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Effect of Shaft Diameter on the Hydrodynamic Torque of Butterfly Valve Disk

In this study, computational fluid dynamics (CFD) software and detached eddy simulation turbulence model were used to simulate butterfly valves with different designs. The effects of shaft diameters on the value and the fluctuation of valve disk torque were studied, and the physical reason was discussed. The simulation results were verified by comparing with the experimental data. The findings revealed that with the closing of the valve, the hydraulic torque of the valve disk first increases and then decreases. Meanwhile, the torque decreases gradually with the increase of the shaft diameter. The variation of torque is caused by the change of pressure on both sides of the valve disk. The result also indicates that the fluctuation of torque is induced by the flow separation phenomenon occurs on the valve disk. The fluctuation is significant for the valve opening from 20% to 60%. The strength of the torque fluctuation is greater for the smaller shaft diameter. This study provides a theoretical basis for the design and optimization of butterfly valves.

[DOI: 10.1115/1.4047795]

Keywords: butterfly valve, shaft diameter, hydrodynamic torque, fluctuation, numerical simulation

1 Introduction

Availability of energy is one of the most important issues in today's society. Energy exploitation, transportation, and utilization have always been popular research topics [1–6]. Valves are indispensable components in pipeline systems for energy transport and are used for the regulation of the transmission media. The butterfly valve is a common regulating valve with a rotatable disk as

the control structure. When the valve is opening, the difference in fluid pressure in different areas of the valve disk forms a torque on the rotating shaft. The value and change law of the torque have a great influence on the design and use of the valve body, the transmission mechanism, and the control mechanism. Therefore, a lot of research has been conducted on the valve disk torque and the flow characteristics in the butterfly valve [7–20].

Caraballo [7] used three-dimensional topology and genetic algorithm to optimize the butterfly valve disk. Sun et al. [8] studied the effect of friction coefficient on the flow coefficient of a tri-eccentric butterfly valve by numerical simulation. Toro et al. [9] investigated the accuracy of using computational fluid dynamics (CFD) technology to predict the performance of butterfly valves.

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Contributed by the Fluids Engineering Division of ASME for publication in the JOURNAL OF FLUIDS ENGINEERING. Manuscript received October 21, 2019; final manuscript received July 2, 2020; published online August 7, 2020. Assoc. Editor: Praveen Ramaprabhu.

The author concluded that the numerical simulation results are accurate at medium openings. Song et al. [10] integrated a met model with finite element method and CFD analysis and used Taguchi orthogonal array technique and Kriging model to obtain the minimum weight of butterfly valves. Yi et al. [11] proposed an optimal design method for butterfly valves by considering the structural safety and flow characteristics. Wang et al. [12] placed a double butterfly valve in a curved channel and investigated the flow in the pipe and the aerodynamic torque of the valve disk with different closing times. Lattouf and Huynh [13] analyzed the flow field of a large caliber butterfly valve by using the CFD method and discussed the maximum torque acting on the valve shaft. Farid and Mahdi [14] also used the CFD method to calculate the torque of a large butterfly valve with different working conditions and openings. The effects of disk shape and deformation, surface roughness, upstream/downstream pressure, and disk offset were also acquired. Morris and Dutton [15] experimentally studied the compressible flow fields inside circular and parallel butterfly valves. The variations of torque on the surfaces of valve disks were also investigated and analyzed. Leutwyler and Dalton [16] used the CFD method to investigate the subsonic and supersonic internal flow fields of a butterfly valve. The aerodynamic torque of valve disk was analyzed with an opening of 45 deg and 70 deg. Morris and Dutton [17] measured the aerodynamic torques of butterfly valves by employing experimental methods and obtained the effects of valve disk shape, flow separation, and reattachment position on the aerodynamic torques of butterfly valves. Nasera-dinmousavi and Natraj [18] analyzed the opening and closing processes of a butterfly valve. The results indicated that the hydrodynamic torque plays an important role in both processes. Liu et al. [19] examined the effects of inlet speed, particle mass fraction, and solid particle diameter on the performance of a butterfly valve. Baran et al. [20] conducted cavitation experiments on a DN100 butterfly valve with different valve openings and discussed the cavitation evolution.

