Simulation and Research on Flow-field of Butterfly Valve in Standard Variable Head Flow Device

F. Lu[1], J.M. Zhang[2] , Y.M. Shen[3]

[1,3] University of Shanghai for Science and Technology, 516 JunGong Road, Shanghai, China
[2] Shanghai Institute of Metrology and testing Technology, 1500 ZhangHeng Road, Shanghai, China
E-mail : ym-shen@usst.edu.cn

Abstract

For the butterfly flow-regulating valve commonly used in the variable head flow standard device, the three-dimensional flow field in the valve body was simulated during the flow regulating process by CFD dynamic mesh technology. The flow field changes with cloud maps in the internal and downstream piping of the valve body under several operating conditions of 10°, 30°, 45°, 60°and 90° opening was proposed in the condition of constant water head. The simulation results also show that there are two opposite vortices in the flow field downstream of the valve body at 10° and 30° opening, and the valve opening has a nonlinear function relationship with the flow. Meanwhile, The flow control function of butterfly valve was presented to keep the flowrate constant under variable head conditions. Experiments were carried out on a variable head simulation device with an effective head of 3m and a pipe diameter of 150mm. Experiments show that the control function can be used to open-loop control the butterfly valve, and the control accuracy of flow fluctuation less than 1% can be obtained.

1. Introduction

The butterfly valve is a flow control device for start-stop control or flow regulation in the standard flow device of constant and variable head. In the variable head device, the flow rate in the calibration line is controlled to be close to a stable value by controlling the opening degree of the butterfly valve. In order to obtain the ideal flow characteristics, domestic and foreign scholars have conducted extensive research on butterfly valves. For example, Leutwyler and Shen Yang[3,4] et al. studied the fluid-pneumatic torque characteristics of the centerline butterfly valve under steady-state conditions, and obtained the relationship between the aerodynamic torque and the valve opening under different pressure differences; Using three-dimensional numerical simulation technology, the flow of incompressible fluid inside the butterfly valve under the fixed opening was analyzed by Huang and Kim[5]. The three-dimensional steady-state simulation calculation on the hydrodynamic characteristics of the butterfly valve were performed by Henderson and Yang Zhixian[6,7] respectively. The phenomenon of flow separation and vortex formation in the downstream pipeline of butterfly valve was analyzed, and the variation law of dynamic torque coefficient with valve opening degree was discussed. Most of these studies discuss the torque characteristics of the flow field to the butterfly valve. In this paper, using dynamic grid and CFD technology, three-dimensional dynamic simulation of the internal and upper flow fields of the butterfly valve during the opening process is carried out under the condition of constant water head; the evolution process of the flow field vortex downstream of the butterfly valve is simulated; and for the specific variable head standard device, under the unsteady condition, the butterfly valve-based control function is used to obtain a constant flow with a fluctuation of less than 1% control precision.

2. Modeling and Gridding

Taking the DN150 butterfly valve as an example, take the butterfly valve and the upstream pipe $L_1 = 2D$ (D is the inner diameter of the pipe) and the downstream pipe L_2=10D =10D as the calculation domain. The valve is horizontally placed in the +X flow direction and ignoring the mass force.

The calculation domain is divided into grid using ANASYS ICEM. The calculation domain of the dynamic grid in the 0.5D length range of the upstream and downstream of the butterfly valve is divided into triangle unstructured grids and the grids is encrypted. The total number of grids is about 450,000. The upstream and downstream pipelines of the butterfly valve are divided into tetrahedral grid and connected to the dynamic grid pipeline through the interface. The total number of grids is about 340,000. By programming the UDF code, UDF (User Defined Functions) method is adopted to realize the process of opening the butterfly valve at a uniform rotation speed of 0.05 rad/s. In the process of numerical simulation, the dynamic grids region of the butterfly valve motion is reconstructed by the Smoothing, Layering and Remeshing methods, and the iterative iteration is used to solve the dynamic grid problem of the unsteady flow field during the butterfly valve opening process.

