The Viscosity of Oil Influence on the Working Characteristics of Electric Submersible Pump under Variable Speed

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Abstract. The viscosity of oil in different oil fields varies greatly, and the widespread use of polymer flooding also has a great impact on the viscosity of the oil. The submersible electric pump is one of the main mechanical oil recovery methods, and its working performance directly affects the production efficiency of the oil well. The application of the Computational Fluid Dynamics (CFD) method to study the effect of viscosity on the internal and external characteristics of a submersible electric pump with variable speed is an effective complement to the experimental method. The inner flow passages of the impeller and the vane of the pump (model is Q10.) were selected as a fluid domain for the CFD study. The results show that As the viscosity increases from 1 mPa·s to 215 mPa·s, the efficiency of the electric submersible pump decreases from 56.8% to 49.7, the power consumption increases from 142 W to 163W, and the head decreases from 6.8m to 5.6m. This paper proposes the use of CFD technology to study the internal and external characteristics of electric submersible pumps under variable speed and variable viscosity conditions.

Keywords: Electrical submersible pump; Viscosity; Variable speed; Inner flow field.

1. Introduction

Electric submersible pumps are one of the three major artificial lifting equipment in my country and are the main production method for water drive wells and high-yield wells. The factory test of pump performance is measured with clean water as the medium, but it’s a mixture of oil and water, will cause misjudgment of the actual performance of the electric submersible pump, crude oil viscosity varies greatly. Therefore, it is necessary to study the influence of viscosity on the performance of electric submersible pumps.

Therefore, it is necessary to study the influence of viscosity on the performance of electric submersible pumps. Numerical research on pumps has increasingly entered engineering applications and scientific research. In 2008, Li took the lead in using CFD technology to obtain the correlation law between centrifugal pump performance and medium viscosity. The results show that: the calculated head is not only close to the experimental value but also higher than the head when transporting water at a certain liquid viscosity, this confirms the existence of the "sudden lift" phenomenon of the pump [1]. In 2009, after the CFD simulation, Pan and others believed that with the same flow rate, as the viscosity increases, the head decreases. Near the design operating point, the viscosity is not sensitive to the effect of efficiency, at the non-design operating point, the opposite is true [2]. In 2012, Li used FLUENT software to calculate the necessary cavitation margin for single-stage, single-suction, cantilever centrifugal pumps when conveying viscous oil, it is believed that the increase of liquid viscosity and non-condensable gas content will increase the dynamic pressure drop coefficient of the blade. After the non-condensable gas content increases, gas will continue to evolve under the higher effective cavitation
margin, causing the pump head to continuously drop \cite{3}. In 2013, Thiago Sirino and others used CFX software to numerically simulate the 3-stage electric submersible pump at different flow rates, speeds, and different fluid viscosities, until it reaches 0.5 times the best working condition flow \cite{4}. In 2014, Stel Henrique et al. performed viscous fluid dynamics simulation calculations on a three-stage electric submersible pump, researchers believe that the flow direction of fluids with a viscosity greater than water at the optimal efficiency point is not necessarily facing the blade, and also discussed the influence of fluid viscosity and speed change on the performance of electric submersible pump \cite{5}. Li \cite{6} conducted a CFD study on the effect of viscosity on the performance of pump turbines. Rouhollah believes that for crude oil with a viscosity of 90 cSt, its head drops by 14% at 0.5 times the design flow rate. The document \cite{8} indicated show that when the oil viscosity rises from 10cp to 100cp at the optimal point of pump efficiency, the increased pressure decreases by 30-40%.

The viscosity of the medium is an important parameter that affects the performance of the centrifugal pump, and it is also one of the important factors influencing the efficient and stable operation of the submersible centrifugal pump on site. Due to the complex structure of the flow domain in the multistage centrifugal pump, the law of flow evolution is not easy to capture, the flow mechanism is difficult to reveal, and most researchers use experiments to study the effect of viscosity on centrifugal pumps, however, there are not many kinds of literature on the detailed study of the flow law caused by the viscosity change inside the pump. In recent years, CFD technology has been widely used in the research of fluid machinery internal flow mechanism and hydraulic performance structure design, but there are few pieces of research on electric submersible pumps. Therefore, the use of CFD technology to study the change of oil viscosity and impeller speed to simulate the external characteristics and internal flow of electric submersible pumps provides theoretical support for the optimal design of mechanical oil extraction equipment.

