Simulation and Analysis on Flow Field of Ball Valve Based on Fluent Software

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Abstract. In this paper, ANSYS Fluent is used to simulate the three-dimensional flow of the ball valve under different pressure conditions. The flow field torque, speed and pressure distribution are obtained. By normalizing the mass flow and torque, a relationship formula between the flow coefficient and torque that varies with the opening degree is constructed. The problem that it is difficult to obtain the flow coefficient and torque coefficient of the ball valve is solved. The results show that the data after the normalization process basically coincide, indicating that the results have a high degree of confidence.

Keywords: ball valve, fluent, flow coefficient, torque, curve fitting

1. Introduction

Ball valves originated in the 1950s and are mainly used for the regulation and control of fluids. Owing to its simple structure, good sealing ability and long service life [1-3], it is widely used in petroleum refining, long-distance pipelines, chemical, papermaking, pharmaceutical, water conservancy, power, municipal, steel, aerospace and other industries [4-7]. The technical indicators of the ball valve are mainly reflected by the flow coefficient and torque coefficient [8-10]. For flow characteristics and torque characteristics, researchers at home and abroad have done a lot of research through CFD software, mathematical relationship derivation and experiments. For instance, Zhao Ying from National University of Defense Technology used CFD software to simulate the flow field of the ball valve. The hydraulic experiment were used to verify the flow coefficient and torque coefficient. The results show that the conclusion obtained by using the CFD software are basically consistent with the experimental data. The CFD software can greatly improve the efficiency [11]. In addition, Sun Fengwei from Lanzhou University of Technology established a mathematical relationship between the flow area and the opening degree of the ball valve by mathematically deriving the flow area of the ball valve, obtaining the flow coefficient of the ball valve in combination with the CFD software [12]. Tahami et al. used CFD software to calculate the torque of the valve disk according to the disk shape, surface roughness, offset, pressure loss of the butterfly valve, which explained the reason why the direction of valve disk torque changes [13].

This paper uses Fluent and Matlab software to characterize the flow coefficient curve and the torque coefficient curve of the ball valve, which not only solves the problem of obtaining flow area difficultly
during the research of the ball valve, but also provides the basis for the optimization of the ball valve structure.

2. Establishment of Mathematical Model of Flow Field

2.1. Flow and torque equation

The flow equation of the ball valve is to simplify the ball valve flow into orifice compensated mode, the equation of which is [14]

\[ Q_v = \sqrt{2C_vA_v \frac{\Delta P}{\rho}} \]  

(1)

In which \( Q_v \) is the volume flow rate, \( C_v \) is the outflow coefficient, \( \Delta P \) is the pressure loss in two side of the valve, \( \rho \) is the density of the liquid, and \( A_v \) is the effective flow area. Since \( C_v \cdot A_v \) reflects the inherent properties of the valve, in the industry they are usually replaced by \( K_v \), the flow coefficient, which is only related to the rotation angle of the spool [15-18].

\[ f(\beta) = K_v = Q_m/\sqrt{2\Delta P \cdot \rho} \]  

(2)

In this equation, \( Q_m \) is replaced by \( Q_v \cdot \rho \) and \( \beta \) is the rotation angle of the spool.

The torque equation is:

\[ T = m \cdot d \cdot \Delta P \]  

(3)

where \( m \) is the torque coefficient, which is only related to the opening degree, \( d \) is the diameter of the valve spool, and \( \Delta P \) is the pressure loss in two side of the valve. Formula (3) shows that \( m \cdot d \) is an inherent characteristic of the ball valve structure, able to be described by its angle of rotation with the valve spool:

\[ F(\beta) = T/\Delta P \]  

(4)

2.2. Governing equation:

In this paper, the Reynolds time-averaged two-equation standard \( k-\epsilon \) model and the semi-implicit pressure coupling algorithm SIMPLEC are selected to solve the flow field in the valve. Its governing equation is as follows [19]:

Continuity equation:

\[ \frac{\partial u_i}{\partial x_i} = 0 \]  

(5)

Momentum Equation:

\[ u_j \frac{\partial u_i}{\partial x_j} = f_i - \frac{1}{\rho} \frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_i} [(v + v_i)(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i})] \]  

(6)

\( k \) equation for turbulent kinetic energy:

\[ \frac{\partial u_i k}{\partial x_i} - \frac{\partial}{\partial x_i} [(v + v_i) \frac{\partial k}{\partial x_i}] = P_i - \epsilon \]  

