Investigation on the influence of valve opening on measurement accuracy for ultrasonic flowmeters

Jieqiang Ji[1], Xuemei Geng[1], Yan Fang[1], Xiaojie Wu[1], Guofu Chen[1], Ningning Zhang[1], Zhiyu Fang[1], Leming Cheng[2]

[1]Zhejiang Province Institute of Metrology, Hangzhou, China, 310018.
[2]State Key Laboratory of Clean Energy Utilization, Institute for Thermal Power Engineering, Zhejiang University, Hangzhou, China, 310027.

E-mail (corresponding author): jjqq@zju.edu.cn

Abstract

The applications of portable clamp-on ultrasonic flowmeters in on-line detection have lots of advantages. However, the measurement accuracy of ultrasonic flowmeters is often affected by various factors, such as pipe characteristics, flow fields and fluid medium. In this work, both experiments and CFD simulations are carried out to study the flow field changing caused by valves, and the influences of valve opening on measurement accuracy for ultrasonic flowmeters.

The experiment results showed that, with the decrease of valve opening, the value of repeatability of indication error is increasing. At the same valve opening, with the distance closer to the valve, the deviation of the indication error for multiple measurements is increasing. In the simulation section, an error calculation model based on the numerical simulation is proposed, which is in good agreement with the experimental results. Both ball valve and butterfly valve are calculated, and the following conclusions are obtained: (1) for the ball valve, when the distance of measurement point to valve is less than 10D, the indication error is greatly affected by the orientations of linear velocity extracting (U_L). When the valve opening is lower than 50%, the variation tendency of measurement error at different orientations of U_L are relatively random. (2) Compared with the ball valve, the variation tendency of measurement error downstream of the butterfly valve are more regular. With the increase of the distance to the butterfly valve, the measurement error is less affected by the orientations of U_L. The correction factors of error at different distances downstream of the butterfly valve are given for different valve opening degrees.

Key words: Metrology; On-line detection; Ultrasonic flowmeter; Flow field; CFD simulation

1. Introduction

Nowadays, the portable clamp-on transit time ultrasonic flowmeter (TTUF) is more and more widely used in on-line detection for large-scale pipework[1]. According to the measurement principle of the TTUFs, the factors affecting the measurement accuracy can be divided into geometric factors, signal factors, flow field factors and medium factors[2]. Among them, the flow field variation has a greater impact on the measurement accuracy of the TTUFs.

For the TTUFs, the linear average velocity along the pipeline direction is detected directly during measurement. In order to obtain the fluid flowrate, the linear average velocity should be converted into the surface average velocity along the pipeline direction. Two methods are usually used to calculate the surface average velocity of the fluid, one is the weighted integral method, and the other is to introduce the flow field correction coefficient (k factor)[3]. The latter method is often used for the single beam measurement principle of TTUFs, and the k factor can be obtained from the mathematical expressions by analysing the relationship between the detected line average velocity and the surface average velocity of actual flow. In Sanderson's work[1], the k factor variation with Reynolds number for smooth pipes was proposed. In fully developed flow, the value of k depends on Reynolds number and pipe wall roughness.

For the measurement positions in water industry, it is hard to form a fully developed flow, due to the influences of pumps, valves, curved pipes and other disturbances[4, 5]. The asymmetric flow field distribution and the radial component of velocity will change the direction and velocity of the ultrasonic propagation, and then affect the measurement of transit time, thus affecting the accuracy of flow measurement[6]. Therefore, it is important to investigate the influences of various disturbances on the flow fields of pipework and measurement accuracy of the TTUFs.

The previous studies about the effects of disturbances on the flow field and measurement accuracy of TTUFs are summarized as follows. Zheng[7] studied the influences of pipe diameter, flow velocity and the straight pipe length on the flow field of the downstream of the single elbow for TTUFs. Tang[8] used the CFD method to study the effects of straight pipe, 90° elbow and 180° elbow on fluid velocity distribution. In 1999[9] and 2002[10], the National Engineering Laboratory (NEL) of the United Kingdom used LDV test and CFD simulation to study the downstream flow field of flow disturbances such as reducer, diffuser, single elbow, double elbow and three elbow. It is reported that the measurement accuracy of TTUFs will be affected by the arrangement of ultrasonic channel, the installation position of ultrasonic probe and the amount of ultrasonic channels.

