EFFECT OF FLOW DISTURBANCE ON MULTI-PATH ULTRASONIC FLOWMETERS

Liang Zhang, Heming Hu, Tao Meng, Chi Wang
Division of Thermometry and Materials Evaluation,
National Institute of Metrology, China
No.18, North Third Ring Road East, Chaoyang Dist, Beijing, P. R. China
E-mail: zhangliang@nim.ac.cn

Abstract: Experimental study of multi-path ultrasonic flowmeters measurement accuracy in complex flow fields was carried out in the water flowrate standard facility of National Water Large Flowrate Measurement Station. Several muti-path ultrasonic flowmeters with different path arrangement were studied. The flow disturbances were created by bend, tapered pipe, diverging pipe and butterfly valve. By studying the measurement errors of different types of ultrasonic flowmeters, it is confirmed that the cross plane ultrasonic flowmeter is more adaptable to the complex flow field. The installation angle of flowmeter affects measurement accuracy. The sources of measurement error were analysed by CFD simulation.

Keywords: Multi-path ultrasonic flowmeter; Installation effect; Disturbance; Cross plane; Installation angle;

1. Introduction

With the increasing demand of large diameter water flow measurement in turbine efficiency monitoring, large water transfer project and industrial process control, multi-path ultrasonic flowmeters have been widely used. As a velocity-type flowmeter, the ultrasonic flowmeter measurement accuracy is impacted by the flow fields inside the pipe. To ensure the accuracy of measurement, certain lengthes straight pipe upstream and downstream of the flowmeter installation position are required. But sometimes due to on-site condition, this requirement can not be met. The flow disturbances caused by bend, tapered pipe, diverging pipe and butterfly valve upstream of flowmeter affect the measurement accuracy. How to choose the path arrangement, installation angle and the distance from upstream disturbance are the critical factors for improving the flowmeter measurement accuracy.

Several authors have studied the installation effect of single and dual diametric path ultrasonic flowmeters. Hojholt et al[1] studied the impact of flow field disturbance on single and dual path ultrasonic flowmeter. The Study showed that in order to obtain better measurement results, 40D upstream straight pipe is needed for an axially disturbed flow, and 80D upstream straight pipe length is not enough for a rotational flow. Heritage et al[2] studied the effects of gate valve, single and double bends, straight-sided reducer on downstream single and dual path ultrasonic flowmeter measurement accuracy, which showed single path ultrasonic flowmeter installed 15D downstream of the disturbance still had large error. Double bend had significant impact on both single and dual path flowmeter. Compared with single path flowmeters, dual path flowmeters have smaller measuremt errors in the same flowfield. Hakansson et al[3] observed that measurement error associated with the meter installation angle.

Compared with single-path ultrasonic flowmeters, multi-path ultrasonic flowmeters can get richer flow field data, therefore the measurement accuracy has been greatly improved[4-8]. National Engineering Laboratory[9-11] investigated the installation effects of double and triple bends on diametric-path and multi-path ultrasonic flowmeter. Studies show that in a complex flow field measurement accuracy is very sensitive to the path arrangement, mid-radius multi-path ultrasonic flowmeter need shorter straight pipe length and have higher measurement accuracy than single and dual diametric-path ultrasonic flowmeter. IEC41[12] and PTC18[13] point out that, in order to obtain a lower measurement error, 8-path cross plane ultrasonic flowmeter need 10D upstream length and 3D downstream length for normal disturbance, and need more than 20D upstream straight pipe for pump disturbance, 4-path single plane flowmeter require more than 20D upstream straight pipe.

Although there are many research papers related to ultrasonic flowmeter installation effect, previous studies did not involve more than 8-path ultrasonic flowmeter and the study aiming at installation effect of batterfly valve is very limited. In this paper, measurement errors of multi-path ultrasonic flowmeter with different path arrangement and installation angle downstream of bend, tapered pipe, diverging pipe and butterfly valve were obtained experimentally. The sources of measurement errors were analyzed using Computational Fluid Dynamics(CFD) method. The recommended path arrangement, installation angle and upstream straight pipe length were obtained.

2. Experimental Test Method

2.1 Test Facilities

The experiment was carried out in the water flow standard facility of Kaifeng national water large flowrate measurement station. The uncertainty of this facility is 0.1% and it uses static volumetric method. The experimental system is shown in Figure 1. A 20m high tower is used to stabilize the pressure, while flow control valves are used to adjust the flowrate. Part of test lines are inside the building and the other part are outdoor. The indoor test lines can directly calibrated using a static volumetric tank. The outdoor test lines use a magnetic flowmeter and a 5-path ultrasonic flowmeter as transfer standards. The experiment was conducted in DN1000 test line, which maximum flowrate can reach 3.5m/s. The experiments of tapered pipe, diverging pipe and butterfly valve installation effect were conducted in the indoor test line. Due to space limitation, experiment of bend installation effect was carried out in the outdoor test line, while the electromagnetic flow meter was used as the transfer standard, and the 5-path ultrasonic flowmeter was used for data verification. Before and after the experiment, standard electromagnetic and ultrasonic flowmeters were calibrated using the standard volumetric tank.

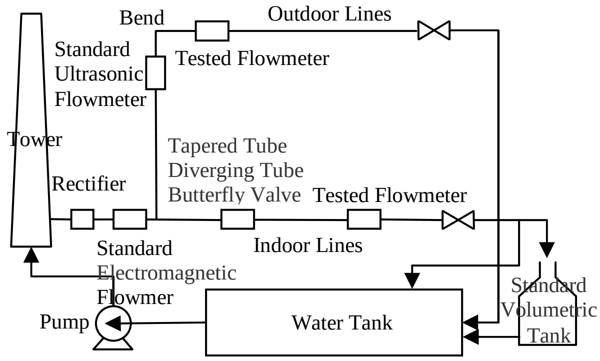


Fig. 1 Experimental setup

2.2 Test Meters

A DN1000 18-path wetted-transducer ultrasonic flowmeter was used in this study. The flowmeter transducer were installed between the protrusion and recessed position(the center points of transducers were located on the pipe wall cylinder)[14-15], which can minimize the errors caused by transducer protrusion or recess. The flowmeter path angle is 65°and the meter path arrangement is based on Gauss-Jacobi integration. According to PTC18, the transducer positions of 8-path ultrasonic flowmeter are the same as A2, B2, A4, B4, A6, B6, A8 and B8 transducer positions of 18-path ultrasonic flowmeter, therefore the flowrate of 8-path ultrasonic flowmeter can be obtained by integrating the relative path velocity values. In addition, in order to reduce the impact of non axial velocity on the flowrate measurement in the case of not increasing the number of path, some flowmeter manufacturers use staggered arranged cross plane ultrasonic flowmeter. Therefore the flowrate measurement value of different path arrangement flowmeters based on Gauss-Jacobi integration can be obtained using the path velocity of 18-path ultrasonic flowmeter. The measurement accuracy in disturbed flow fields of these meters can be compared. The flowmeter path arrangements in this paper are shown in Table 1.