(7)

Turbulent energy dissipation rate \( \epsilon \) equation:

\[ \frac{\partial u_i \epsilon}{\partial x_i} - \frac{\partial}{\partial x_i} [(v + v_i) \frac{\partial \epsilon}{\partial x_i}] = \frac{\epsilon}{k} \left( C_{\epsilon1} P_i - C_{\epsilon2} \epsilon \right) \]  

(8)
Where \( x_i \) \((i=1,2,3)\) is the Cartesian coordinate system coordinate, \( u_i \) \((i=1,2,3)\) is the velocity component in the \( i \) direction, \( f_i \) is the mass force in the \( i \) direction, \( P \) is the pressure, \( \rho \) is the liquid density, \( v \) is the kinematic viscosity coefficient of the liquid, and \( P_r \) is the turbulent kinetic energy generation rate.

Turbulent kinetic energy generation rate \( P_r \) equation:

\[
P_r = v_i \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \frac{\partial u_i}{\partial x_j}
\]

(9)

Vortex viscosity coefficient \( v_t \) equation:

\[
v_t = C_\mu \frac{k^2}{\varepsilon}
\]

(10)

The value of each item in the \( k-\varepsilon \) model is \( C_\mu=0.09, C_1=1.44, C_2=1.92, \sigma_k=1.0, \sigma_\varepsilon=1.3 \) according to the empirical formula.

3. Flow field grid and boundary conditions

The structure of the ball valve is shown in Fig 1. where Figure (a) is the three-dimensional structure of the ball valve, and Figure (b) is the internal flow field grid of the ball valve after pretreatment. Ball valve inlet and outlet pipe diameters are both 26mm.

Each time the spool is rotated through 10°, a flow field model is established. Non-structured meshing is adopted. The number of grid cells in each flow field model ranges from 110000 to 160000. The mesh skewness of the flow field model is less than 0.8, showing a good quality of the mesh.

The boundary conditions set the inlet and outlet as the pressure type. The pressure value is the value given by each working condition. The rest of the boundary is the slip boundary, indicating that the speed at the boundary is 0. The liquid medium uses liquid methane. Due to the differences in methane physical properties under various pressure conditions, the US National Standards Agency SUPERTRAPP physical property model is used to obtain the specific parameters shown in Table 1 at a temperature of 124K.
Table 1. Physical properties of methane

| Working condition | Inlet pressure (MPa) | Outlet pressure (MPa) | Average pressure (MPa) | Density (kg/m$^3$) | Dynamic viscosity (Pa) |
|-------------------|---------------------|-----------------------|------------------------|---------------------|------------------------|
| condition1        | 17.85               | 14.5                  | 16.175                 | 419.5716            | 1.0572×10$^{-4}$       |
| condition2        | 16.13               | 11.68                 | 13.905                 | 417.6836            | 1.034×10$^{-4}$        |
| condition3        | 9.985               | 4.973                 | 7.479                  | 411.8521            | 9.679×10$^{-4}$        |
| condition4        | 9.018               | 4.245                 | 6.6315                 | 411.0243            | 9.589×10$^{-5}$        |
| condition5        | 6.122               | 2.496                 | 4.309                  | 408.6731            | 9.3417×10$^{-5}$       |

4. Simulation results and analysis

Enter the methane density and kinematic viscosity parameters under different working conditions to get the calculation results of each working condition. The data obtained are shown in the table.

Parameters of working condition 1: pressure loss 3.35MPa, density 419.5716kg/m$^3$. The results are shown in Table 2.

Table 2. Calculation results of working condition 1

| $\beta$ (°) | Q (kg/s) | $K_v$ | T(NM) | $(T/\Delta P)\times10^{-7}$ |
|------------|----------|-------|-------|-----------------------------|
| 10         | 1.656    | 0.0000312 | 1.402 | 4.19                        |
| 20         | 3.768    | 0.0000711 | -0.16 | -0.48                       |
| 30         | 5.451    | 0.000103  | -1.954 | -5.8                        |
| 40         | 8.187    | 0.000154  | -2.803 | -8.4                        |
| 50         | 10.689   | 0.000202  | -1.226 | -3.7                        |
| 60         | 12.14    | 0.000229  | 2.43   | 7.25                        |
| 70         | 13.017   | 0.000246  | 4.27   | 12.7                        |
| 80         | 13.745   | 0.000259  | 4.789  | 14.3                        |
| 90         | 14.019   | 0.000264  | 4.99   | 14.9                        |

Parameters of working condition 2: pressure loss 4.45MPa, density 417.684kg/m$^3$. The results are shown in Table 3.

