Simulation of Flow Field and Calculation of Moment on Valve Plate for Butterfly Valve

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Abstract

In order to control the flow rate in a butterfly valve accurately, the moment, which acts on the rotation axis of valve plate, caused by flowing fluid must be considered. Taking air as the medium, the parameters of internal flow fields, such as the velocity and pressure, are simulated by CFD for a standard butterfly valve. The distribution of velocity and pressure fields that changes with various openings and a curve of aerodynamic moment are obtained. The results show that, as the opening of valve goes larger, the resultant moment on valve plate is monotonically increased. At the opening of 70° around, the moment reaches its maximum. After the opening of 70° the moment begins monotonically decreasing and the resultant moment is close to zero at 90°.

Keywords: Aerodynamic Moment, Flow Field, Simulation

1. Introduction

Butterfly valve is a piping system on-off and flow control component that widely used in petroleum engineering, chemical engineering as well as energy system pipeline etc. It is suitable for liquid, semi-fluid and solid powder pipeline container as a regulator or throttling device. Fig. 1 shows a structure schematic diagram of a butterfly valve. As an opening and closing part, the circular valve plate is installed in the radial direction of pipe to realize opening control with the rotation of the axis of valve plate. When the valve plate stays at a certain opening, both sides of it will bear the distributed force by air flow, then moment on the valve plate is formed. With various openings of valve plate, the pressure distribution changes, so does the moment. So, study on the distribution of pressure and the change of the moment of valve plate is valuable to the flow control of butterfly valve.

Figure 1. Schematic diagram of a butterfly valve

In recent years, there are some contributions in the flow characteristics of butterfly valves. For example, Feng Weimin, Xiao Guangyu and Yuan et al. [1] analyzed the inner flow field for double eccentric butterfly valve, single butterfly valve, truss-type butterfly valve and turtle-type butterfly valve based on the numerical method. Peiman Naseradinnousavi, C. Nataraj [2] described high fidelity modeling and analysis of the opening and closing processes of butterfly valves driven by solenoid actuators using multiphysics models, which shows that the behavior of hydrodynamic torque plays an important role in the closing and opening processes. Danbon F. and Solliec C [3] researched the interior flow field of butterfly valve. Xue Guan Song, Lin Wang, and Seok Heum Baek et al. [4] proposed a new process to meet desired needs in butterfly valve design that is characterized by the complex configuration by CFD and FEM. Minqiang Pan, Dehuaui Zeng and Yong Tang et al. [5] calculated the velocity distribution among multiple parallel microchannels with triangle manifolds for a three-dimensional CFD model. Zhikun Chen, Yutian Wang and Ruiheng Zhang et al. [6] performed ADRC static decoupling technology and the dynamic decoupling method based on extended state...
observer (ESO) for a gas mixture butterfly valve with string couplets system which was serious
decoupling, uncertainty, easily disturbed and nonlinear characters. Lin and Schohl [7] performed the
analysis about the application of CFD in butterfly valve field. Chen and Wang [8] investigated fluid
flows through a ball valve and estimated relevant coefficient of a ball valve by STAR-CD. Park
Zachary Leutwyler and Charles Dalton [12-15] studied the pressure and moment characteristics when
the compressible fluid flowing through the symmetric butterfly valve. The above researches all provide
some references for this text.

By taking a standard butterfly valve of gas equipment as the research object in this text, the
numerical simulation of flow field is studied, as well as flow characteristics and aerodynamic moment.

2. Mesh generation and boundary conditions setting

The mesh is the geometric expression of CFD model. The quality of mesh has important effect on
the computational accuracy and efficiency of CFD. Boundary conditions are the solved variables on the
boundary of scatter domain or the discipline of first derivative changing with location and time, so the
problem can be solved only by the proper boundary conditions.

2.1. Mesh model of flow field

The diameter of butterfly valve is $D=2m$ and pipeline length is $L=10D$. Because the mesh model
nearby the butterfly valve is quite irregular, the entire CFD model is divided into two parts: valve body
and pipeline. Denser grids are used near plate area, which is to check flow filed near the valve plate
better. Then the grids of two parts are meshed respectively. The denser unstructured tetrahedral mesh is
used to the valve body, but the higher computational accuracy structured hexahedral grid is used to
pipeline, which advantage is not only giving the exact calculation but also saving the calculation time.
The mesh model of valve with the opening of $40^\circ$ is shown in Fig. 2 and the number of mesh elements
is 133682. The mesh models with other openings are similar with it, but only different in grid quantity.