2.3 Test Procedure

Before each set of installation effect experiments, the ultrasonic flowmeter was test in long straight calibration pipeline as reference condition. The errors caused by disturbed flow condition were calculated according to formula (1). By subtracting the flowmeter errors in reference state, flowmeter inherent errors were excluded. Different path arrangement flowmeter subtracted its own error in the reference state.

$$\text{Error} = \text{Error}_{Disturb} - \text{Error}_{Refernece} \quad (1)$$

Install effect experiments include the following parts.
(1) Install effect of bend
(2) Install effect of tapered pipe
(3) Install effect of diverging pipe
(4) Install effect of butterfly valve (valve fully open, 45° opening, 20° opening)

The experimental condition varied. The distances between the flowmeter and disturbance were 1D, 3D and 10D. The flow rate range was from 0.5m/s to 3.5m/s. In the bend and butterfly valve installation effect experiments, the meter installation angles included 0° and 90°. When the accoustic plane (consist of two crossed paths) parralael to the plane of bend, the installation angle is 0°. Moreover, when the accoustic plane perpendicular to the valve shaft, the installation angle is 0°.

Tab. 1 Ultrasonic flowmeter path arrangement

Plane	A									B								
Path No.	1	2	3	4	5	6	7	8	9	1	2	3	4	5	6	7	8	9
18AB	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•	•
9A	•	•	•	•	•	•	•	•	•									
9B										•	•	•	•	•	•	•	•	•
9AB	•		•		•		•		•		•		•		•		•	
9BA		•		•		•		•		•		•		•		•		•
8AB		•		•		•		•			•		•		•		•	
4A		•		•		•		•										
4B											•		•		•		•	
1A					•													
1B														•				
1AB					•									•				

3. CFD simulation method

The commercial computational fluid dynamics software Fluent was used to simulate the flow fields. The simulation setup was speed inlet, pressure outlet, and no-slip wall boundary conditions, while the upstream inlet velocity was assumed to be fully developed turbulent pipe flow. After comparing and screening, Reynolds Stress Model was finally adopted, which is considered suitable for simulation of secondary flow in the pipeline. The near-wall flow was handled using non-equilibrium wall functions, the pressure interpolation used Second Order scheme, while the convective kinematics used QUICK scheme. The average axial and transverse velocities of each path were obtained by linear interpolation, which were used for installation effect error analysis.

4. Result and discussion

4.1 Installation effect

4.1.1 Installation effect of bend

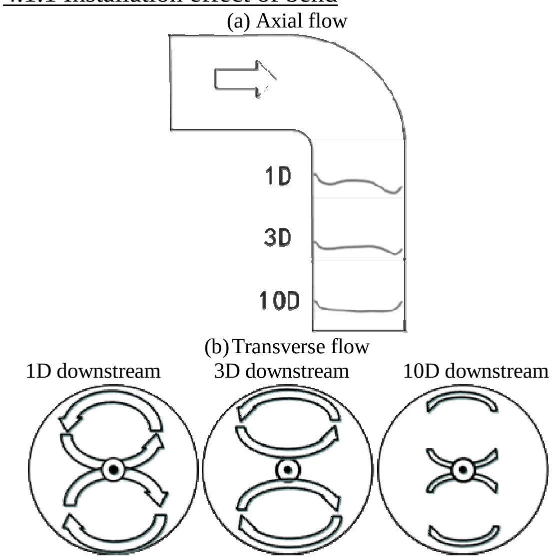
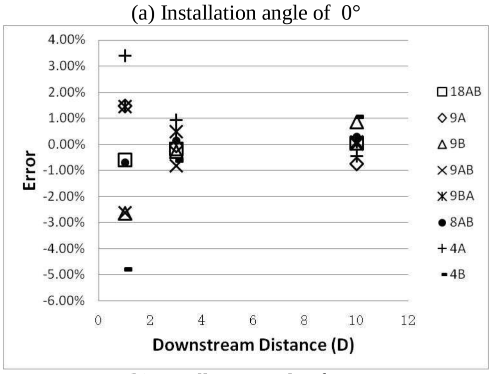


Fig. 2 Downstream flow field of the bend

The axial velocity distribution is changed after the fluid flow through the bend, at the same time transverse flow is produced. The flow disturbance impacts the measurement accuracy of ultrasonic flowmeter installed in the downstream. The axial and transverse velocity distribution can be obtained by the path velocities of cross plane multi-path ultrasonic flowmeter, as shown in Figure 2. As the downstream distance increase, the axial flow gradually become fully developed velocity profile, at the same time the transverse flow gradually reduce, so the ultrasonic flowmeter measurement error decreases, as shown in Figure 3. When the distance reach 10D, the measurement errors of different path arrangement multi-path ultrasonic flowmeters are within ± 1.1%.

The Flowmeter accuracy is correlate to the meter installation angle. When the flowmeter installation angle is 0°, the transverse flow within the pipeline has large components in the accoustic planes. But when the flowmeter is installed at an angle of 90 °, the accoustic plane is perpendicular to the main direction of transverse flow, and the transverse flow components for each path are symmetrical. Therefore the measurement error of the flowmeter installed in 0°is larger than it installed in 90°.