In summary, most research on butterfly valve focuses on internal flow fields and the valve disk torque by using CFD and experimental methods. But the research on torque is mainly in steady-state. According to the flow around the blunt body, it was found that the flow separation around the bluff body caused pressure pulsation, which in turn caused transient effects [21,22]. The flow in the butterfly valve is also similar to the flow around the blunt body, and pressure fluctuations will also occur on the valve disk. Long-term instantaneous pressure pulsation will cause torque fluctuations that will affect the strength of the rotating shaft, valve disk and actuator, and cause fatigue fracture. The rotating shaft is an important part for the transmission of valve torque. Its diameter affects the structure of the valve disk (a large shaft diameter results in a thick valve disk), thus changing the flow performance of the butterfly valve. However, in previous studies, the variation of valve disk torque with the diameter of the shaft has not been obtained. Therefore, it is necessary to analyze the fluctuation of the valve disk torque with different shaft diameter.

The CFD method has been effective in investigating the internal flow and the corresponding problems in hydraulic components, such as pumps, valves, tubes, etc. [23–41]. Thus, in this study, butterfly valves with different shaft diameters (different valve disks) were explored by transient CFD simulations. The time-averaged disk torque was compared and analyzed. The effect of shaft diameter on the valve disk torque was obtained. To explain the reason for the variation of the disk torque, pressures on the surfaces of disks were also extracted for in-depth analysis. The fluctuation of the instantaneous torque under different opening degrees was also studied for the first time. This study provides a reference for the optimization of butterfly valves.

2 Problem Statement

This research used a DN50 butterfly valve as the research object, and the structure is illustrated in Fig. 1. The butterfly valve

Fig. 1 Structure of the butterfly valve

is mainly composed of four parts: valve body, rotating shaft, seal ring, and disk. The valve disk rotates from 0 deg (fully closed) to 90 deg (fully open). The working medium is water, and the density is 998.2 kg/m³. The tests and simulations were initially performed for the original valve disk to verify the simulation.

A nondimensional parameter Z was used to represent the relationship between the rotary shaft and the valve disk

$$Z = \frac{D_{\text{shaft}}}{D_{\text{disc}}} \quad (1)$$

where D_{shaft} denotes the diameter of the shaft, whereas D_{disc} denotes the diameter of the disk. In this study, the Z value of the original model is 0.36. Three valve disks were then created on the basis of the original model to investigate the effect of the shaft diameter. The valves examined had Z values of 0.1, 0.2, and 0.4.

In the simulation, 14 pressure monitoring points were set on the midsection of the valve disk, as shown in Fig. 2. A1, A2, G1, and G2 denote the end points of the valve disk. B1, B2, F1, and F2 denote the midpoints of the disk. C1, C2, E1, and E2 denote the junction points of the shaft and the flat disk. D1 and D2 denote the vertexes of the shaft.

3 Experimental Method

Figure 3 illustrates the schematic and shows a photograph of the experimental system. The valve test system is a closed cycle hydraulic loop and includes a water tank, a variable-frequency pump, many circulation pipes, certain pressure sensors, a flowmeter, a torque meter, and a test valve. The main purpose of the experiment is to measure the pressure at the inlet and outlet and the torque of the valve disk, so as to provide the basis for the accuracy of the subsequent numerical simulation. The pipe diameter (D) of the tube is 50 mm. The test range of the flowmeter is 0–60 m³/h. The test range of pressure sensors is 0–150 kPa, with the measuring accuracy of 0.2%. The range of the torque meter is 0–20 N·m, with the measuring accuracy of 0.001 N·m. Four pressure holes (top, bottom, left, and right) were drilled around the cross sections (5D upstream the valve and 10D downstream), and the average pressure for each section was calculated. The rotating

Fig. 2 Position of monitoring points

Fig. 3 The structure of the computational domain

shaft of the butterfly valve was connected to the torque meter. A bearing was added to the shaft to reduce the friction torques and to make them smaller than the corresponding hydrodynamic torques. Pressures and torques were recorded when they were basically stable.