The UDF program for the butterfly revolution:

```
#include "udf.h"
DEFINE_CG_MOTION(moving_body, dt, vel,
omega, time, dtime)
{
    omega[0] = 0.0;
    omega[1] = 0.0;
    omega[2] = 3.14/20;
}
```

The dynamic grid computing domain is shown in Figure 2.

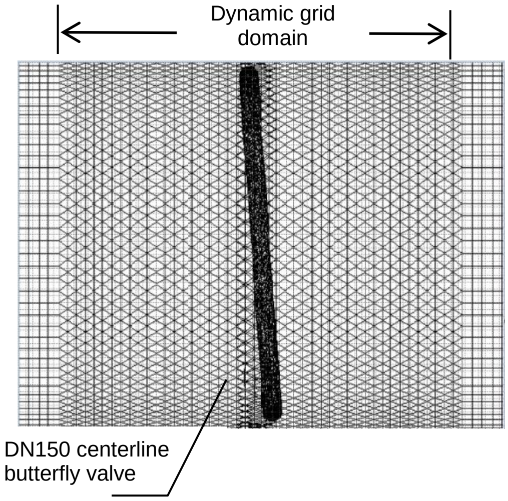


Figure 1: Butterfly valve gridding

3. Control equations and boundary conditions

Assuming that the inside of the butterfly valve is an unsteady, incompressible viscous liquid flow, the Reynolds equations (continuity equation and NS momentum equation) and the Realizable k-ε model with swirl correction are used to form a closed equation group. Among them, the Reynolds average equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \bullet \left(\rho \vec{U}\right) = 0 \qquad (1)$$

$$\frac{\partial}{\partial t}\left(\rho \vec{U}\right) + \nabla \bullet \left(\rho \vec{U}\vec{U}\right) = -\nabla p + \mu \nabla^2 \vec{U} + \vec{S}_M \qquad (2)$$

Where: $\vec{U}$ is the velocity vector of the liquid; p is the liquid pressure; ρ and μ is the density and dynamic viscosity of the liquid respectively.

The transport equations for the turbulent flow energy and dissipation of the Realizable k-ε model are:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_j) = \frac{\partial}{\partial x_i}\left[\left(u + \frac{u_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\varepsilon \qquad (3)$$

$$\frac{\partial}{\partial t}(\rho \varepsilon) + \frac{\partial}{\partial x_j}(\rho \varepsilon u_j) = \frac{\partial}{\partial x_j}\left[\left(u + \frac{u_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_j}\right] + \rho C_1 S_\varepsilon + C_{1\varepsilon}\frac{\varepsilon}{k}C_{3\varepsilon}G_b - \rho C_2 \frac{\varepsilon^2}{k + \sqrt{u\varepsilon}} \qquad (4)$$

Where, $C_1 = \max\left[0.43\frac{\delta}{\delta+5}\right], \delta = S\frac{k}{\varepsilon}$, k is the turbulent flow energy, ε is the turbulent flow dissipation, $C_{1\varepsilon}$, C_2 , $C_{3\varepsilon}$ are constants, G_k , G_b is the turbulent energy generated by the velocity gradient and buoyancy. σ_k , σ_ε is the turbulent Prandtl number, the turbulent viscosity $u_t = \rho \frac{1}{A_0 + A_S \frac{kU}{\varepsilon}} \frac{k^2}{\varepsilon}$, U is a function of laminar flow strain and rotation. S_ε is the user-defined turbulent dissipative source.

Numerical simulations were carried out at two water heads of 3.5m and 2.5m respectively. The boundary conditions are shown in Table 1. The medium is water and is assumed to be an incompressible fluid. Among them, at the water head of 3.5m, the flow rate at the valve opening degree of 20° is simulated; and under the condition that the valve is fully open, the curve of the flow variation from the head of 3.5m head until zero is simulated. At the same time, the opening of the valve from 0° to 90° is simulated separately to observe the flow field change and flow characteristics of water under different opening degrees of the butterfly valve.