(a) Installation angle of 0°



(b) Installation angle of 90°

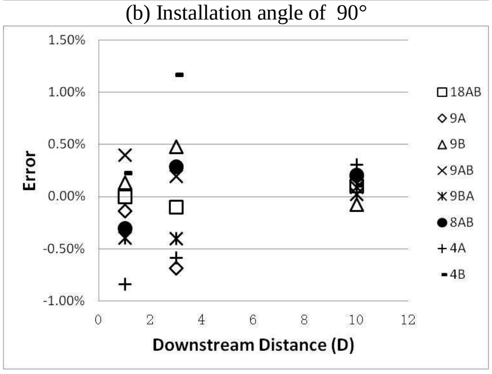
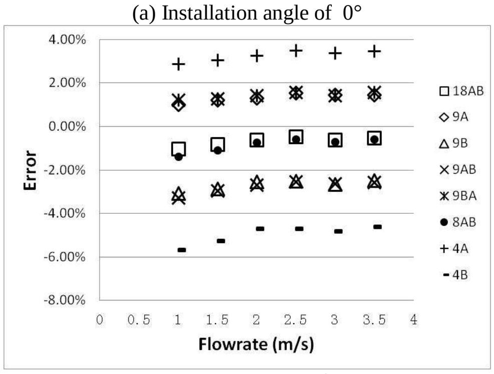


Fig. 3 Multi-path ultrasonic flowmeter installation effect in different downstream distances of the bend (3m/s)

The bend flow disturbance has different impact on multi-path ultrasonic flowmeters with different path arrangements. When calculate the errors caused by flow disturbance, the flowmeter inherent errors are already subtracted, so the errors only reflect the impact of disturbed flow field. The measurement errors of different path arrangements flowmeter 1D downstream of the bend are shown in Figure 4. Compared with other flowmeters, the flowmeter with cross plane (18AB and 8AB) achieve the highest accuracy. The measurement errors of 18AB and 8AB installed in 0° are less than ± 1.1% and ± 1.4%, the errors of flowmeter installed in 90°are less than ± 0.4% and ±1.1%, respectively. It is difficult to distinguish which kind of flowmeters, staggered layout (9AB, 9BA) and single plane(9A, 9B, 4A, 4B), are more accurate downstream of the bend, the errors depend on the pipe axial and transverse velocity distribution.

Compared with the multi-path ultrasonic flowmeters, single and dual diametric-path ultrasonic flowmeters measurement errors are large, as shown in Figure 5. The measurement errors of single path ultrasonic flowmeters installed in 0° and 90° angle, 1D downstream of the bend, can reach -43.2% and -17.9%. Even the downstream distance increase to 10D, the errors can get -11.7% and -9.4% respectively. The measurement accuracies of crossed dual path flowmeters are better. The errors can reach -11.8% and -13.0% for the flowmeters installed in 0° and 90° angle, 1D downstream of the bend, and the errors can reach -4.9% and -4.3% 10D downstream of the bend.

(a) Installation angle of 0°



(b) Installation angle of 90°

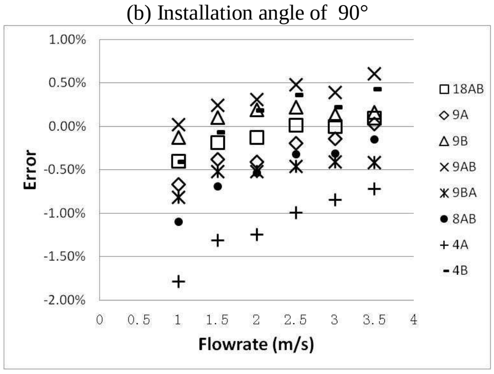


Fig. 4 The measurement errors of multi-path ultrasonic flowmeter 1D downstream of the bend

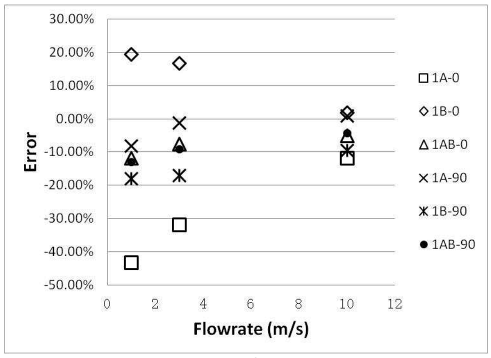


Fig. 5 The measurement errors of diametric single and dual path ultrasonic flowmeters downstream of the bend

4.1.2 Installation effect of tapered pipe and diverging pipe

The tapered pipe and diverging pipe have less impact on the downstream flow field. The axial velocity distribution downstream of tapered pipe is relatively flat compair with the fully developed tubulent flow. In contrast, the center position of the axial velocity downstream of diverging pipe is higher, and the near wall flow rate decrease rapidly. In the tapered pipe and diverging pipe extremely weak single vortex exists. In contrast to the flow field downstream of the bend, the disturbances created by tapered pipe and diverging pipe are symmetrical, so measurement errors are small, as shown in Figure 6 and Figure 7. The multi-path ultrasonic flowmeter measurement errors caused by tapered pipe are within ± 0.5%. As the downstream distance increases, the measurement error decreases significantly. In 10D downstream of the tapered pipe, measurement errors are within ± 0.1%. Compared with the error caused by tapered pipe, the multi-path ultrasonic flowmeter measurement errors caused by diverging pipe are slightly larger, which are within ± 0.6%. In 10D downstream of the diverging pipe, measurement errors are within ± 0.25%. For the cross plane multi-path ultrasonic flowmeter, measurement errors of 18AB and 8AB caused by tapered pipe are less than ± 0.26% and ± 0.31%, the measurement errors caused by diverging pipe are less than ± 0.31% and ± 0.50%, respectively. In most cases of tapered pipe and diverging pipe installation effects, staggered layout multi-path flowmeters have higher accuracy than single plane flowmeters.

The measurement errors of single and dual diametric-path ultrasonic flowmeters downstream of tapered pipe and diverging pipe are also small. Because the transverse velocity is small, the errors of single and dual path meter are similar. The measurement errors of diametric flowmeter 1D and 10D downstream of the tapered pipe can reach -3.9% and -3.4%, and the errors downstream of the diverging pipe can reach -6.3% and -2.5%.