In the experiment, the idling torque (friction torque) for each valve opening was measured first. Then, the torque of the working state as recorded. Finally, the actual hydrodynamic torque was calculated by adding idling torque with working torque. The uncertainty of torque measurement is caused by turbulence fluctuation and the measurement accuracy. To reduce the experimental error, each experiment was repeated ten times, and the average values were calculated. Uncertainty evaluations were performed for ten tests, and the results are shown in Fig. 4. The maximum uncertainty of the torque measurement is $\pm 1.6\%$ (Relative to the mean torque). The experimental uncertainties of the pressure, the

Fig. 4 Mesh of the computational region

Fig. 5 Schematic of the experimental system

Fig. 6 Uncertainty of experimental results

mass flowrate, and the valve flap angle are $\pm 1.1\%$, $\pm 0.4\%$, and $\pm 0.7\%$, respectively. The Reynolds number of all working conditions in this paper ranges from 6831 to 88826.

Uncertainty U was calculated as follows:

$$U = \sqrt{U_a^2 + U_b^2} \quad (2)$$

$$U_a = \sqrt{\frac{\sum_{i=1}^n (y_i - \bar{y})^2}{n(n-1)}} \quad (3)$$

$$U_b = \alpha / \sqrt{3} \quad (4)$$

where y is the measured value of each experiment, $\bar{y}$ is the average of ten tests, n is the number of tests, and α is the measurement accuracy of the instrument.

4 Numerical Method and Validation

To obtain the flow characteristics inside the butterfly valve, the CFD method was used with the commercial software ANSYS-FLUENT 15.0. In the simulation procedure, the computational region was divided into three parts: upstream pipework, butterfly valve, and downstream pipework, as displayed in Fig. 5. The length of the upstream pipe is five times of the pipe diameter, and the downstream pipe is ten times of the pipe diameter.

To ensure the quality of the grid and improve the calculation efficiency, the mesh in the valve part was refined, as shown in Fig. 6. The performance characteristics of the butterfly valve with different opening were achieved using transient simulation. Steady numerical results obtained by the realizable $k-\epsilon$ model were set as the initial condition. To achieve adequate resolution of unsteady simulation results, time-step is set as $\Delta t = 1 \times 10^{-4}$ s, and convergence criteria of the momentum and mass are also set as 5×10^{-5} . The total pressure inlet and static pressure outlet were adopted for the inlet and outlet boundaries (the pressure values at the inlet and outlet of different opening degrees are shown in Table 1). Nonslip boundary conditions were used for wall surfaces. The pressure values were determined in accordance with the experimental values under different openings.

By the comparison of the transient simulation methods, in order to ensure the calculation accuracy and reduce the calculation resources, the detached eddy simulation method [42–45] was

Table 1 Boundary conditions of different valve openings

Open angle (°)	Inlet pressure (kPa)	Outlet pressure (kPa)
10	97.67	15.36
20	97.10	16.41
30	95.55	16.95
40	90.85	21.76
50	79.52	16.65
60	68.92	18.42
70	49.30	21.34
80	41.18	23.93
90	38.03	25.25
100	36.81	25.52

adopted. This method combines the advantages of the large eddy simulation (LES) method and the Reynolds-averaged Navier–Stokes (RANS) equation method. It handles the motion of large-scale vortices in the flow field by using the LES method, while calculates the boundary layer of the appendage by using the RANS method. This method has also been applied and verified in the simulations of the transient internal flow properties and the flow-induced problems of pumps and valves [46–48]. The solver type was pressure-based, and the pressure–velocity coupling scheme was simple. Spatial discretization selected the second-order upwind, whereas the momentum chose bounded central differencing.

The grid independence test was performed for the original butterfly valve. Table 2 shows the deviation of average torque between two adjacent grids. After grid sensitivity checks, it is

Table 2 Change of torque with grid number

Grid number (million)	M (N·m)	Discrepancy (%)	Experimental value (N·m)
1.03	0.266535	0.74	0.3116
1.46	0.268512	12.57	
2.11	0.307119	2.60	
3	0.315327	0.29	
3.83	0.316256	0.11	
4.55	0.315896		

found that the discrepancy of the torque is smaller than 0.29% when the overall mesh element exceeds 3×10^6 . Thus, the grid number of 3.8×10^6 was applied for the whole computational region. The mesh must guarantee the y plus <30 in the critical computational domain.

Numerical torques of the original valve disk for different valve openings were obtained and compared with the experimental results, as displayed in Fig. 7. The simulation results agree well with the experimental results, and the largest relative difference between them is 4.5%. Therefore, the present simulations are accurate and reliable.