There are relatively few studies on the flow field affected by valves and the measurement accuracy of TTUFs. In literature[11-13], the FLUENT was carried out to simulate the internal flow field of different types of valves such as ball valve, butterfly valve and stop valve, and the calculation results were used to optimize the structure of the valves. In Zhang's work[14], numerical simulations were applied to study the pressure drop in the pipeline for different valve openings, and the water hammer caused by rapid opening and closing of valves in pipelines has also been studied. Guo[15] used the FLUENT combined with user-defined functions (UDF) to investigate the mechanisms of water hammer caused by valve closing in a straight pipeline. All of the above researches focus on the transient procedure of valve opening and closing. However, the flow field distribution and its effects on measurement accuracy of TTUFs at the exact valve openings is rarely mentioned in the previous literature, and it is the main content of this work.

2. Experiment study

The experiments are implemented in the volumetric water flow standard facility. It is composed of power system, pressure stabilizing equipment, straight pipe of upstream and downstream, fluid diverter and stand volume, which is shown in Figure 1. The flowrate range of the device is (1~2000) m^3/h, and its expanded uncertainty (k=2) is 0.05%. The diameter of pipe is from 125 mm to 400 mm. The clamp-on transit time ultrasonic flowmeter used in the test is the FLUXUS F601 (FLEXIM), and its maximum allowable error is ±1.0%. During the experiments, the water temperatures are controlled at about 20 ℃. The positions of the measurement points are shown in Figure 2. The distance of the measurement point to the ball valve is 5D.


Figure 1. Volumetric water flow standard facility

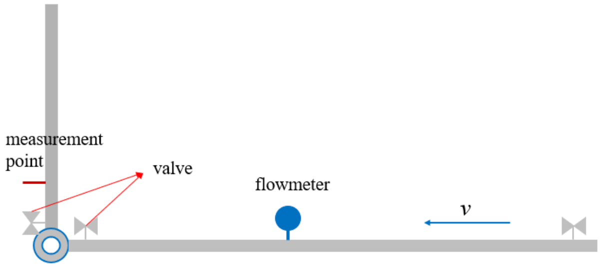

Figure 2. Position of the measurement points

The valve is a typical disturbance in the pipework. When the valve is not fully open, the flow field in the pipeline will be disturbed, resulting in changes in fluid velocity and pressure distribution, which will affect the measurement accuracy of the TTUFs. In order to study the influences of the change of ball valve opening on the measurement accuracy of the TTUF, a series of tests are carried out in the facility of Figure 1. The indication errors of the TTUF at different valve openings (15%, 25%, 50%, 60%, 100%) are obtained, which is shown in Table 1. It can be seen that when the valve opening is higher than 50%, the standard deviation of three measurements at the same flow rate are less than 1.0%. As the valve opening is reduced from 50% to 15%, the deviation of the indication error for three measurements is increasing. It shows a worse repeatability test result when the valve opening is lower than 50%.

From the experiment study, it shows that the changes of valve opening have an impact on the measurement accuracy for TTUF, and more attention should be paid when the opening is under 50%.

Table 1. Indication error under different valve openings

Position	Opening (%)	Flowrate (m^3/h)	Error (%)	Repeatability (%)
5D downstream from the ball valve	100	976	3.10	0.65
		987	4.21	
		980	3.58	
	60	896	-2.34	0.36
		906	-1.67	
		905	-1.69	
	50	862	-2.11	0.11
		864	-2.32	

		862	-2.17	
	25	558	0.26	4.3
		578	3.63	
		538	-3.58	
	15	248	-11.6	8.7
		289	3.05	
		268	-4.44	

3. Numerical simulation

2.1 Modelling

In this section, the calculation method is proposed. The calculation object is the facility shown in Figure 1. The 3-D structure of the facility are constructed by the software of SolidWorks, and it is appropriately simplified in the modelling. The meshes are generated by the software of Gambit. All the computational domain is divided by hexahedral mesh, while the tetrahedral mesh is applied for the header part. The meshes approaching the pipe wall and ball valve are refined. Approximately 600000 grids cells are contained in the meshes.

The standard *k*-*ε* turbulence model is selected. The fluid medium is liquid water, and its density is 998.2 kg/m^3. The boundary conditions of the pipe inlet and pipe outlet are velocity inlet and outflow, respectively. The interface is adopted for the connection surface between the computational domain. The dynamic grid technology is used to realize the switch of ball valve in the pipeline, and the code is compiled by the user-defined function (UDF). The pressure-velocity coupling is realized by SIMPLE algorithm. The first order upwind discrete scheme is used for turbulent kinetic energy and turbulent dissipation term calculation.