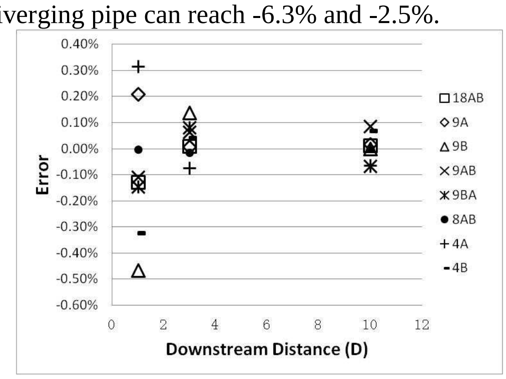


Fig. 6 Multi-path ultrasonic flowmeter installation effect in different downstream distances of the tapered pipe (3m/s)

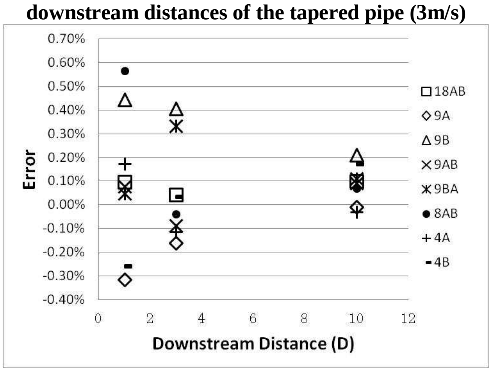


Fig. 7 Multi-path ultrasonic flowmeter installation effect in different downstream distances of the diverging pipe (3m/s)

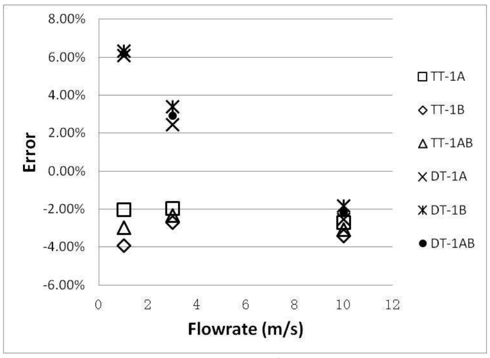


Fig. 8 Single and dual diametric path flowmeters installation effect in different downstream distances of the tapered pipe and diverging pipe (3m/s)

4.1.3 Installation effect of butterfly valve

The butterfly valve create strong downstream flow disturbances. Especially when the valve opening is small, strong transverse flow is formed in short distance downstream of the valve. The path velocity of multi-path flowmeter shows that the flow field downstream of the valve is unsteady and nonperiodic. Figure 9 shows the 18-path ultrasonic flowmeter path velocity 1D downstream of the valve, the velocity fluctuation is exceeded the average velocity value. Although the flow rate fluctuation reduces with the increasing downstream distance, notable velocity variation still exists in 10D downstream of the valve.

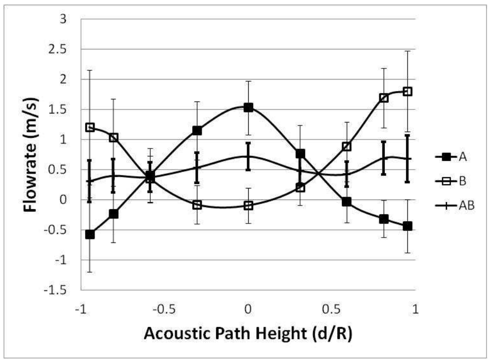
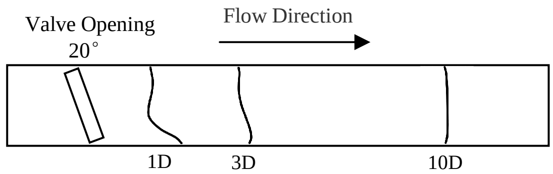
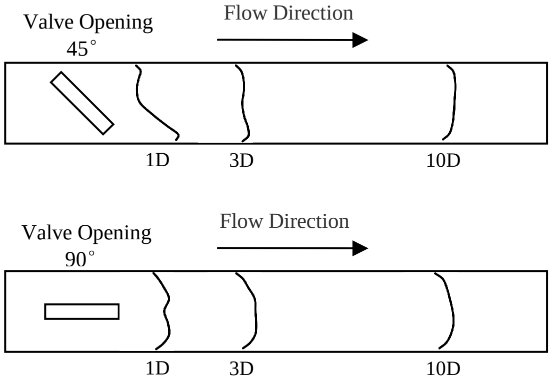


Fig. 9 Flow field change magnitude in the downstream of butterfly valve

Although the flow field changes dramatically, the average path velocities have certain regularity. the velocity profile can be obtained using the multi-path ultrasonic flowmeter path velocities, as shown in figure 10. When the valve opening is small, there are significant changes in the axial velocity. The axial velocity increases sharply at the valve opening position. When the valve opening increases the axial velocity tends to symmetric. Figure 10 (b) shows the transverse velocity, double vortex are created 1D and 3D downstream of the valve. As the distance increases, the vortex intensity greatly reduces, when the distance reaches 10D, the transverse flow becomes a single vortex structure.

(a) Axial flow





(b) Transverse flow

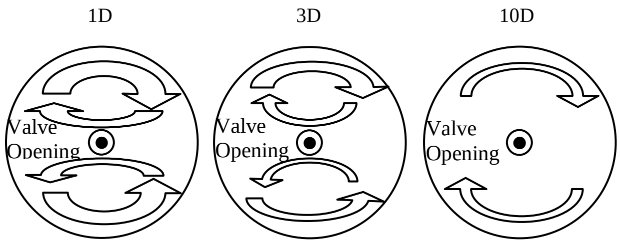


Fig. 10 Butterfly valve downstream flow distribution

As the downstream distance increases, flow disturbance caused by the butterfly valve gradually decreases, therefore the measurement error are reduced, as shown in Figure 11. When the flowmeter is installed 1D downstream of the valve, part of the multi-path ultrasonic flowmeter measurement errors reach more than 30%, the cross plane 18AB and 8AB ultrasonic flowmeter measurement errors reach 15.4% and 19.5%, respectively. When the distance increases to 10D, the multi-path flowmeter measurement errors are within ± 2%, while the cross plane 18AB and 8AB ultrasonic flowmeter measurement errors are within 0.5% and ± 0.9%.