2. Fluid Dynamics Equations and Turbulence Models

The net mass flow at the inlet and outlet of the electric submersible pump should be consistent, expressed by the mass conservation equation (formula 1):

\[
\frac{\partial \rho}{\partial t} + \frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} + \frac{\partial (\rho w)}{\partial z} = 0
\]

Where \( \rho \) —Fluid density, kg/m\(^3\); \( u, v, w \) —Velocity components in x, y, z directions, m/s.

In unit time, the sum of the momentum flowing into the fluid domain in the electric submersible pump and the external force acting on the control surface of the fluid domain and the body of the fluid domain is equal to the increase in momentum in the fluid domain, The Navier-Stokes conservation equation in the x, y, z directions (as shown in formula 2-4):

\[
\frac{\partial (\rho u)}{\partial t} + \text{div}(\rho \vec{u} \vec{U}_u) = -\frac{\partial p}{\partial x} + \frac{\partial \tau_{ux}}{\partial x} + \frac{\partial \tau_{uy}}{\partial y} + \frac{\partial \tau_{uz}}{\partial z} + F_x
\]

\[
\frac{\partial (\rho v)}{\partial t} + \text{div}(\rho \vec{u} \vec{U}_v) = -\frac{\partial p}{\partial y} + \frac{\partial \tau_{vx}}{\partial x} + \frac{\partial \tau_{vy}}{\partial y} + \frac{\partial \tau_{vz}}{\partial z} + F_y
\]

\[
\frac{\partial (\rho w)}{\partial t} + \text{div}(\rho \vec{u} \vec{U}_w) = -\frac{\partial p}{\partial z} + \frac{\partial \tau_{wx}}{\partial x} + \frac{\partial \tau_{wy}}{\partial y} + \frac{\partial \tau_{wz}}{\partial z} + F_z
\]

Where \( p \) —Pressure on the microfluid, Pa; \( \vec{U} \) —Flow velocity of the fluid in micro-element; \( \tau_{ux}, \tau_{vy}, \tau_{wz} \) —The component of viscous stress on the surface of the infinitesimal element; \( F_x, F_y, F_z \) —The volume force of the infinite element in 3 directions.

3. Meshing and Boundary Setting

This paper chooses the Q10 electric submersible pump as the research object, and constructs the 3D CAD model of the impeller and guide vane, as shown in Figure 1 and Figure 2. The rated working speed
of the electric submersible pump is 2900r/min, the head under design conditions is 7m, the rated working flow is 100 m³/d. The basic structural parameters of the impeller and guide vanes are listed in Table 1.

|             | Inlet diameter /mm | Hub diameter /mm | Outlet diameter /mm | Inlet width /mm | Exit width /mm | Number of blades |
|-------------|--------------------|------------------|---------------------|----------------|----------------|-----------------|
| Impeller    | 35.8               | 22.5             | 81.5                | 6.6            | 6.9            | 7               |
| Vane        | 84.5               | 25.8             | 37.4                | 6              | 5.8            | 10              |

Figure 1. Impeller  
Figure 2. Guide vane  
Figure 3. 3D full runner grid

Use IGG software to establish the meridian flow channel curve and blade characteristics respectively, then use AutoGrid5 to mesh the moving blade and static blade flow channel. Figure 3 shows the 3D grid of the fluid domain in the electric submersible pump. The total number of grids of the model is 445,600, the impeller runner is 217,700, and the guide wheel runner is 231,900. Check the non-negative grid, the orthogonality is between 67.5-89.8, the angular offset is 96.629, the overall aspect ratio is 626.86, and the extension ratio is 3.557. All the above mesh quality parameters meet the convergence requirements of CFX software.

The simulation boundary conditions are set as follows: Pressure inlet boundary, flow outlet boundary, no wall slip, standard wall function. The blade wall surface and the hub wall surface are rotating wall surfaces, and the remaining wall surfaces are stationary. The symmetry is that the nose tip is symmetrical around the axis, and the interface between the impeller and the stationary blade rotates and freezes the rotor method.

