate contour maps at 100% valve opening for the flow channels of different structures of the control valve under an inlet flow rate of 5 m3/h. It can be observed that the strain rates near the wall surface of the channels are higher than those at the center of the channels.

This is because the velocity gradient near the wall surface increases, leading to higher shear rates. On the other hand, the velocity variation at the center of the channels is smaller, resulting in lower velocity gradient and lower shear rates.

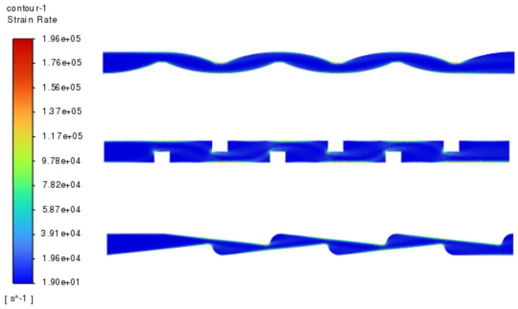


Figure 11. Shear rate cloud plot comparison chart

Figure 12 compares the average shear strain rates of the flow channels of different structures of the control valve at various inlet flow rates. The average shear strain rate of the arc-shaped channel is consistently lower than the other two types of channels at different openings. To minimize significant viscosity loss, it is desirable to keep the shear rate low within the channel. The arc-shaped channel exhibits overall lower shear rates, suggesting that from the perspective of viscosity loss, the arc-shaped channel should be chosen for the flow channel design.

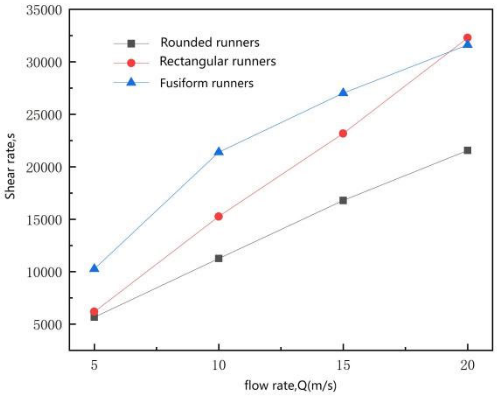


Figure 12. Different flow channel shear rates and opening change curves

Comparing the shear rates at different openings for the three valve core structures, the priority should be given to the valve core with lower shear rates in the flow channel to reduce viscosity loss. Therefore, after comparing the three structures, the arc-shaped flow channel is chosen as the preferred flow channel structure for the valve core.

3.4. Arc-shaped flow channel, flow channel pressure distribution and pressure drop law

Taking the arc-shaped flow channel as the research goal, the flow channel is numerically simulated to explore the pressure distribution and pressure drop law.

3.4.1. Numerical calculation, analysis and optimization of structural parameters of arc-shaped runners

Shear rate is an important parameter for the flow channel and directly affects its viscosity retention effect. Therefore, using shear rate as the target parameter, numerical simulation analysis of the flow channel is conducted to investigate the factors influencing the shear rate.

The length (L) of the flow channel is a critical model parameter. Under constant boundary conditions, fluid parameters, and solution models, the influence of varying the flow channel length (L) on the shear rate is analyzed.

As shown in Figure 16, numerical simulations are performed for flow channel lengths of 20mm, 25mm, and 30mm while maintaining constant boundary conditions, fluid parameters, and solution models. The shear rates under different parameters are obtained. It can be observed from the figure that the shear rate decreases with increasing flow channel opening. A smaller flow channel opening corresponds to a higher average shear rate, making the fluid viscosity more prone to loss. When comparing the flow channel lengths of 20mm, 25mm, and 30mm at different flow channel openings, it is evident that the shear rate of the L=20mm flow channel is consistently greater than that of L=25mm and L=30mm. Particularly, at a flow channel opening of 25%, the shear rate of the L=20mm flow channel reaches 13500S-1, whereas the shear rates of the L=25mm and L=30mm flow channels are approximately 11500S-1 and 10500S-1, respectively.