Table 1: Boundary conditions

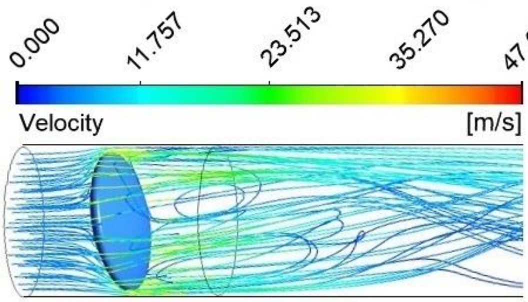
Name	Boundary Type	Value
Inlet	Pressure-inlet	30000 pa

Inlet	Pressure-inlet	25000 pa
Outlet	Pressure-outlet	0 pa
Pipe wall,valve plate	Wall	No slip

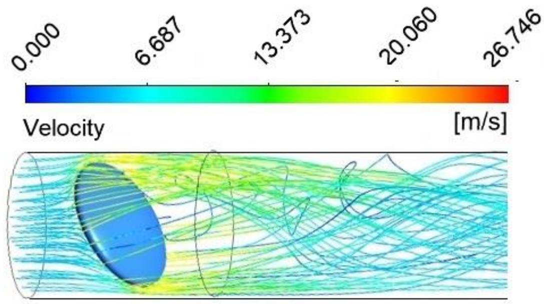
4. Simulation Results and Analysis

4.1 Flow field evolution behind valve

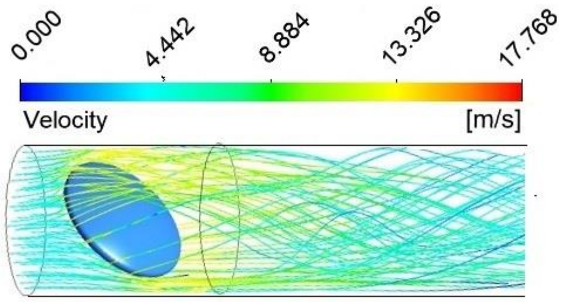
It is assumed that the butterfly valve has the same physical characteristics during the opening and closing process. In this paper, only the opening of the butterfly valve is simulated. Figure 2 shows the evolution of the 5D longitudinal profile flow field of the butterfly valve at the 10°, 30°, 45°, 60° and 90° opening angles during the opening of the butterfly valve from 0° to 90°. It can be seen from the velocity streamline diagram that when the butterfly valve opening α is 10°, two vortices of upper and lower in opposite rotation directions are formed behind the valve. The upper vortex rotates counterclockwise, opposite to the rotation direction of the butterfly valve; the lower vortex rotates clockwise, in the same direction as the butterfly valve. The upper and lower vortexes together affect the flow field behind the valve. When the butterfly valve opening α is 30°, the upper vortex gradually weakens, the flow field is dominated by the lower vortex, and the influence range becomes smaller than before. When the butterfly valve opening α is 45°, the flow field vortex immediately behind the butterfly valve disappears, and a small amount of velocity streamline deflects, but does not affect the overall flow field. When the butterfly valve opening α are 60° and 90°, the flow field behind the valve changes only with the change of valve plate angle. As the angle increases, the speed orientation change is more gradual.