4. Internal and External Characteristics of an Electric Submersible Pump

For offshore electric submersible pump wells with high water cut and large displacement, due to the large changes in liquid production, speed regulation technology can be used, makes the machine mining device has higher adaptable. In this section, under variable speed conditions, numerical simulation technology is used to study the effect of viscosity on the external characteristics of the electric submersible pump and the flow evolution of the internal flow passage.

4.1. The Influence of Rotating Speed on the External Characteristics of ESP under Different Viscosity

Case study of external characteristics of electric submersible pump includes 5 speeds: 0.8n, 0.9n, 1n, 1.1n, 1.2n (Where n refers to the rated speed of the electric submersible pump 2900r/min), and 3 kinds of viscosity: 1Pa·s, 50.3mPa·s, 215mPa·s.

Figures 4–6 show the comparison of external characteristic curves of electric submersible pumps under variable speed conditions under different viscosities, including head-flow H-Q, power-flow N-Q, and efficiency-flow η-Q performance curves. The liquid viscosity is 1mPa·s, 50.3mPa·s, and 215mPa·s, respectively. When the viscosity is constant, as the speed of the electric submersible pump increases, the curves of the three characteristics all shift to the right and upward, and the best working area is to move to the right. The efficiency peak value increases with the increase of the speed, and the changing trend of the efficiency peak value is the same under different viscosity. As the speed of the electric submersible pump increases, the head also increases. However, when the flow rate is greater than 120m³/d, the head decreases sharply, and the greater the viscosity, the more the head suddenly drops to the left. As the speed increases, the power curve of the pump becomes steeper, and as the viscosity increases, the power consumed is greater, indicating that the electric submersible pump consumes more energy.
It can also be seen from Figures 4–6 that as the viscosity of the liquid delivered by the pump increases, the friction loss between the liquid and the wall will increase, leads to greater viscosity, lower head, more power consumption, and lower efficiency. Under different speed conditions, the influence of viscosity on the external characteristics of electric submersible pumps are consistent, which is consistent with the results of the pump hydraulic external characteristics experiment. The external characteristics of the electric submersible pump obtained by the CFD numerical simulation method also satisfy the relationship of the proportional law. Therefore, the CFD numerical method of the external characteristic curve is a reliable supplement to the electric submersible pump. As the viscosity increases from 1 mPa·s to 215 mPa·s, the efficiency of the electric submersible pump decreases from 56.8% to 49.7, the power consumption increases from 142W to 163W, and the head decreases from 6.8m to 5.6m.
4.2. Influence of Viscosity on Pressure Distribution of Electric Submersible Pump under Variable Speed

In this section, the working conditions of the electric submersible pump at the rotational speeds of 0.9n, 1.0n, and 1.2n are taken as research cases. Figure 7 shows the static pressure distribution on the cross-section of the inner flow passage of the single-stage electric submersible pump. It can be seen from the 9 graphs in Figure 7, under different viscosities and different speeds, most of the flows are two-dimensional laminar flows, the laminar flow area means that the viscous loss of the flow is relatively small. In the trailing edge area of the impeller blade, there are different degrees of wake area, which is a three-dimensional turbulent area. The flow loss here is relatively large, especially in the wake area under non-design conditions, indicating that the flow loss is also relatively large.

![Figure 7](image)

**Figure 7.** The static pressure diagram of the passage cross-section of a single-stage pump.

5. Conclusion

This paper studies the variable speed external characteristics and internal flow field distribution of the Q10 electric submersible pump under the conditions of 3 viscosities and 5 speeds. When the viscosity is constant, the lift and efficiency gradually increase with the increase in speed, the peak power of the
pump moves to the upper right, and the curve becomes steeper. This can prove that the head, power, and speed in the law of proportionality are two powers and three powers. From the distribution of the flow field in the electric submersible pump, when the liquid viscosity is constant, with the increase of the speed, the static pressure value at the inlet decreases, while the static pressure value at the outlet increases. The external characteristic curve of the electric submersible pump shows that the increase of the working fluid viscosity will reduce pump efficiency. In particular, the flow separation phenomenon occurred at the leading edge of the impeller blade, resulting in a low-pressure area at the leading edge, and this situation aggravated the separation with the increase of the viscosity of the conveyed liquid, which is disadvantageous to the efficient operation of the pump.

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