Analysis and Research on Turbulent Kinetic Energy of Three-way Regulating Valve

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Abstract. In a system with the 3-way regulating valve, low energy consumption high efficiency based on fluid dynamics CFD software, for the 3-way regulating valve of the 3 d simulation for internal flow property research, obtained the pressure within the valve flow turbulence kinetic energy and turbulence dissipation rate etc. The results show that the flow field information with the increase of the opening, the seat area on the turbulence kinetic energy and turbulence dissipation rate increases sharply, change law instead of the seat position. The existence of transition cone can greatly reduce the turbulent kinetic energy and the turbulent dissipation rate of the upper seat in the wide opening range and the valve in the small opening range. Long-term avoidance of the valve working in the minimum-opening condition will be beneficial to the protection of the valve.

1. Introduction
Numerical simulation method has become an important method to study the flow inside the valve. It can obtain the flow characteristics, such as turbulent kinetic energy, turbulent dissipation rate and so on, which can not be completely obtained by traditional test methods. Many scholars have done research on the internal flow performance of the valve, but the research on the internal flow performance of the three-way control valve is less, and the influence of structural parameters on the internal flow field is not studied, which can not clearly reflect the turbulent flow characteristics of the three-way valve. Based on this, the in-depth study of the three-way control valve has a certain significance for the optimization and improvement of its subsequent structure, the application in engineering practice and the theoretical study of its flow performance.

2. Structure Principle and Performance Parameters
2.1. Structure Principle
The internal schematic diagram of three-way control valve the three-way control valve is mainly composed of valve body, spool, seat, stem, bracket and other components (Fig. 1). Its working principle is that the actuator drives the stem to move up and down, and the sealing surface of spool and seat can be sealed up and down within the three-way valve stroke. By adjusting the spool in different positions, the flow of main inlet and side inlet can be controlled, so as to ensure the smooth operation The current outlet flow meets the functional requirements of the system.
2.2. Performance Parameters

Table 1. Performance Parameters of Three-way Control Valve

| Name                        | Value       |
|-----------------------------|-------------|
| Nominal diameter            | DN100       |
| Working pressure (MPa)      | 1.0         |
| Temperature range (℃)       | -10 ~ 45    |
| Valve core stroke (mm)      | 50          |
| Medium                      | water, oil  |

3. Numerical Simulation

3.1. Governing equation

In this paper, the more mature standard k - ε model is used for numerical simulation [3]. The governing equations are composed of continuity equation, momentum conservation equation, turbulent kinetic energy k equation and dissipation energy ε equation.

- Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_j} (\rho u_j) = 0 \quad (1)$$

- Momentum conservation equation (N-S equation) formula

$$\rho \frac{du}{dt} = \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_j}{\partial x_j} + \frac{\partial u_i}{\partial x_i} - \frac{2}{3} \frac{\partial u_i}{\partial x_i} \right) \right] + \frac{\partial}{\partial x_j} \left( -u_i u_j \right) \quad (2)$$

- The turbulent kinetic energy k and turbulent kinetic energy dissipation rate transport equation ε of the standard turbulence model can be expressed as,
In the formula, \( u_i \) is the velocity component in direction \( i, i=1, 2, 3 \), \( \mu \) is kinematic viscosity coefficient of medium, \( \mu_t \) is vortex viscosity coefficient, \( \delta_k \) is Prandtl number Corresponding to Turbulent Kinetic Energy \( K \), \( \delta_\varepsilon \) is Prandtl number Corresponding to Turbulent Kinetic Energy Dissipation Rate \( \varepsilon \), \( P \) is turbulent kinetic energy generation term.

\[
\frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \left( \mu + \frac{\mu_t}{\delta_k} \right) \frac{\partial u_i}{\partial x_j} \right] + P - \rho \varepsilon \tag{3}
\]

\[
\frac{\partial (\rho \varepsilon)}{\partial t} + \frac{\partial (\rho \varepsilon u_i)}{\partial x_j} = \frac{\partial}{\partial x_j} \left[ \frac{\mu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} \left( C_{\varepsilon 1} P + \rho C_{\varepsilon 2} \varepsilon \right) \tag{4}
\]

Among them,

\[
\mu_t = C_{\mu} \rho \frac{k^2}{\varepsilon} \tag{6}
\]

| Table 2. Coefficient in k-\( \varepsilon \) Model |
|---------------|----------|----------|-----|-----|-----|
| \( C_{\varepsilon 1} \) | \( C_{\varepsilon 2} \) | \( C_{\mu} \) | \( \delta_k \) | \( \delta_\varepsilon \) |
| 1.44          | 1.92     | 0.09     | 1.0 | 1.3 |

3.2. Flow Channel Model Establishment and Grid Division

The three-way control valve with nominal diameter DN = 100 mm is selected as the simulation experimental object. According to the specific structural parameters, the three-dimensional model of the three-way control valve is established by using SolidWorks software, and the internal flow channel model of the three-way valve is generated by importing the reverse modeling of the hydrodynamics software (Fig. 2).