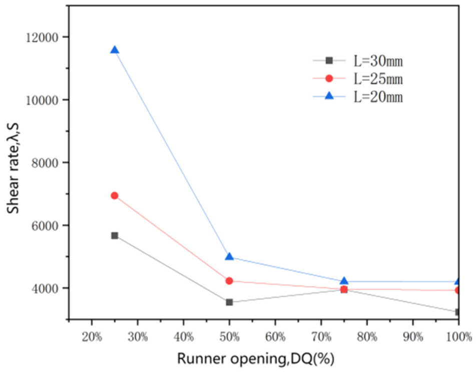
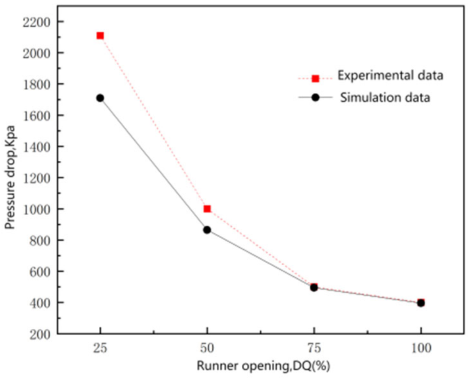


Figure 13. Comparison chart of shear rate and opening degree for different valve section lengths

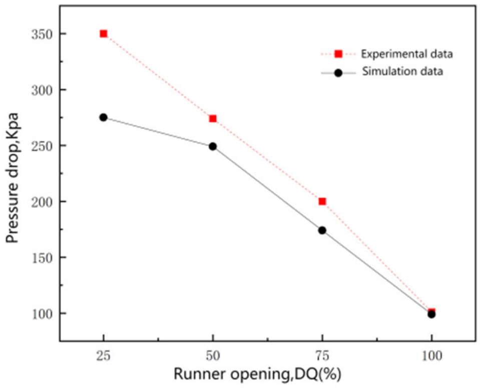
Therefore, it is advisable to select the flow channel with a longer valve core length. In this case, the flow channel length L=30mm is chosen to achieve the desired reduction in viscosity loss.

4. Verified by Laboratory Experiments

The figure shown in Figure 14 is a comparison between simulated and experimental data for pressure drop at different inlet flow rates. From the figure, it can be observed that under three different inlet flow rates, the experimental data closely matches the simulated data when the flow channel opening is large. However, when the flow channel opening is small, the simulated data is slightly higher than the experimental data. This is because at higher flow velocities in the flow channel, significant shear effects lead to a decrease in fluid viscosity and subsequently a reduction in pressure drop.



a The flow rate is5m3/h



c The flow rate is15m3/h

Figure 14. Comparison of pressure drop simulation data and experimental data under different inlet flow

Based on the optimized structure, a working sample of the throttling valve core was manufactured. Laboratory experiments were conducted to study the hydraulic characteristics using water as the fluid. The results of the experiments, showing the polymer viscosity loss at different flow rates, are depicted in Figure 15. It can be observed that when the flow rate is less than 10m3/h, the viscosity loss is below 4%. At a flow rate of 15m3/h, the viscosity loss ranges from 8% to 11%. This is significantly lower compared to the average viscosity loss of 12% for other types of valve cores used in oilfields.

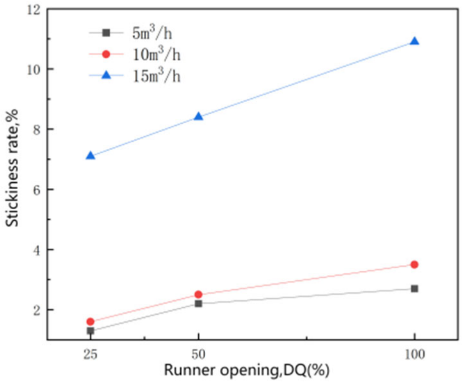


Figure 15. Spool viscosity rate

5. Conclusion

The paper presents the design of a novel electrically controlled stratified injection and polymer throttling valve core, and discusses the effects of three common valve core structures on pressure drop and shear rate. A reasonable valve core structure was selected, and the length of the throttling valve core was optimized by analyzing its impact on shear rate.