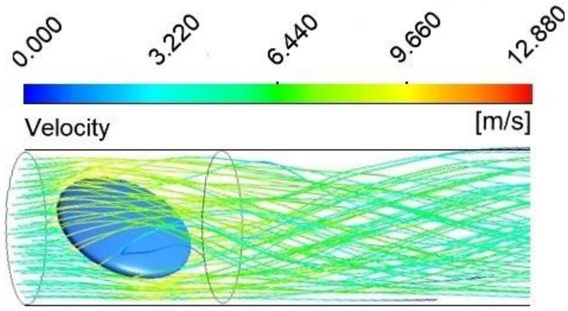
(a) α=10



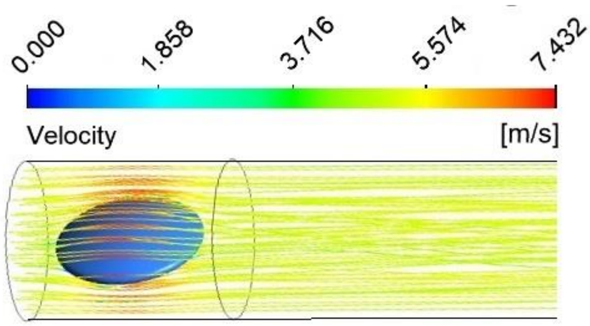
(b) α=30°



(c) α=45°



(d) α=60°



(e) α=90°

Figure 2: Flow diagram of the flow field downstream of the butterfly valve at H=2.5m and different opening degrees

4.2 Flow characteristics

Figure 3 is the calculation result of the flow rate changing with the opening degree of the butterfly valve at the head of H=2.5m. It can be seen from the figure that there is a nonlinear function relationship between the valve opening and the flow rate. Because the butterfly valve is not added with a seal when modeling, the flow rate has reached 90% when the opening is α=45°. During the opening changes from 25° to 45°, the flow rate and the valve opening degree have a fast opening flow characteristic (i.e., a quadratic relationship). While when the opening of the butterfly valve is changed from 0° to 25°, the flow rate and the valve opening are linearly increased rapidly, which is consistent with the trend of flow characteristics obtained by Song Hanwu[10] et al. based on actual experiments on the medium pressure butterfly valve.

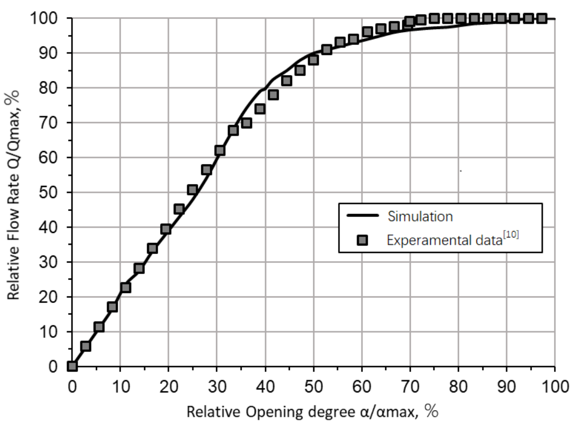


Figure 3: Flow and opening curve of the butterfly valve

For a cylindrical water tank with a height of 3m and a diameter of D=1.5m, Figure 4 shows the simulation results of the relationship between the flow rate and the time when the butterfly valve keeps the valve opening degree constant, that is, at α=90°, 45°, and 30° free outflows and the flow drops. This is consistent with the flow-time function proposed by Zhao Xueduan[11] et al., as shown in (5).

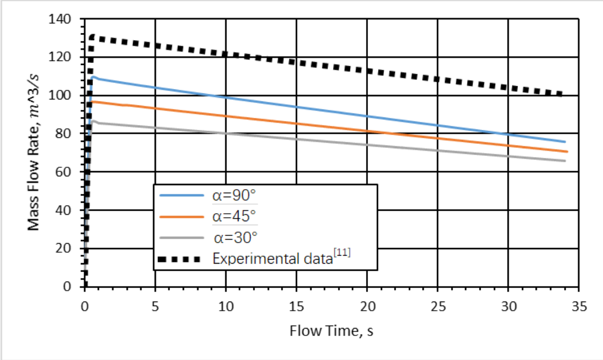


Figure 4: Flow rate versus time curve when the butterfly valve degree is constant

$$Q_1(t) = -\frac{\pi}{2}aD^2t + \frac{\pi}{4}D^2b \tag{5}$$

Where, a and b are constants related to the structure of the device, as shown in Table 2.