The flow channel model was imported into ANSYS ICEM CFD for mesh generation (Fig. 2). Considering the complexity of the internal flow channel of the three-way valve, the tetrahedral / mixed mesh was used for numerical calculation [4], and the local refinement was carried out at the bend of the flow channel to make the calculation results more accurate, and the mesh independence test was carried out based on the mass flow rate in the fully open state [5].

Combined with the actual working conditions of the three-way control valve, the internal flow model under typical working conditions is established. The three-dimensional incompressible Reynolds time average equations and K-\( \varepsilon \) turbulence model are used to form a closed equations to solve the internal
flow field of the three-way control valve. The fluid medium is water, and the change of temperature is not considered in the solution process. The main inlet and side inlet of three-way valve are set as velocity inlet boundary condition, the velocity is 1.5m/s, the outlet is pressure outlet boundary condition, and the wall of three-way valve is set as adiabatic non slip boundary condition.

4. Analysis and Study of Turbulence Kinetic Energy and Turbulence Dissipation Rate

4.1. Spool Structure Diagram
Considering the stability and energy saving of the system operation, the valve core of the three-way control valve studied in this paper adopts a special structural design, and the upper and lower seats are provided with ring-transition cones, as shown in Figure 3. The influence law of the existence of ring-transition cones on turbulence kinetic energy and turbulence dissipation rate inside the three-way control valve is comparatively analyzed and studied.

![Figure 3. The valve core structure.](image)

(a) valve core with transition cone (b) valve core without transition cone

4.2. Turbulent Kinetic Energy Analysis
FIG. 4 shows the distribution law of the maximum turbulent kinetic energy at different openings of the three-way regulating valve and the upper and lower seats under the condition of with or without transition cone. It can be known that the flow kinetic energy variation law of the upper and lower seats is basically the same whether the throttle cone exists or not during the change process of the three-way control valve with different openings. With the increase of the opening, the turbulent kinetic energy at the upper seat position transitions smoothly first and then increases continuously. The turbulent kinetic energy at the lower seat changes in the opposite way. The throttle cone has a certain effect on turbulent kinetic energy during the whole process. The turbulent kinetic energy of the upper seat under the condition of large opening is greater than that of the non-throttled cone, and the difference is greater with the increase of opening. Under the condition of small opening of the lower seat, the turbulent kinetic energy of the non-throttled cone is greater than that of the one with throttled cone, and the difference increases with the decrease of opening. According to the above analysis, the existence of throttling cone can obviously improve the flow stability of upper seat under the condition of large opening and lower seat under the condition of small opening, and reduce energy loss.
4.3. Turbulence dissipation factor analysis

FIG. 5 shows the distribution law of turbulent dissipation rate at different openings of the three-way regulating valve and the upper and lower seats under the condition of no throttling cone. By comparing FIG. 5 with FIG. 4, it can be seen that the distribution of turbulence dissipation rate and turbulence kinetic energy is very similar. At the upper seat, the turbulent dissipation rate first transitions smoothly and then increases sharply with the increase of the opening. At the lower seat the turbulent dissipation rate changes in the opposite direction. Throughout the whole process, the throttle cone has a certain effect on the turbulence dissipation rate. Under the condition of large opening, the turbulent dissipation rate of upper seat without throttling cone is higher than that of upper seat with throttling cone, and the difference is larger with the opening increasing. Under the condition of small opening, the turbulent dissipation rate of the lower seat without throttling cone is greater than that of the lower seat without throttling cone, and the difference increases with the decrease of opening. It is known that the presence of a throttling cone can significantly reduce the flow energy dissipation of the upper and lower seats with large and small openings.

5. Conclusion
The turbulent kinetic energy and the turbulent dissipation rate at the upper seat position increase sharply with the opening of the three-way regulating valve in the wide opening range. Within the range of small opening, the turbulent kinetic energy and the turbulent dissipation rate at the lower seat position increase
sharply with the decrease of opening. The existence of transition cone can greatly reduce the turbulent kinetic energy and the turbulent dissipation rate of the upper seat within the range of large opening and the lower seat within the range of small opening.

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