Contours of the velocity distribution for 50% valve opening are displayed in Figure 3. It shows that the half open of valve leads to the distortion of the velocity distributions. An obvious boundary is shown between the high velocity zone and the low velocity zone. With the increase of the distance to the ball valve downstream, the axial velocities tend to be uniformly distributed.

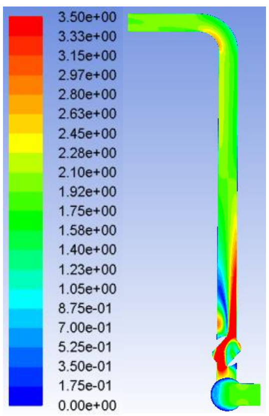

Figure 3. Contours of the velocity distribution for 50% valve opening (m/s)

Furthermore, an error calculation model based on the numerical simulation is proposed. The errors of flowrate at different positions could be calculated based on (1) ~ (3):

$$U_A^D = U_L^D \cdot F \quad (1)$$

$$F = U_A / U_L^{\infty} \approx U_A / U_L^{out} \quad (2)$$

$$\varepsilon = (U_A^D \cdot S - U_A \cdot S)/(U_A \cdot S) \quad (3)$$

where *ε* is the error, *F* is the correction factor, *S* is the sectional area. U_L^D, U_L^{out} is the mean linear velocity at position D, outlet. U_A^D is the mean velocity of cross section at position D.

Based on equations (1) ~ (3), the errors obtained from the simulation result are compared with those in Table 1. A good agreement is shown between the simulation and test results.

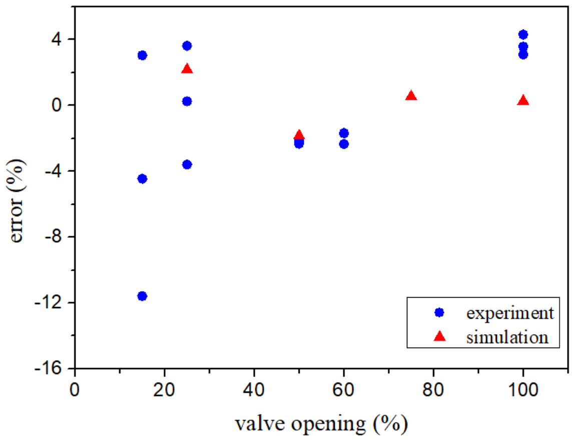

Figure 4. Comparisons between simulation and test results

2.2 Effects of ball valve opening

In order to investigate the influences of valve opening on measurement accuracy for ultrasonic flowmeters, a long straight circular pipe is selected as the simulation object in this section. The diameter of the pipe is 15 mm, and the ball valve is placed in the middle of the pipe. The distances between the ball valve and the pipe inlet, as well as the pipe outlet, are both 200 mm. The modelling process could be found in our previous work[16].

In this simulation, the unsteady calculations are proceeded. Figure 5 shows the error variation with the time when the valve opening is 50%. It can be seen that the error at each position basically remains unchanged with the increase of time, indicating that when the calculation time is more than 10s, the flow field in the pipeline is in a stable state.

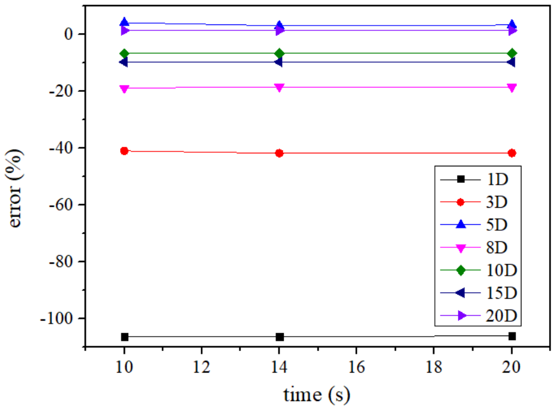

Figure 5. Error variation with time when the ball valve opening is 50%

The calculation results of t=20s are selected for further analysis. Figure 6 shows the relationship between the calculation errors and downstream distance of ball valve (L_d) at different valve openings (indication errors are exacted from z=0). It can be seen that the absolute value of the calculation error gradually decreases with the increase of the distance from the valve. When the L_d is less than 10D, the changes of valve opening have a great impact on the measurement accuracy for TTUFs. The deviation of the indication error at different positions is larger for 50% opening, when comparing with those for 25% and 75% openings. It should be noticed that the calculation errors of 75% opening are positive, which are opposite to those of 25% opening and 50% opening.