Table 2: Values of a and b under different valve opening degrees

Valve opening degree	a	b
90	0.281	61.681
45	0.228	54.721
30	0.168	48.55

Exact solution formula based on the complete venting time of the nozzle outlet container

$$T = \frac{8A}{\mu_j \pi d^2 \sqrt{2g}}\sqrt{H} \tag{6}$$

Where, A is the cross-sectional area of the variable head water tank; d is the diameter of the test pipeline; μj=0.8 is the flow coefficient of the variable head water tank. It can be calculated that when the butterfly valve opening degree α=90°, the complete venting time of the head water tank is T=95.3734s, and the numerical simulation result is about 96.214s. It can be seen that the simulation results are basically consistent with the exact solution.

4.3 Flow resistance characteristics

Under ideal conditions, the opening and closing process of the butterfly valve directly affects the flow resistance coefficient of the butterfly valve, which in turn affects the overcurrent capability of the butterfly valve. Therefore, it is helpful to adjust the flow rate by obtaining the flow resistance coefficient corresponding to the opening degree. Figure 5 is a graph showing the flow resistance coefficient of a butterfly valve under different opening degrees. It can be seen from the figure that the flow resistance coefficient is inversely proportional to the valve opening. With the increase of the opening degree, the flow resistance coefficient tends to decrease. This is consistent with the hydraulics[12] theoretical value and the experimental data of Guan Honger[13].

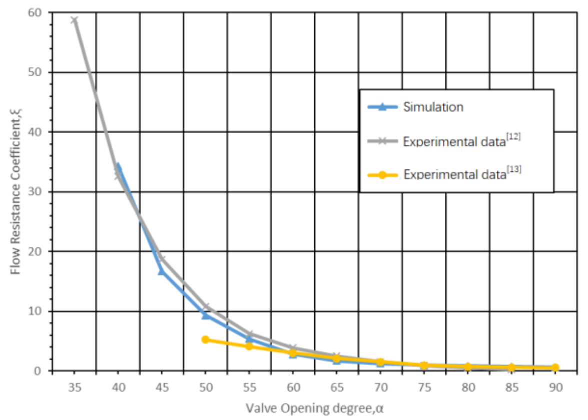


Figure 5: Flow resistance coefficient at different opening degrees

4.4 Establishment of control functions

According to the simulation calculation, the corresponding flow resistance coefficient of the butterfly valve opening at 90°, 45°, 30°, setting of the corresponding back pressure, numerical simulation of the relationship between water level and flow when D=1.5m and cylinder water level drops from 3m to 1m is shown in Figure 6. It is particularly noted that due to the narrow water head range, the relationship between the water level and the flow rate is linear when water level is below 2.98 m.Experimental data[12]

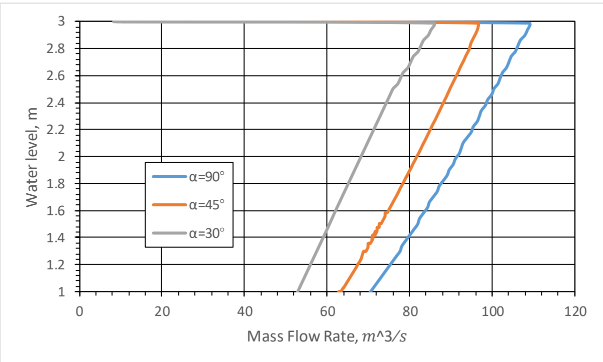


Figure 6: Curve of water height and variable heads flow under various opening conditions

Based on the relationship between the flow resistance coefficient and the opening degree of the butterfly valve and the relationship between the flow rate and the water level at a fixed opening, the curve of the valve opening degree and the water level height under the constant flow rate can be obtained, as shown in Fig. 7.