5 Results and Discussion

In this research, the numerical simulation method is used to study butterfly valves. The changes of the valve disk torque and the surface pressure distributions of the different shaft diameters of the butterfly valves are discussed. The details are as follows.

5.1 Instantaneous Torque Fluctuations. Figure 8 shows the time-history fluctuation of torque for the valve opening of 30%, 60%, and 90%. A large shaft diameter makes a relatively small fluctuation amplitude, that is, the fluctuation is the strongest for $Z = 0.1$. Meanwhile, the torque fluctuation decreases as the valve opening increases. When the valve opening is 30%, the fluctuation amplitude for $Z = 0.1$ is 4.45% (relative mean torque). The fluctuation amplitude changes to 1.42% when the valve opening becomes 60% and changes to 1.41% when the valve opening turns to 90%. The figure also demonstrates that the fluctuations are irregular for most situations. For the cases of the valve opening of 90% and $Z = 0.2$, torque periodically fluctuates. In this case, the deviation of the leading edge from the central axis is exactly equal to the radius of the rotating shaft. When Z increases to 0.4 (valve opening of 90%), the rule of periodicity changes, and the uniform periodic fluctuation turns to the repeat of a period of stochastic fluctuation.

5.2 Time-Averaged Torque. The disk torque fluctuates around a value after 0.1 s, so the torque of different valve openings between 0.1 s–0.45 s was averaged, as shown in Fig. 9. It also covers the time response of all key flow structures. As valve opening increases, the torque coefficient increases first and then decreases. The maximum torque occurs at the valve opening between 50% and 60% due to the variation of pressure distribution on the valve disk. This variation is caused by the change of flow fields. These factors are discussed in Sec. 5.6. By comparing the results of different shafts, the maximum torque decreases as Z increases.

Fig. 7 Comparison of simulation results with experimental data

The mean square deviation of disk torque between 0.1 s and 0.45 s is calculated to express the intensity of torque fluctuation, as shown in Fig. 10. The larger the mean square deviation, the more violent the fluctuation. The figure illustrates that the torque fluctuation is relatively large when the valve opening varies between 20% and 60%. The maximum value occurs at the valve opening of 30%. When the opening is larger than 60%, the fluctuation intensity decreases as valve opening increases. Meanwhile, the small shaft diameter leads to a greater torque fluctuation.

5.3 Valve Disk Pressure Distribution. The change of valve disk torque is caused by the pressure distribution of the valve disk. Figure 11 shows the distribution of the static pressure on the valve disk when the opening is 30%, 60%, and 90%. For the valve opening of 30%, the pressure in the middle of the front side is relatively high, and the value decreases toward the edge and shows a convex trend. The pressure distribution on the left side is symmetrical with that on the right side, but the high-pressure area on the left side is slightly larger than that on the right side. For the valve opening of 60%, the pressure on the front side is unevenly distributed, and the pressure at the inlet end is greater than the pressure at the outlet end. For the valve opening of 90%, the pressure at both ends of the front side is high, the pressure of the shaft part is low, and the whole body has a concave distribution. However, the pressure at the inlet end is greater than the pressure at the outlet end. The low-pressure zone easily appears at the top of the front side rotating shaft, and the high-pressure zone easily appears at the junction of the rotating shaft and the valve plate. This phenomenon is evident as the diameter and opening of the rotating shaft increases.

The back side of the valve disk is in the separation zone, and the pressure of the back side is smaller than that of the front side. The pressure at the edge of the valve disk and the shaft is low. This phenomenon is also evident as the opening and diameter of the shaft increase. The uneven distribution of the valve disk pressure leads to the change of the valve plate torque. The more uneven the pressure distribution on the upstream and downstream sides of the valve disk, the greater the valve plate torque.

5.4 Valve Disk Centerline Pressure Change. To obtain the specific pressure value on the valve disk, the pressure distribution on the valve disk centerline is extracted. Figure 12 illustrates the static pressure distribution of the monitoring points along the valve disk centerline, in which the longitudinal coordinate represents the time-averaged static pressure value of the monitoring point. In addition, the abscissa represents the monitoring point. For the valve opening of 30%, the difference in the pressure distribution of the shaft portion is small. As the valve opening increases, the low pressure occurs in the shaft portion, and the low-pressure value on the shaft decreases as the diameter of the shaft increases. The maximum pressure can appear at the junction of the shaft and the valve disk (point C). The pressure distribution in the middle of the valve disk (from points B to F) is symmetrical, and the pressure values at points A and G are quite different. The pressure at both ends of the valve disk has a greater influence on the torque of the valve plate. On the front side, the pressure at point A1 is greater than the pressure at point G1. On the back side, the pressure at point A2 is less than that at point G2, and the pressure difference between points A1 and G1 is greater than that between points A2 and G2. Therefore, the pressure distribution on the front side has a greater influence on the torque than that on the back side.