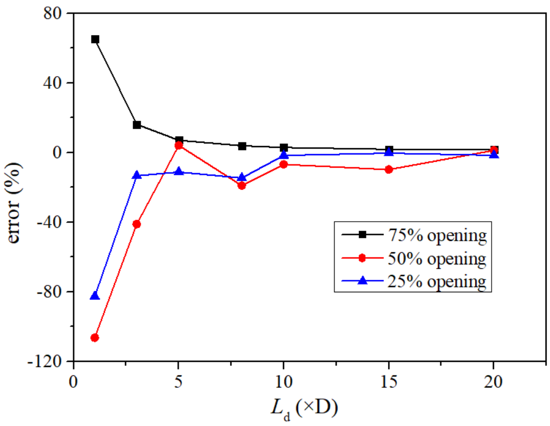

Figure 6. Relationship between the indication errors and L_d

For the single beam measurement principle of TTUFs, the orientations of linear velocity extracting may affect the measurement accuracy for TTUFs, which are discussed as follows. In this section, the calculated errors are exacted from four typical orientations (z=0, x=0, x=z and x=-z) for comparison, as shown in Figure 7. The rotation direction of the ball valve is marked by the red arrow in Figure 7. Figure 8~10 display the calculation results.

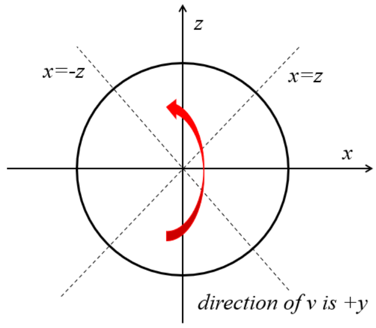

Figure 7. Orientations of extracting linear velocity

From Figure 8~10, it can be seen that the calculated errors obtained from different orientations of liner velocity are quite different when the L_d is less than 10D, indicating that the changes of valve opening induce obvious velocity distortions. With the increase of the L_d, the calculated errors of different orientations gradually approach.

Comparing the calculated errors of different valve openings, it can be seen that the variations of calculated errors show a regular tendency with the increase of L_d at 75% opening, which are quite different from those at 50% opening and 25% opening. It could be obtained from Figure 8~10 that the orientations of extracting linear velocity have a greater impact on the measurement accuracy for TTUFs with the decreasing of ball valve opening.