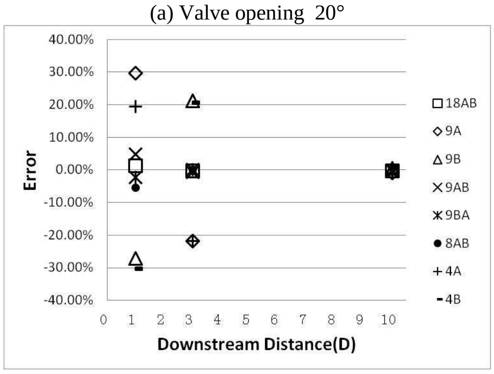
As the valve opening increases, the flow disturbance caused by the valve decreases, so the measurement errors are reduced, as shown in Figure 12. When the valve is fully open, measurement errors of multi-path flowmeter 1D downstream of the valve are less than ± 2%.

The measurement errors are highly relevant to the flowmeter installation angle. When the flowmeter installed 1D downstream of the 45° opening valve, the mainstream of the transverse flow is horizontal. As the flowmeter accoustic plane is horizontal when the installation angle is 0°, large measurement errors were obtained, as shown in Figure 13. When the flowmeter installation angle is 90°, the accoustic plane perpendicular to the mainstream of the transverse flow, so high measurement accuracies are acquired.

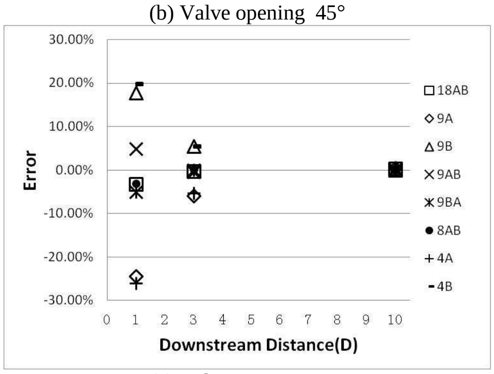
when the valve opening is 20°, the valve may produce slightly deformation, an additional transverse flow is existed in 1D downstream of the valve, as shown in Figure 14. The mainstream of the transverse flow exist in both horizontal and vertical directions, therefore, in two different installation angle, the multi-path ultrasonic flowmeter measurement errors are large, as shown in Figure 15.

In the flow field downstream of the butterfly valve, the cross plane muti-path ultrasonic flowmeters achieve the highest accuracy. Staggered layout (9AB, 9BA) multi-path flowmeters measurement accuracies are higher than single plane flowmeters(9A, 9B, 4A, 4B). However, in 1D downstream of the valve, even the cross plane multi-path ultrasonic flowmeters measurement accuracies are difficult to meet the precise measurement needs, it would be better to ensure at least 10D straight pipe between the valve and the flowmeter. Compared with the multi-path ultrasonic flowmeters, single and dual diametric path ultrasonic flowmeters are not suitable to use within 10D downstream of the butterfly valve. Single path ultrasonic flowmeter measurement errors can reach up to 180.0%. Although the measurement accuracy of dual cross path flowmeter can be improved, the measurement errors still can reach -67.8%. Even at 10D downstream of the valve, single and dual diametric path ultrasonic flowmeter measurement errors can get -11.1% and -7.2%.

(a) Valve opening 20°



(b) Valve opening 45°



(c) Valve opening 90°

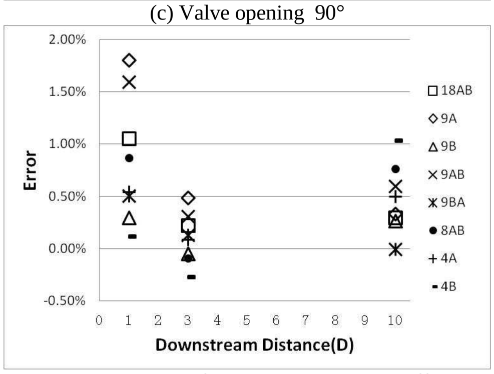


Fig. 11 Multi-path ultrasonic flowmeter installation effect in different downstream distances of the butterfly valve(1m/s)

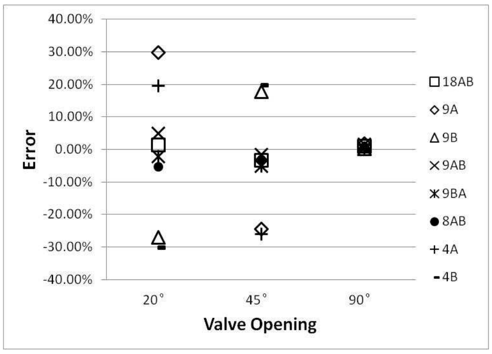
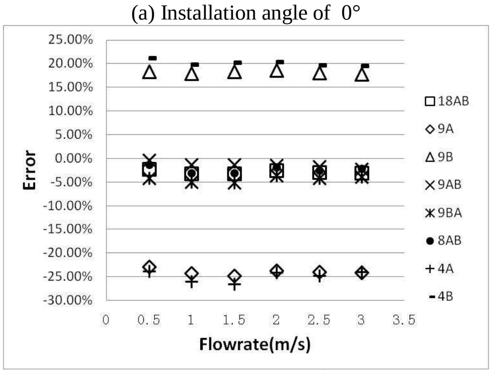


Fig. 12 The effects of valve opening on multi-path flowmeter measurement accuracy(1m/s, 1D downstream, installation angle 0°)