The pressure difference between the front and back sides is calculated. The pressure difference in the middle of the valve disk is found relatively symmetrical and has little effect on the torque. The pressure difference at the inlet end of the valve disk (A1–A2) is the largest, and the pressure difference at the outlet end of the valve disk (G1–G2) is the smallest. Therefore, the pressure difference between the two ends of the valve disk has a greater impact

Fig. 8 Time history variation of butterfly valve torque under different opening degrees

on the valve plate torque. For the opening degree of 30%, the pressure difference at the inlet end (A1–A2) of the valve disk with different Z values is basically the same, and that at the outlet end (G1–G2) increases as the Z value increases. Hence, the torque of the valve disk decreases as the diameter of the shaft increases. For the opening of 60%, the pressure difference at the inlet end (A1–A2) increases as the Z value decreases and that at the outlet end (G1–G2) increases as the Z value increases. Thus, the disk torque decreases as the diameter of the shaft increases. For the opening of 90%, when $Z = 0.4$, the pressure difference at the inlet end (A1–A2) is the largest, and the pressure difference at the inlet end of other valve disks is small. The pressure difference at the outlet end (G1–G2) of the different disk is basically the same. Therefore, the valve plate torque decreases as the diameter of the shaft increases.

Pressure fluctuation in different areas of the valve disk causes the fluctuation of the valve plate torque. The pressure fluctuation on the valve disk centerline was extracted. Figure 13 shows the static pressure fluctuation of the monitoring point along the valve disk centerline when the opening is 30%, 60%, and 90%. The longitudinal coordinate represents the variance of static pressure fluctuation at the monitoring point, and the abscissa represents the monitoring point. When the opening degree is small, the pressure fluctuations at both ends of the valve disk are severe. As the opening increases, the maximum pressure fluctuation intensity in the valve disk decreases. However, the influence of pressure fluctuation on the shaft area can be evident, especially the pressure fluctuation at the top of the shaft as the opening and Z value increase. Therefore, the pressure fluctuation at the end of the valve disk and at the top of the shaft is large. Moreover, the pressure fluctuation

Fig. 9 Torque coefficients of valve disk for valve openings

Fig. 10 Torque fluctuation of valve disk under different opening degree

at point G1 is greater than that at point A1 on the front side, and the pressure fluctuation at point A2 is greater than that at point G2 on the back side.

5.5 Valve Disk Front and Rear Edge Pressure Difference Changes. From the above analysis, the pressure changes of the front and rear edges of the valve disk have a great influence on the torque of the valve disk. Therefore, pressure monitoring points are

set at the front and rear edges of the valve disk, and the pressure difference between the front and rear edges of the valve disk is obtained. The time variation of the pressure difference between the front and back of the valve disk over the period 0.1–0.45 s is shown in Fig. 14. The ΔP represents the differential pressure at corresponding monitoring points A and G. For the opening degree of 30%, the pressure difference at the inlet end (A1–A2) fluctuates greatly, and the amplitude of the pressure difference fluctuation of the $Z = 0.1$ disk is up to 21% (relative mean pressure difference). The amplitude decreases as shaft diameter increases. The pressure difference at the outlet end (G1–G2) is small. The amplitude decreases as the shaft diameter increases. Therefore, the amplitude of the torque fluctuation decreases as the shaft diameter increases. For the opening of 60%, the fluctuation intensity of pressure difference between inlet and outlet is less than 30%; hence, the fluctuation of torque is small. The pressure difference of $Z = 0.1$ is the most severe, so the torque fluctuation of the small diameter disk is also severe. Moreover, the pressure difference at the inlet end of $Z = 0.4$ valve disk fluctuates periodically, but the irregular fluctuation at the outlet destroys the periodicity. Thus, the torque does not fluctuate periodically. For the opening of 90%, the pressure fluctuation at the inlet end and outlet end is small. At this time, the pressure difference fluctuation of the valve disk with $Z = 0.4$ is intense. Under the influence of the shaft, the flow of the valve disk with large diameter can be unstable, which can cause additional fluctuation of the pressure difference. The pressure difference between the inlet and outlet of the valve disk with $Z = 0.2$ has periodic fluctuations because the deviation of the leading edge from the central axis is exactly equal to the radius of the rotating shaft. At this time, the medium flow state is suitable for the valve disk, and the flow can be stable. As a result, periodic pressure fluctuations occur, as shown in Fig. 10, at which time the disk torque also produces periodic fluctuations.