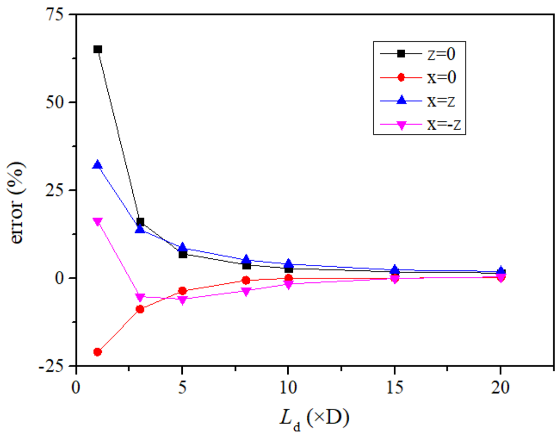

Figure 8. Calculated errors for different L_d at 75% valve opening

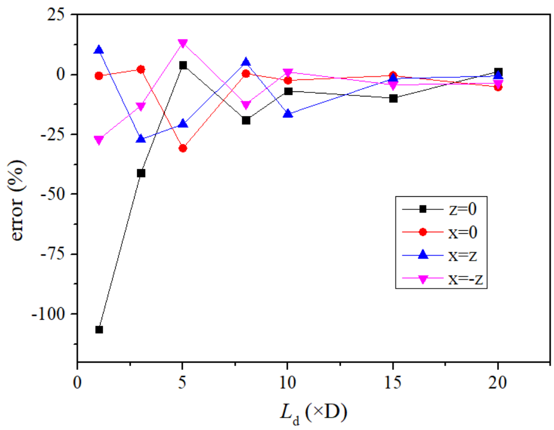

Figure 9. Calculated errors for different L_d at 50% valve opening

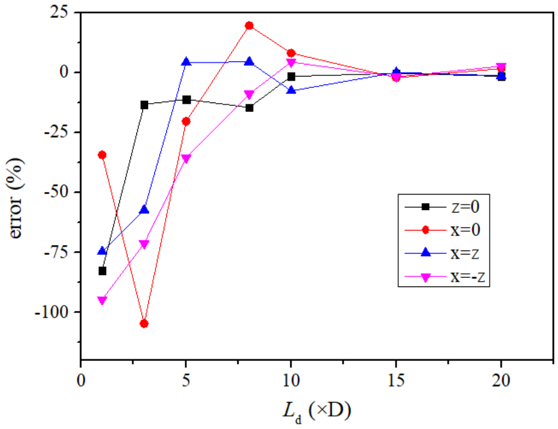

Figure 10. Calculated errors for different L_d at 25% valve opening

It can be concluded that when the downstream distance of ball valve is less than 10D, the measurement accuracy is greatly affected by the orientations of liner velocity. Hence, for the L_d is less than 10D, it is difficult to find an appropriate correction formula to eliminate the influences of ball valve opening during on-line measurement for TTUFs.

2.3 Effects of butterfly valve opening

In this section, the influences of butterfly valve openings on the measurement accuracy for TTUF are investigated using the 3-D simulation for comparisons with those of ball valve. The simulation object is the same as that in section 2.2, and the butterfly valve is arranged at the same position in the straight circular pipe. Tetrahedral mesh is used for the whole computing domain. Approximately 360000 grids cells are contained in the meshes. The calculation models, boundary conditions, fluid parameters are set as the same as that in section 2.2.

Figure 11 shows the variation of calculated errors with the real time at 50% valve opening. It shows that when the real time is more than 10s, the calculated errors are almost kept constant with the increase of real time.

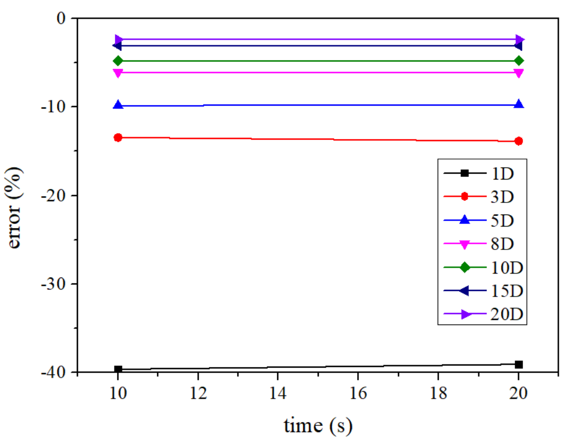

Figure 11. Error variation with time when the butterfly valve opening is 50%

The calculation results of t=20s are taken for further analysis. It can be seen from Figure 12 that the calculated errors gradually decrease with the increase of L_d for different valve openings, and the variations of calculated errors of different valve openings show a same tendency. In Figure 12, all the calculated errors are negative for different valve openings at each distance of downstream of the butterfly valve, which are quite different from those in Figure 6, indicating that different types of valves will affect the measurement accuracy for TTUFs in different ways.

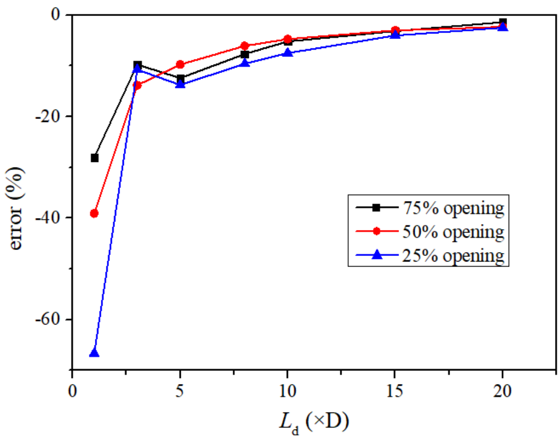

Figure 12. Relationship between the indication errors and L_d

In order to study the influences of orientations of extracting linear velocity on the measurement accuracy for TTUFs, the calculated errors are exacted from four typical orientations (z=0, x=0, x=z and x=-z) for comparisons.