1. A novel electrically controlled stratified injection and polymer throttling valve core was designed. Compared to traditional valve core structures, this new structure is shorter in length, reducing the overall dimensions and enabling better flow control.

2. Finite element analysis was conducted on three valve core structures. Three-dimensional models of the injection tool were established using meshing software, and mesh division was performed. Fluent finite element analysis was used to obtain the flow characteristics of polymer solutions in injection tools with different structural parameters, validating the advantages of the arc-shaped flow channel.

3. Finite element analysis of the arc-shaped flow channel was performed to analyze the shear rates of different valve core lengths at the same inlet flow rate. Ultimately, a valve core length of 30mm for the arc-shaped flow channel was selected based on comprehensive analysis results, leading to the optimization of the flow channel structure.

4.The optimized structure was validated through indoor experiments. The experimental results demonstrated that the average viscosity loss of the optimized flow channel structure was below 11%, effectively reducing the average viscosity loss.

References

[1] Sun Longde, Wu Xiaolin, Zhou Wanfu and so on. Chemical flooding technology for enhanced oil recovery in Daqing Oilfield [J]. Petroleum exploration and development, 2018,45 (04): 636-645.

[2] Wang Jun. Application research of tertiary oil extraction technology in oilfield [J]. Petrochemical Standards and Quality of China, 2019,39 (23): 226-227.

[3] Quboda. Study on the influence of different factors on the flooding effect of polymer system [J]. Inner Mongolia Petrochemical Industry, 2016,42 (03): 155-156.

[4] Duan Ming, Fang Shenwen, Zhang Peng, etc. Evaluation of tensile flow shear properties of several water-soluble polymers [J]. Petrochemical Industry, 2011,40 (02): 179-183.

[5] Duan Ming, Fang Shenwen, Zhang Peng, etc. Evaluation of tensile flow shear properties of several water-soluble polymers [J]. Petrochemical Industry, 2011,40 (02): 179-183.

[6] Sun Quanquan, Wang Air, Zhang Jun, etc. Experimental study of hydrophobic association polymer APP4 [J]. Journal of Chengdu University of Technology (Natural Science Edition), 2012,39 (01): 104-106.

[7] Ye Zhongbin, Yang Mei, Shi Leiting, etc. Performance study of the hydrophobic association polymer APP5 [J]. Applied Chemical Industry, 2018,47(06):1150-1153+1165.DOI:10.16581/j.cnki.issn1671-3206.2018.06.007.

[8] Wang Yonghe, Wang Yongsheng, He Jia. Progress of hydrophobic associated water-soluble polymers in oil fields [J]. China Petroleum and Chemical Industry Standards and Quality, 2013,33 (10): 91-92.

[9] Sun Daxing. Research on the viscosity loss mechanism and blending technology of reservoir polymer flooding injection

solution [D]. And Harbin Institute of Technology, 2022.DOI:10.27061/d.cnki.ghgdu. 2020.004668.

[10] Zhang Yalan, Ban Xiaojuan, Xu Yanrui, etc. Boundary treatment methods for non-Newtonian fluid simulations [J]. Journal of Computer Aided Design and Graphics, 2019,31 (08): 1341-1349.

[11] Song Xingliang. Structure optimization of polymer flooding under low injection volume [J]. Petroleum Mine machinery, 2022,51 (02): 1-7.

[12] Huang Zechao, Shajile, Luo Changhua, et al. Research and application of stratified measurement and regulation technology for small Wells in offshore oilfield [J]. Instrumentation User, 2022,29 (04): 41-44.