5.6 Flow Field Distribution. Figure 15 displays the pressure distribution on the cross section near the valve disk. Figure 16 Velocity streamline distribution shows the streamline distribution near the valve disk. For the opening of 30%, the restrictive action of the valve disk reduces the flow area, the flow velocity near the front side is low, and a large part of the high-pressure area appears in front of the valve. Flow separation occurs at the edge of the valve disk. Hence, the edge velocity of the valve disk is high, and the pressure is low. Behind the disk, the pressure is small because of the flow separation. This condition also leads to the pressure distribution illustrated in Fig. 11. For the opening degree of 60%, the change of flow area leads to the change of velocity near the

Fig. 11 Valve disk pressure distribution

Fig. 12 Pressure distribution on the valve disk centerline

Fig. 13 Pressure fluctuation on the valve disk centerline

front face, which makes the pressure field in front of the valve nonuniform. At this time, the influence of the shaft increases, the flow separation at the shaft becomes more serious, and the low pressure can appear in the shaft. At the junction of the shaft and the valve disk, stable vortices can be found, and the fluid can stagnate, thereby indicating high pressure. For the opening of 90%,

the flow area increases, the flow velocity increases, the pressure value before the valve decreases, the pressure difference between the front and back sides decreases, the flow separation phenomenon at the shaft becomes more serious, the pressure at the shaft is the smallest, the diameter of the shaft increases, and the flow separation phenomenon at the shaft becomes more evident. Comparing

Fig. 14 Time difference of pressure difference between the front and rear edges of the valve disk

Fig. 15 Pressure distribution of butterfly valve

the pressure distribution of butterfly valves under different working conditions, the separation point at the inlet end of the valve disk is found close to the back side, whereas the separation point at the outlet end is close to the front side. Therefore, in Fig. 12, the pressure at the inlet end of the back side is low, whereas that

at the outlet end of the front side is low. In the vicinity of the separation point, the pressure fluctuates greatly. Hence, the pressure fluctuation at the outlet end of the front side in Fig. 13 is greater than the inlet end, and the pressure fluctuation at the inlet end of the back side is greater than the outlet end.

Fig. 16 Velocity streamline distribution

6 Conclusions

In this study, the effects of shaft diameter on the value and the fluctuation of valve disk torque were analyzed by numerical simulation. Three kinds of shaft diameters and ten kinds of openings are discussed. The validity of the simulation results was verified by comparing the time-averaged torque of butterfly valve disk with the experimental results.

The results show that the hydrodynamic valve disk torque increases first and then decreases with the closing of the butterfly valve. Meanwhile, the hydrodynamic valve disk torque decreases gradually with increases of the shaft diameter. This is caused by the pressure distribution on the front and back sides of the valve disk. The more uneven the pressure distribution on both sides of the valve disk, the greater the torque. It is also indicated that the torque fluctuation of the valve disk is intense and disordered when the opening is small, and it becomes regular with the increase of valve opening. The strength of torque fluctuation decreases with the increases of the shaft diameter. The results reveal that the fluctuation of the torque is induced by the pressure fluctuation at both ends of the valve disk, which is caused by the flow separation occurs on the valve disk.

Funding Data

- National Natural Science Foundation of China (Grant No. 51876193 and Grant No. 51976197; Funder ID: 10.13039/501100001809).
- Key Research and Development Program of Zhejiang Province (Grant No. 2020C03099; Funder ID: 10.13039/50110004731).

Nomenclature

- D = pipe diameter (mm)
 M = torque (N·m)
 P_{avg} = average pressure (kPa)
 SD = mean square error
 Z = ratio of rotary shaft diameter to valve disk diameter
 U = uncertainty
 ΔP = pressure difference (kPa)

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