(a) Installation angle of 0°



(b) Installation angle of 90°

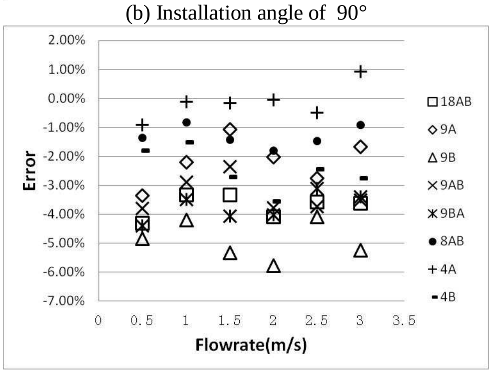


Fig. 13 The measurement errors of multi-path ultrasonic flowmeter 1D downstream of 45°opening butterfly valve

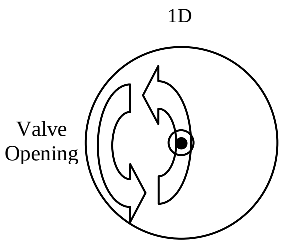
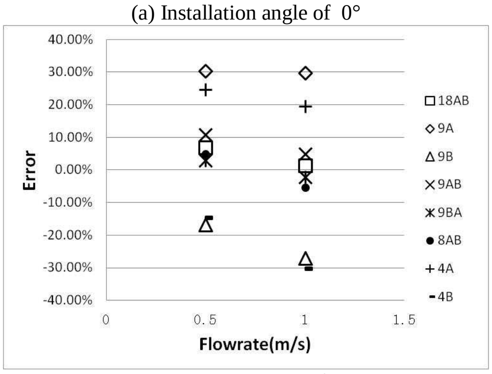


Fig. 14 Additional transverse flow in 1D downstream of 20° opened butterfly valve

(a) Installation angle of 0°



(b) Installation angle of 90°

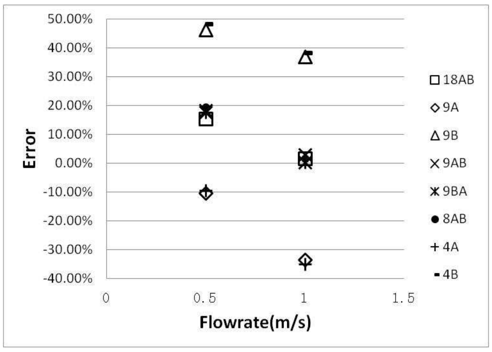
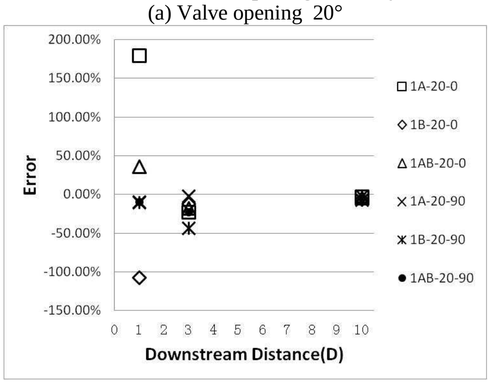
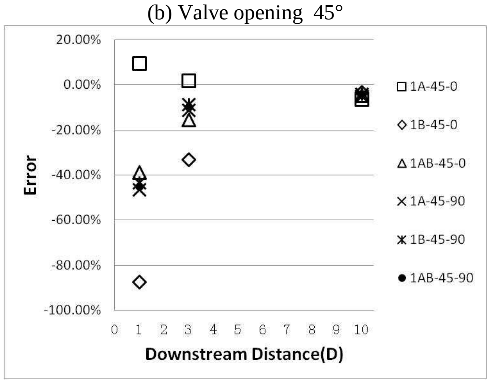


Fig. 15 The measurement errors of multi-path ultrasonic flowmeter 1D downstream of 20°opening butterfly valve

(a) Valve opening 20°



(b) Valve opening 45°



(c) Valve opening 90°

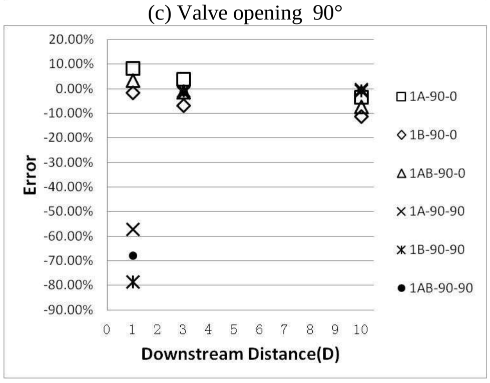


Fig. 16 The measurement errors of single and dual diametric path flowmeters downstream of the butterfly valve (1m/s)

4.2 Error analysis

The transverse flow has great impact on the ultrasonic flowmeter measurement accuracy. The influences of transverse flow on path velocity measurement are mainly in two aspects. Firstly, transverse flow velocity has projection component in the path line, which introduces measurement error, as shown in Figure 17(a). Secondly, for the inclined single or corss plane, the average velocity perpendicular to these planes is constant, which is

$$\bar{v}_c = \frac{Q\sin\theta}{\pi R^2} \tag{2}$$

The transverse velocity V_y and axial velocity V_x all have projection components in V_c direction, as shown in Figure 17(b). The sum of V_x and V_y projection components in the direction of V_c is constant, therefore, the axial velocity changes when transverse flow exist.

Cross plane flowmeter can offset part of the transverse velocity projection error and part of the axial velocity impact error simultaneously by averaging the flowrates of the two plane. To simplify the derivation process, multi-path integration error is not considered, so an infinite number of paths are assumed. After derivation follow formulas can be obtained.