From Figure 13~15, it can be seen that the variations of error curve of x=0 are quite different from those of the other three orientations. The calculated errors gradually approach 0 with the increase of L_d. As the distance to the butterfly valve increases, the calculated errors at different orientations gradually approach. According to the results in Figure 13~15, when the L_d is greater than 5D, the measurement error could be modified by corrections. Table 2 shows the reference values of correction factors from the simulation results.

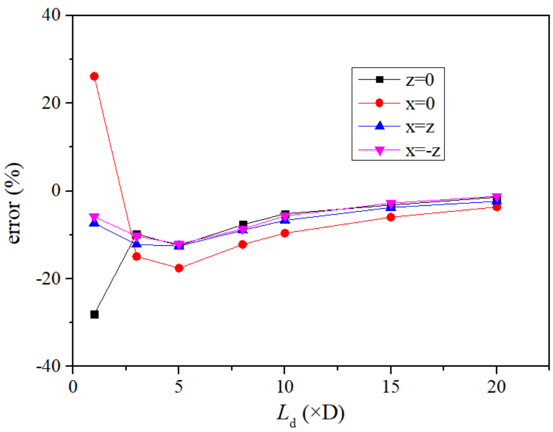

Figure 13. Calculated errors for different L_d at 75% valve opening

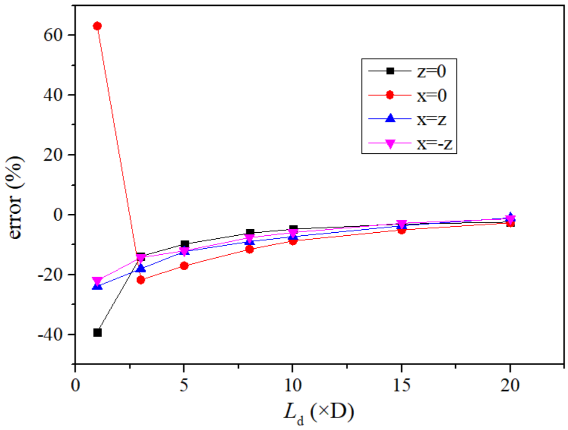

Figure 14. Calculated errors for different L_d at 50% valve opening

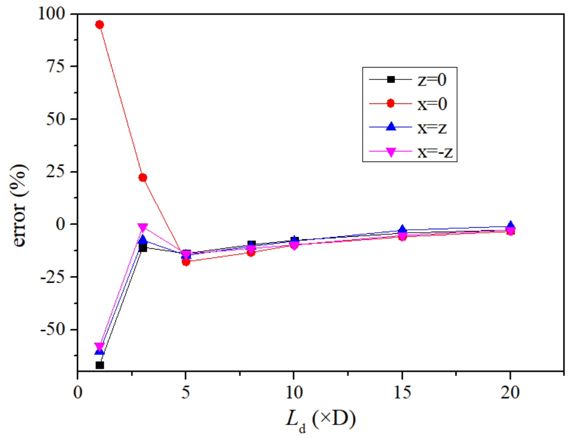

Figure 15. Calculated errors for different L_d at 25% valve opening

Table 2. Correction factors at each position at different butterfly valve openings

Opening	5D (%)	8D (%)	10D (%)	15D (%)	20D (%)
75%	14	9	7	4	2
50%	13	9	7	4	2
25%	15	11	9	4	2

4. Conclusions

Experiments and CFD simulations are carried out to study the influences of valve openings on measurement accuracy for TTUFs in this work.

From the experiment results, with the decrease of valve opening, the value of repeatability of indication error is increasing. At the same valve opening, with the distance closer to the valve, the deviation of the indication error for multiple measurements is increasing.

For the simulation section, an error calculation model based on the numerical simulation is proposed, which is in good agreement with the experimental results. Both ball valve and butterfly valve are calculated, and the following conclusions are obtained: (1) for the ball valve, when the valve opening is lower than 50%, the variation tendency of measurement error at different orientations of U_L are relatively random. When the L_d is less than 10D, it is difficult to find an appropriate correction formula to eliminate the influences of ball valve opening during on-line measurement for TTUFs. (2) Compared with the ball valve, the variation tendency of measurement error downstream of the butterfly valve are more regular. With the increase of the distance to the butterfly valve, the measurement error is less affected by the orientations of U_L. The correction factors of error at different distances downstream of the butterfly valve are given for different valve opening degrees.

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