![Figure 2. Mesh of butterfly valve](image)

2.2. Computation model and boundary conditions setting

(1) Computation model: The viscosity of gas is rather low, mean velocity of flow is less than 50m/s,
the flow state is incompressible turbulence, and the turbulence model is selected as standard $k$-$\varepsilon$ model.
(2) Material parameter: The fluid medium is air with density of 1.225kg/m$^3$, and the temperature is
300K.
(3) Boundary conditions: Velocity inlet and outflow are selected as the boundary conditions and
vin=8m/s. Standard wall function method is adopted at near-wall zones; non-slip boundary condition is
used on solid boundary; the SIMPLE algorithm is employed in the calculation of pressure and velocity;
and second order upwind is adopted as discrete scheme.

3. Control equation about flow filed analysis theory

In the actual numerical solving process, the control equation must be discretized and the discretized
partial differential equations are applied to every grid cells. The flow filed distribution graph can be
drawn based on the data obtained. The airflow flowing through the valve and the pipeline is three-dimensional flow. The sticky double k-ε equation model is adopted as computation model. So the below equations must be followed [9].

1. Incompressible fluid continuity equation
   \[
   \frac{\partial (\rho u_i)}{\partial x_i} = 0 .
   \]

2. Incompressible turbulent motion equation
   \[
   \frac{\partial (\rho u_i)}{\partial t} + \frac{\partial (\rho u_i u_j)}{\partial x_j} = \rho \frac{\partial \overline{u_i}}{\partial x_j} + \frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial u_i}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \frac{\rho \mu}{\sigma_k} \frac{\partial u_i}{\partial x_j} \right).
   \]

3. Standard k-ε equation
   \[
   \mu_t = \rho C_{\mu} \frac{k^2}{\varepsilon} .
   \]

4. Turbulent kinetic energy k equation
   \[
   \frac{\partial k}{\partial t} + u_i \frac{\partial k}{\partial x_j} = v_j \left( \frac{\partial \overline{u_i u_j}}{\partial x_j} \right) - \frac{1}{3} \frac{\partial}{\partial x_j} \left[ \frac{\partial}{\partial x_j} \left( \frac{v_i}{\sigma_k} - v \right) + \frac{\partial}{\partial x_j} \right] - \varepsilon .
   \]

5. Dissipation rating ε equation
   \[
   \frac{\partial \varepsilon}{\partial t} + u_i \frac{\partial \varepsilon}{\partial x_j} = C_{\varepsilon} \left( \frac{\partial \varepsilon}{\partial x_j} \right) - C_{\varepsilon} \frac{\varepsilon^2}{k} .
   \]

In above equations: \(\rho\) is fluid density, \(u_i\) is velocity component of fluid, \(p\) is the pressure acting on infinitesimal bodies of fluid, \(\mu\) is kinetic viscosity, \(\mu_t\) is turbulent viscosity, \(k\) is turbulent kinetic energy, \(\varepsilon\) is dissipation rating. Some model parameters: \(C_\mu=0.09\), \(C_{\varepsilon}=1.44\), \(C_{\varepsilon}=1.92\), \(\sigma_k=1\), \(\sigma_\varepsilon=1.3\).

4. Numerical calculation and analysis of results

4.1. Simulation analyses

With the models established above, set the residual criterion for convergence as 10^{-3}, when the iterations reach about 1000, the results all achieve constringency, and the velocity vector, velocity contours and pressure contours are got from the calculation, some of those are shown in Fig. 3, 4 and 5 respectively.

As shown in Fig. 3, vortex can be seen when air flows around the valve plate. This phenomenon is mainly because the boundary layer separation appears around the backside of valve plate, then fresh airflow is supplementing when boundary layer away from the body and a reverse reflux is formed.

From the Fig. 4, it can be seen that the flow field presents a fairly stable state in upstream of pipeline, however, with the influence of flow past bluff body, flow field becomes disordered and eddies appear at the areas of upper opening and the lower opening. When the valve opening is small, the velocity varies widely and the vortexes are obvious. As the valve opening goes larger, the angle between the valve plate and the direction of air velocity is smaller, and it is beneficial to flow around, then flow filed becomes more and more stable and eddies weakened.
Figure 3. Velocity vector at different openings (a) $\theta=20^\circ$, (b) $\theta=40^\circ$, (c) $\theta=70^\circ$

Figure 4. Velocity contours at different openings (a) $\theta=20^\circ$, (b) $\theta=40^\circ$, (c) $\theta=70^\circ$
As shown in Fig. 5, when air flow around the valve plate, the positive pressure is stable at the upstream of pipeline and the negative pressure is generated near the back of valve plate. With the increase of the opening of valve, the negative pressure zone is gradually expanded and the pressure gradually decreases. At the opening of 60° the negative pressure area begins to come smaller and the pressure becomes bigger, but the pressure gradually decreases and negative pressure region becomes larger again after the opening of 70°. By comparing Fig. 4 and 5, the reasons for the above phenomenon can be known: vortex is generated by the gas flowing around the valve plate, which makes the gas velocity closed to the center of vortex decreases gradually. The dynamic pressure is proportional to the square of velocity, so the pressure reduced significantly and a negative pressure comes out at the local area. The negative pressure zone becomes uniform as the weakening of vortex. Furthermore, the zone is reducing as the vortex disappears gradually.