Table 3. Calculation results of working condition 2

| $\beta$ (°) | Q(kg/s) | $K_v$ | T(NM) | $(T/\Delta P)\times10^{-7}$ |
|------------|---------|-------|-------|-----------------------------|
| 10         | 1.888   | 0.0000310 | 1.866 | 4.19                        |
| 20         | 4.1297  | 0.0000677 | -0.049 | -0.11                       |
| 30         | 6.271   | 0.000103  | -2.608 | -5.90                       |
| 40         | 9.437   | 0.000155  | -3.734 | -8.40                       |
| 50         | 12.305  | 0.000202  | -1.67  | -3.80                       |
| 60         | 13.98   | 0.000229  | 3.229  | 7.26                        |
| 70         | 14.986  | 0.000246  | 5.674  | 12.8                        |
| 80         | 15.82   | 0.000259  | 6.354  | 14.3                        |
| 90         | 16.153  | 0.000265  | 6.592  | 14.8                        |
Parameters of working condition 3: pressure loss 5.012 MPa, density 411.8521 kg/m³. The results are shown in Table 4.

| β (°) | Q (kg/s) | K_v | T (NM) | T/ΔP×10^{-7} |
|-------|----------|-----|--------|--------------|
| 10    | 1.991    | 0.000031 | 2.094   | 4.18         |
| 20    | 4.5      | 0.000007 | 0.0348  | 0.0694       |
| 30    | 6.613    | 0.000103 | -2.927  | -5.8         |
| 40    | 9.936    | 0.000155 | -4.204  | -8.4         |
| 50    | 12.93    | 0.000201 | -1.93   | -3.9         |
| 60    | 14.736   | 0.000229 | 3.632   | 7.25         |
| 70    | 15.794   | 0.000246 | 6.392   | 12.8         |
| 80    | 16.682   | 0.00026  | 7.14    | 14.2         |
| 90    | 16.95    | 0.000264 | 7.383   | 14.7         |

Parameters of working condition 4: pressure loss 4.773 MPa, density 411.0243 kg/m³. The results are shown in Table 5.

| β (°) | Q (kg/s) | K_v | T (NM) | T/ΔP×10^{-7} |
|-------|----------|-----|--------|--------------|
| 10    | 1.941    | 0.000032 | 1.994   | 4.46         |
| 20    | 4.392    | 0.0000724 | -0.132  | -0.3         |
| 30    | 6.453    | 0.000106 | -2.787  | -6.2         |
| 40    | 9.704    | 0.00016  | -4.015  | -9           |
| 50    | 12.62    | 0.000209 | -1.835  | -4.1         |
| 60    | 14.373   | 0.000237 | 3.456   | 7.73         |
| 70    | 15.414   | 0.000254 | 6.088   | 13.6         |
| 80    | 16.271   | 0.000268 | 6.797   | 15.2         |
| 90    | 16.542   | 0.000273 | 7.05    | 15.8         |

Parameters of working condition 5: pressure loss 3.726 MPa, density 408.6731 kg/m³. The results are shown in Table 6.

| β (°) | Q_{in} (kg/s) | K_v | T (NM) | T/ΔP×10^{-7} |
|-------|---------------|-----|--------|--------------|
| 10    | 1.685         | 0.000031 | 1.516   | 4.07         |
| 20    | 3.81          | 0.000069 | 0.099   | 0.266        |
| 30    | 5.623         | 0.000102 | -2.124  | -5.7         |
| 40    | 8.372         | 0.000152 | -2.994  | -8           |
| 50    | 10.982        | 0.000199 | -1.394  | -3.7         |
| 60    | 12.471        | 0.000226 | 0.103   | 2.76         |
| 70    | 13.374        | 0.000242 | 4.629   | 12.4         |
| 80    | 14.122        | 0.000256 | 5.174   | 13.9         |
| 90    | 14.352        | 0.00026  | 5.368   | 14.4         |

The results obtained by curve fitting the data under different working conditions are shown in Fig. 2 and Fig. 3.
It can be seen from the curve that the change trend of each pressure working condition is basically the same. It is the pressure loss that determines the value. The larger pressure loss is, the larger the flow and torque value.