Correlation of axial and transverse velocity

$$\overline{v_{cA}} = \frac{Q\sin\theta}{\pi R^2} = \overline{v_{xA}}\sin\theta + \overline{v_{yA}}\cos\theta \quad (3)$$

$$\overline{v_{cB}} = \frac{Q\sin\theta}{\pi R^2} = \overline{v_{xB}}\sin\theta - \overline{v_{yB}}\cos\theta \quad (4)$$

Projection components of path velocity

$$\overline{v_{PA}} = \overline{v_{xA}}\cos\theta - \overline{v_{yA}}\sin\theta \quad (5)$$

$$\overline{v_{PB}} = \overline{v_{xB}}\cos\theta + \overline{v_{yB}}\sin\theta \quad (6)$$

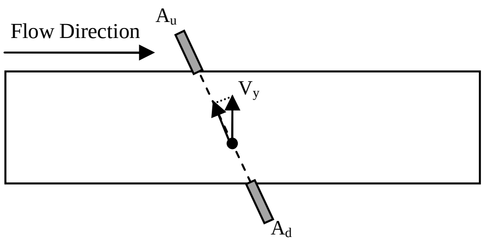
Substitute formula (3)(4) into (5)(6), the indicated flowrates are

$$\overline{v}'_{Ax} = \frac{\overline{v_{PA}}}{\cos\theta} = \frac{Q}{\pi R^2} - \overline{v_{yA}}\cot\theta - \overline{v_{yA}}\tan\theta \quad (7)$$

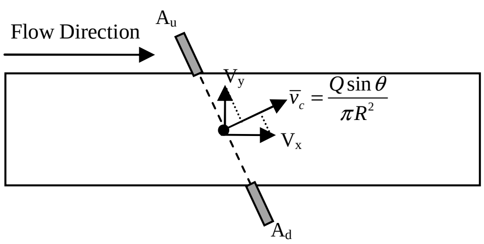
$$\overline{v}'_{Bx} = \frac{\overline{v_{PB}}}{\cos\theta} = \frac{Q}{\pi R^2} + \overline{v_{yB}}\cot\theta + \overline{v_{yB}}\tan\theta \quad (8)$$

In these formulas, $\overline{v_y}\cot\theta$ is the error caused by the correlation of axial and transverse velocity, and $\overline{v_y}\tan\theta$ is the error caused by transverse velocity projection to the path. As shown in formula (7) and (8), the effect of transverse velocity on flowmeter indicate flowrate can be partly offset by averaging the flowrate of the two cross plane. The transverse error can be completely offset if the transverse velocities in two cross plane v_{yA} and v_{yB} are the same.

(a) Transverse velocity path projection



(b) Correlation of axial and transverse velocity



(c) Transverse velocity offset

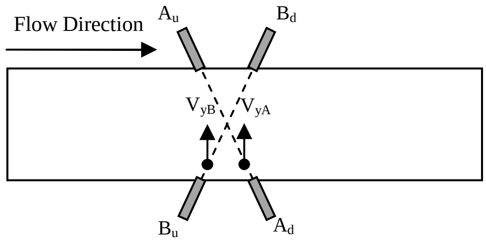


Fig. 17 The measurement errors caused by transverse flow and its compensation mechanism

The flowmeter errors include error caused by transverse flow, integration error and others. Different types of measurement errors can be separated using CFD simulation data. The error sources of 18-path ultrasonic flowmeter downstream of 20° opening butterfly valve are shown in Table 2. Since the valve deformation, velocity profile upstream of the valve and other factors were not considered in the simulation, calculated and experimental results have some difference, but this does not affect the analysis of the error source.

The horizontal transverse flow is extremely severe in 1D downstream of the valve. When the flowmeter installed in the angle of 0 °, for single plane multi-path flowmeter (9A and 9B), error caused by transverse velocity projection and error caused by the correlation of axial and transverse velocity are very large. When averaging the errors of two cross plane, the error introduced by transverse flow reduces significantly. The integration error is related to the velocity distribution in the meter body and this error is smaller than the error caused by transverse flow in this condition. When the flowmeter installation angle change to 90°, the main transverse flow perpendicular to the accoustic plane, therefore the error caused by transverse flow greatly reduces. As the downstream distance increasing, the transverse flow impact error and integration error gradually reduce, while the integral error exceeds the error introduced by transverse flow in 10D downstream. The measurement errors of different path arrangement flowmeters 1D downstream of the valve are shown in Table 3. The transverse flow introduced error of cross plane and staggered layout flowmeters are smaller than single plane flowmeters. The integration errors of single and cross 9 accoustic plane flowmeters (18AB, 9A and 9B) are smaller than the errors of 4 accoustic plane flowmeters (8AB, 4A and 4B).

When the transverse flow is very intense, the transverse flow error is the main error source. It is difficult to substantially increase the level of measurement accuracy only by increasing the number of path, while cross plane layout and installation angle optimization need to be used. When the transverse flow is weak, integration error is the main error source, so the measurement accuracy can be improved by increasing the number of path and optimize the integration method.

Tab. 2 The error distribution of 18-path ultrasonic flowmeter in different downstream distances of 20° opening butterfly valve (1m/s)

Downstream distance	1D	1D	3D	3D	10D	10D
Installation angle	0°	90°	0°	90°	0°	90°
A9 transverse flow projection error	22.9%	5.4%	-2.9%	-0.2%	0.1%	-0.1%
B9 transverse flow projection error	-14.6%	2.7%	3.3%	-0.1%	-0.1%	0.0%

AB18 transverse flow projection error	4.2%	4.1%	0.2%	-0.1%	0.0%	0.0%
A9 axial velocity correlation error	5.0%	1.2%	-0.6%	0.0%	0.0%	0.0%
B9 axial velocity correlation error	-3.2%	0.6%	0.7%	0.0%	0.0%	0.0%
AB18 axial velocity correlation error	0.9%	0.9%	0.0%	0.0%	0.0%	0.0%
A9 integration error	2.1%	0.5%	0.3%	0.2%	0.2%	0.2%
B9 integration error	1.7%	0.5%	0.3%	0.2%	0.2%	0.2%
AB18 integration error	1.9%	0.5%	0.3%	0.2%	0.2%	0.2%
A9 other error	-2.2%	-1.7%	-1.1%	-0.8%	-0.3%	-0.3%
B9 other error	-1.1%	-1.7%	-0.4%	-0.8%	-0.2%	-0.3%
AB18 other error	-1.6%	-1.7%	-0.7%	-0.8%	-0.3%	-0.3%
A9 totle error	27.8%	5.4%	-4.3%	-0.8%	0.0%	-0.2%
B9 totle error	-17.2%	2.1%	3.9%	-0.7%	-0.2%	-0.1%
AB18 totle error	5.3%	3.8%	-0.2%	-0.8%	-0.1%	-0.1%

Tab. 3 The error distribution of different path arrangement flowmeters 1D downstream of 20° opening butterfly valve (1m/s)