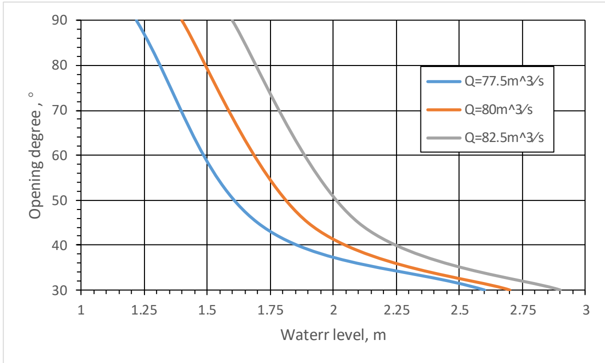


Figure 7: Curve of valve opening and water level

According to Figure 7, under constant flow, the butterfly valve opening and the water level are approximately inversely related, and the mathematical expression is shown in Equation 7:

$$\alpha = \frac{W}{H} \tag{7}$$

Where W is a parameter related to the structure of the device and the height of the water level, as shown in Table 3.

Table 3: W values at different water levels and valve openings when constant flow is 80m^3/s

Water level	Butterfly valve opening	W
2.7	30	81
1.9	45	85.5
1.4	90	126

Experiments show that using the control function to open-loop control the butterfly valve ($Q = 80\,m^3/s, 77.5\,m^3/s, 82.5\,m^3/s$), the control accuracy of flow fluctuation less than 1% can be obtained.

4. Conclusion

In this paper, a three-dimensional numerical model of the butterfly valve pipeline is established for the butterfly valve in the standard variable heads device. Combined with the dynamic grid technology, through the three-dimensional numerical simulation of the opening process of a butterfly valve, the flow vector diagram of the butterfly valve under different opening degrees, the relationship curve between the flow rate and the opening angle of the butterfly valve and the relationship curve between the flow rate and time under full opening condition of the butterfly valve are obtained. At the same time, the butterfly valve control function of the variable head device to ensure the flow fluctuation less than 1% control accuracy is also discussed.

References

[1] Shi Jiabao. Application of large diameter hydraulic control butterfly valve in minjiang river water transfer project [J]. Water Technology, 2012(2): 22-24.
[2] Cui B, Lin Z, Zhu Z, et al. Influence of opening and closing process of ball valve on external performance and internal flow characteristics [J]. Experimental Thermal & Fluid Science, 2016, 80:193-202.
[3] Leutwyler Z, Dalton C. A CFD study of the flow field, resultant force, and aerodynamic torque on a symmetric disk butterfly valve in a compressible fluid [J]. Journal of Pressure Vessel Technology, 2008,130(2): 021302.
[4] Shen Yang, Jin Xiaohong, Yang Ke. Three-dimensional flow field simulation of the butterfly valve and the solution of valve plate driving torque [J]. Chinese Science and Technology Papers, 2013, 8(8): 820-823.
[5] Huang C D, Kim R H. Three-dimensional analysis of partially open butterfly valve flow [J]. Transactions of the ASME, 1996, 118:562-568.
[6] Henderson A D, Sargison J E, Walker G J, et al. A numerical study of the flow through a safety butterfly valve in a hydro-electric power scheme [C]. 16th Australasian Fluid Mechanics Conference, 2007.
[7] Yang Zhixian, Yu Na, Mao Weiping, et al. Numerical simulation and flow characteristics analysis of flow field of central butterfly valve [J]. Hydraulic & Pneumatics, 2016(1): 95-99.
[8] Youngchul P, Song X. Numerical analysis of large diameter butterfly valve [M]. Advances in Computational Algorithms and Data Analysis. Springer Netherlands, 2009:349-363.
[9] Toro A D, Johnson M C, Spall R E. Computational fluid dynamics investigation of butterfly valve performance factors [J]. Journal American Science and Technology, 2012, 26(9): 2799-2806.
[10] Song Hanwu, Wu Rongfang. Experimental study on flow and resistance characteristics of butterfly valves [J]. Power Generation Equipment, 1995(2): 3-4.
[11] Zhao Xueduan, Zheng Ronggen. Numerical analysis of standard variable head and big flow system [J]. Journal of University of Shanghai for Science and Technology, 2011(1):1-10.
[12] Wu Chigong. Hydraulics [M]. Beijing: Higher Education Press, 2003.
[13] Guan Honger. Numerical simulation of internal flow field and structural static analysis of butterfly valve and multi-plate valve [D]. Liaoning: Northeastern University, 2010.