According to the change trend of the flow data, the angle of the spool is selected to be 10°, 40°, 70°. Under the conditions of working conditions 1 and 3, the internal pressure distribution and speed changes will be analyzed. The pressure velocity distribution is shown in the Fig 4. Fig 5. and Fig 6.
Fig 4. Pressure-speed distribution diagram of angle 10° under working condition 1

(a) Pressure region map in YZ direction  
(b) Velocity region map in YZ direction  
(c) Velocity profile in XZ

Fig 5. Pressure-speed distribution diagram of angle 40° under working condition 1

(a) Pressure region map in YZ direction  
(b) Velocity region map in YZ direction  
(c) Velocity profile in XZ
Fig 6. Pressure-speed distribution diagram of angle 70° under working condition 1

It can be seen from the pressure-speed distribution diagram that in the case of working condition 1, when the valve core rotates through 10°, because of the small effective flow area, the pressure loss seems large while the flow velocity in the valve is small. Due to the fluid impulse, the torque causes the spool to open. When the spool is rotated to 40°, the flow rate in the valve increases due to the increased effective flow area. However, since the spool is not completely opened and due to the eccentricity of the spool, there is a strong flow around the hemispherical spool in the valve, coupled with eddy currents of different sizes in the valve, causing the spool to close. When the angle increases to 70°, the effective flow area is further enlarged, the spool is basically open, the high-speed flow path in the valve is basically formed, and the strength of the swirling flow in the valve decreases, resulting in the fluid impulse cause the spool to open. After that, the spool continues to increase in angle, but will not change the flow pattern inside the valve.

The pressure velocity distribution at the angle of 10°, 40°, and 70° of the spool in working condition 3 is shown in the Fig7. Fig 8. and Fig 9.
Comparing the pressure and velocity diagrams at the same opening of working condition 3 and working condition 1, it can be seen that when the spool in different working conditions rotates at the same angle, the flow pattern and pressure-velocity distribution in the valve are substantially the same. However, the speed value of working condition 3 is greatly improved at various openings than that of
working condition 1, which is mainly because the pressure loss of working condition 3 is greatly improved than that of working condition 1. With reference to the data under each working condition, it can be seen that under five working conditions, the flow pattern in the valve mainly depends on the opening of the valve. Due to the different pressure loss in each working condition, the flow rate will change accordingly. Therefore, it is concluded that, for the same medium, the flow pattern in the valve does not change significantly with the change in pressure loss. The main factor affecting the internal flow of the ball valve is the structure inside the ball valve.

5. Data normalization

The obtained data is fitted with a polynomial using Matlab. After comparing the polynomials to fit the R-square values of different orders and considering the stability of the control system, the $K_v$ is selected by a third-order fit, and the $T/\Delta P$ is selected by a fourth-order fit. The result is shown in the Fig.10 and Fig.11.

![Fig 10. K_v curve fitting](image)

![Fig 11. T/\Delta P curve fitting](image)

The R-square value of the $K_v$ fitted curve is 0.9965. The R-square value of the $T/\Delta P$ fitted curve is 0.9614. The analytical formula of the fitted curve is brought into equations (2) and (4), and the relationship between the mass flow rate and the torque with respect to the opening degree is obtained:

$$Q_m = (-5.426 \times 10^{-10} \cdot \beta^3 + 5.176 \times 10^{-8} \cdot \beta^2 + 2.643 \times 10^{-6} \beta) \cdot \sqrt{2\Delta P}$$  \hspace{1cm} (11)

$$T = (-5.626 \times 10^{-13} \cdot \beta^4 + 8.459 \times 10^{-11} \beta^3 - 2.584 \times 10^{-9} \beta^2 - 3.868 \times 10^{-7} \beta + 1.054 \times 10^{-5}) \cdot \Delta P$$  \hspace{1cm} (12)
6. Conclusion

- The $K_v$-$\beta$ curve can reflect the inherent flow adjustment characteristics of the ball valve, solving the problem of difficult to obtain $K_v$ in engineering. According to the $K_v$-$\beta$ curve, it can be seen that when the turning angle of the spool of the ball valve is in the range of 0° to 70°, the flow regulation performance is basically linear. When the angle is 70° to 90°, the flow rate increase gradually decreases.
- The trend of the torque curve shows a trend of firstly helping the valve core to open, and urging the valve core to close next, then opening the valve core. The reason is that the flow around the hemispherical spool and eddy currents.
- The normalized fitting relation provides a direction for exploring the ball valve adjustment performance and targeted optimization of structure, as well as a certain theoretical basis for the precise control of the ball valve.

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