Installation angle	Error type	AB18	A9	B9	AB54	AB45	AB8	A4	B4
0°	Transverse flow projection error	4.1%	22.9%	-14.6%	6.3%	2.0%	4.5%	21.1%	-12.1%
	Axial velocity correlation erro	0.9%	5.0%	-3.2%	1.3%	0.4%	1.0%	4.6%	-2.6%
	Integration error	1.9%	2.1%	1.7%	3.2%	0.6%	-3.8%	-4.6%	-2.8%
	Other error	-1.6%	-2.2%	-1.1%	-5.2%	-2.1%	-1.7%	-2.0%	-1.4%
	Totle error	5.3%	27.8%	-17.2%	5.7%	0.8%	0.0%	19.0%	-19.0%
90°	Transverse flow projection error	4.1%	5.4%	2.7%	4.2%	3.9%	3.8%	5.0%	2.6%
	Axial velocity correlation error	0.9%	1.2%	0.6%	0.9%	0.9%	0.8%	1.1%	0.6%
	Integration error	0.5%	0.5%	0.5%	0.5%	0.5%	3.8%	3.8%	3.8%
	Other error	-1.7%	-1.7%	-1.6%	-3.8%	-3.6%	-1.6%	-1.6%	-1.6%
	Totle error	3.8%	5.4%	2.1%	1.8%	1.7%	6.8%	8.2%	5.3%

5. Summery

The measurement errors of different path arrangement flowmeters downstream of the bend, tapered pipe, diverging pipe and butterfly valve were studied. The results show that the flowmeter measurement accuracy is greatly impact by the butterfly valve. The tapered pipe and diverging pipe have less effect on the flowmeter accuracy. The measurement accuracies of mid-radius multi-path ultrasonic flowmeters are significantly improved compare to single or dual diametric path flowmetesr. The cross plane multi-path flowmeters are most accurate, while the measurement accuracy of staggered layout and single plane flowmeters depend on the flow field conditions. The measurement accuracy is affected by the installation angle, therefore let the accoustic plane perpendicular to the mainstream of transverse flow can effectively reduce the measurement error. The sources of measurement errors can be seperated using the CFD simulation data. When strong transverse flow exist, error introduced by transverse flow is the main error source. As the downstream distance increases, the error caused by transverse flow and integration error are gradually decrease. When the transverse flow is weak, integration error is the main contribution of the errors. In the strong transverse flow field, cross plane path arrangement and installation angle optimization are the way to improve multi-path ultrasonic flowmeter measurement accuracy. In the weak transverse flow field, increasing the number of path and improving the integration method are the way to enhance the measurement accuracy.

Acknowledgements

The authors gratefully acknowledge financial support from National Science and Technology Support Program Foundation (Grant No. 2013BAK12B01) ,
National Public Benefit (Quality Inspection) Research Fou ndation (Grant No. 200910104) and the National Natural S cience Foundation of China (Grant No. 51009125).

Reference

[1] P. Hejholt, Installation Effects on Single and Dual-Beam Ultrasonic Flowmeters, International Conference on Flow Measurement, 1986.
[2] J. E. Heritage, The Performance of Transit Time Ultrasonic Flowmeters Under Good and Disturbed Flow Conditions, Flow Measurement and Instrumentation, Vol. 1, No. 1, pp. 24-30, 1989.
[3] E. Hakansson, J. Delsing, Effects of Flow Disturbance on an Ultrasonic Gas Flowmeter, Flow Measurement and Instrumentation, Vol. 3, No. 4, pp. 227-233, 1992.
[4] H. Hu, C. Wang, T. Meng, Integration Method of Multi-Chord Ultrasonic Flowmeter and its Accuracy Analysis, Chinese Journal of Scientific Instrument, Vol. 31, No. 6, pp. 1218-1223, 2010.
[5] A. Nichtawitz, P. Grafenberger, J. Tormann, etc. Discussion on Acoustic Flow Measurement Method, International Group for Hydraulic Efficiency Measurement, 2004.
[6] F. R. Yang, J. Y. Chen, J. H. Shaw, etc. Installation Effects of a Multi-Path Ultrasonic Meter by Flow Simulation and Experiments, Flomeko Conference, 2007.
[7] D. Zheng, P. Zhang, L. Sun, etc. Study on Installation and Performance Measurement of Ultrasonic Flowmeter at Downstream of Single Bend Pipe, Chinese Journal of Scientific Instrument, Vol. 31, No. 7, pp. 1601-1607, 2010.
[8] C. He, F. Liu, L. Zhang, etc. Adaptability Study of Multi-Path Ultrasonic Flowmeter Installed in a Bend Pipe, Chinese Journal of Scientific Instrument, Vol. 32, No. 1, pp. 6-12, 2011.
[9] National Engineering Laboratory, In-Service Performance of Ultrasonic Flowmeters—Investigation of Installation Effect, National Measurement System Directorate, Department of Trade and Industry, 2002.
[10] National Engineering Laboratory, Velocity Distribution Effects on Ultrasonic Flowmeters. Part 2—Determination by Computational and Experimental

Methods, National Measurement System Policy Unit, 1999.
[11] National Engineering Laboratory, In-Service Performance of Ultrasonic Flowmeters—Application and Validation of CFD Modeling Methods, National Measurement System Directorate, Department of Trade and Industry, 2002.
[12] IEC41-1991, International Code for the Field Acceptance Test of Hydraulic Turbines, International Electrotechnical Commission, 1991.
[13] PTC18-2002, Hydraulic Turbines and Pump-Turbines Performance Test Codes, American Society of Mechanical Engineers, 2002.
[14] L. Zhang, T. Meng, C. Wang, H. Hu, C. Qin, Probe Installation Effects on Feed Thru Ultrasonic Flowmeters Accuracy, Chinese Journal of Scientific Instrument, Vol. 10, pp. 2307-2314, 2012.
[15] D. Zheng, P. Zhang, T. Xu, Study of Acoustic Transducer Protrusion and Recess Effects on Ultrasonic Flowmeter Measurement by Numerical Simulation, Flow Measurement and Instrumentation, Vol. 22, pp. 488–493, 2011.