![Figure 5](image)

**Figure 5.** Pressure contours at different openings (a) $\theta=20^\circ$, (b) $\theta=40^\circ$, (c) $\theta=70^\circ$

4.2. The aerodynamic moment characteristics

In order to obtain the aerodynamic moment characteristics of valve, the pressure inlet and pressure outlet are taken as the boundary conditions in the case of other conditions being equal to simulate the butterfly valve internal once again, and let the differential pressure as 0.2MPa, 0.4MPa and 0.6MPa respectively. Fig.6 shows the pathlines of differential pressures at the maximum aerodynamic moment. It can be seen that there are intenser vortexes for a larger differential pressure.
The total aerodynamic moment of valve for the butterfly valve is \( T_o = T_m + T_f \), wherein, \( T_m \) is the aerodynamic moment and \( T_f \) is the frictional moment of valve. For a small changing of opening, the \( T_m \) will be changed greatly, but the \( T_f \) changed little. Therefore a approximate relationship between the operating torque of butterfly valve and valve opening is found, i.e \( T_o = f(\theta) + C \), wherein, \( f(\theta) = T_m \) and \( C \) is a constant. The z axis is assigned as the rotation axis of valve plate, so the aerodynamic moment about the z axis can be obtained as follow [3].

\[
T_m(\theta) = \sum_{i=1}^{n} F_x \cdot y + \sum_{i=1}^{n} F_y \cdot x
\]

Where \( n \) is the total number of mesh cells, \( z \) is the rotational axis, \( i \) is the limited number of mesh cells.

The Report tool in Fluent is used to find the aerodynamic moment about the z axis at the different openings. The specific procedure are as follows: check the moment label, the moment center is set as (0, 0, 1), and select the two surface of the valve plate, then the moment data are acquired. The relationship is shown in Fig. 7.

Meanwhile, the moments about the x axis and the y axis are obtained in the same way and the results show that the aerodynamic moments are small and can be ignored.

Figure 6. Pathlines of different pressure difference (a) \( p_{in} = 0.2 \) MPa, (b) \( p_{in} = 0.4 \) MPa, (c) \( p_{in} = 0.6 \) MPa

Figure 7. Aerodynamic moment with opening of valve

From the Fig. 7, the moment is monotonically increase with the opening of valve becomes larger. When the opening of valve plate is about 70°, the total moment on the shaft of valve plate being
applied in the both sides of the valve plate reaches the maximum, and then the moment is monotonically decrease. When the opening reaches 90°, the moment is close to zero. When the pressure difference is smaller, the moment increases slowly, and the pressure difference is greater, the moment increases rapidly. In addition, as the pressure difference is gradually increased, the position where the maximum moment occurs shift to left relative to the transverse axis, i.e. when the pressure difference is 0.2MPa, the maximum moment occurs at 74° around, the differential pressure is 0.4MPa, it occurs at about 70°, and with the differential pressure of 0.6MPa, it is at about 65°. In the increasing process of the opening of valve, the flow states of both sides of valve plate are different. The lower side of valve plate moved along the direction of airflow, the upper side is rotated against the direction of airflow. An airflow couple is applied to both sides of the valve, and a total moment on the valve plate is formed. Differential pressure between the positive pressure and the negative pressure on the upper side of valve plate becomes larger in the opening process. So the moment becomes larger gradually. The pressure difference on the lower side is getting smaller and smaller, then the moment is increasingly smaller, and the total moment will inevitably increase gradually. When the opening of valve is increased to a certain angle, the total moment of valve reaches maximum. With the airflow reaction force of the opposite side of valve plate increased gradually, a reverse moment will be formed to prevent the valve to open. If the valve continues to open, the increase of reverse moment will be greater than the forward torque value added, and the aerodynamic resultant moment began to decrease gradually at this time.

5. Conclusions

In this study, it is concluded by the three-dimensional visual simulation of butterfly valves, as the airflow through the valve plate, boundary layer separation occurs after the air flows around the edge of the valve plate because of the blunt bodies flowing around, which makes vortex emerges at the back of valve plate. Thereby a negative pressure is generated. As the valve opening increases, the changes of velocity of airflow decreases, vortex weakened, and meantime the negative pressure area will become uniform. The maximum airflow velocity appeared the back of the valve plate when the airflow through it.

According to the study of the aerodynamic moment of valve, it is concluded that the aerodynamic moment increases gradually until the valve plate is deflected to about 70°. With the opening of valve plate continues to increase, the moment of valve starts to decrease. At the opening of 90° the shaft moments of valve plate on both sides are equal but the directions are opposite and the resultant moment is close to zero. Moreover, as the pressure difference is gradually increased, the point of the maximum moment may shift slightly.

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7. References


