Study on the influence factors of on-line measurement accuracy of portable clamp-on ultrasonic flowmeters

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Abstract

The portable clamp-on ultrasonic flowmeters are now widely used for on-line measurement in water resource systems, due to the advantages of convenience, economy and safety. However, the measurement accuracy of the clamp-on ultrasonic flowmeter is affected by various factors. During the on-line measurement process, the flow field distributions inside the pipeline have a greater impact on the measurement accuracy. The slope of the pipe and the opening degree of the valve are the two factors that affect the distributions of the flow field inside the pipe. To study the influences of these two factors, experimental tests are carried out on the water flow standard facility. The results show that the measurement errors obtained on the horizontal installation pipe are different from that obtained on the vertical installation pipe, and the absolute value of error deviation is 2.3%. The change of valve opening degree will significantly affect the measurement accuracy of ultrasonic flowmeters. With the decrease of opening degree, the variation range of indication error increases, and the repeatability is difficult to meet the requirements. At the same opening of the valve, the variation range of indication error becomes larger when the measurement point is closer to the valve. The CFD method is applied to simulate the flow filed inside the testing pipeline, and the influence mechanism of the above two factors is analysed. An error calculation model based on the numerical simulation is proposed, which is in good agreement with the experimental results.

Key words： Metrology；Ultrasonic flowmeter；Flow field；Valve；CFD

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1. Introduction

The portable clamp-on ultrasonic flowmeter is widely used in industrial field for online measurement. Its measurement accuracy is affected by a variety of factors, such as the characteristics of pipe, fluid medium and flow field inside the pipe [1]. Among them, the influence of the flow field distribution is particularly significant [2]. The flow pattern distortion caused by the blocking of the disturbances result in the asymmetric flow field distribution and the changing of radial velocity component, which affect the measurement of transit time and thus influence the measurement accuracy for the portable clamp-on ultrasonic flowmeter [3].

Pipeline disturbances are the main factors changing the distribution of the flow field inside the pipe, such as elbow, valve, pump, etc. In 1999[4] and 2002[5], the British National Engineering Laboratory (NEL) studied the downstream flow field of reducing pipe, increasing pipe, single elbow, double elbow and triple elbow using the LDV technology and CFD simulation. It is proposed that the arrangement of the ultrasonic channel, the installation position of the ultrasonic probe and the amount of ultrasonic channel will affect the measurement accuracy of ultrasonic flowmeters. Tang [6] used CFD method to study the influences of straight pipe, 90° elbow and 180° elbow on the fluid velocity distribution. Valve is an important component of pipeline system. In references [7-9], the FLUENT software was applied to carry out numerical simulations on the internal flow of three types of valves: ball valve, butterfly valve and cut-off valve, and a method for optimizing the internal structure of the valve was proposed according to the calculation results. Guo [10] applied the user-defined function (UDF) combining with the FLUENT to study the water hammer phenomenon caused by valve closing in a simple straight pipeline.

In previous work, many studies concentrated on the influences of elbows, reducing pipe and increasing pipe on the flow field, while relatively few studies are related to the influences of valves. In this paper, the effects of valve are taken into consideration. In addition, the experimental study from Kumar’s work[11] showed that the slope of pipe has an impact on the measurement accuracy of ultrasonic flowmeter. Considering that the mechanism of the influence of pipe slope is not clear, it is another research content of this paper.

Comparing with experiments, the computational fluid dynamics (CFD) has many advantages, such as cost-effective, time-consuming, strong adaptability, and can be applied to the simulation of working conditions in special dimensions and special environments. The CFD method has been used in the study of fluid flow in pipelines for decades [12, 13]. Combining the numerical simulation and experiment, the influence of flow field changes on the measurement accuracy of ultrasonic flowmeters could be studied more comprehensively.

In this work, two factors of pipeline slope and valve opening are selected to investigate the effects of flow field changing on the measurement accuracy of ultrasonic flowmeters. Experiment studies were carried out on the water flow standard facility to obtain the indication error and repeatability under the change of pipeline slope and different valve openings. In addition, based on the CFD method, the test device was constructed by a 3-D model for computational study. By calculation, the flow field distributions downstream of the valve were obtained, and the influences of the pipe slope and the valve opening changing on the flow field and measurement accuracy were further analysed.

2. Experiment

Experiment studies are carried out in the volumetric water flow standard facility, and the structure diagram of the test system is shown in Figure 1. The available pipe diameter for measuring is DN125~DN400. The flowrate range is (1~2000) m^3/h, and its expanded uncertainty $(k=2)$ is 0.05%. The portable clamp-on ultrasonic flowmeter used in this work is FLEXIM (model: FLUXUS F601), and the available pipe diameter for measuring is DN50 ~ DN3600, while its maximum allowable error is ±1.0%.

The diameter of the pipe used in this work is DN400. In the measuring process, the temperature of fluid is controlled at 20~25 ℃.

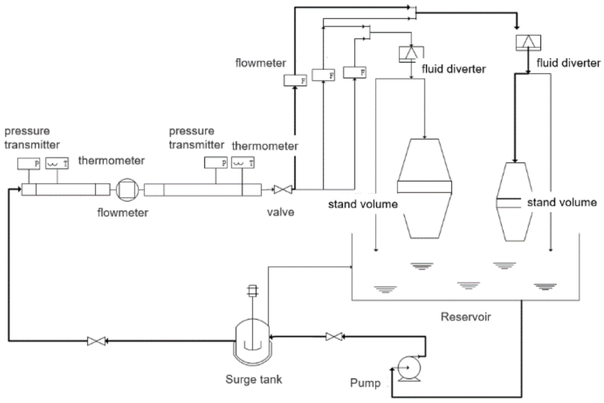


Figure 1. Structure diagram of the test system

2.1 Effects of pipe slope

Relevant studies have shown that for the slope pipe, the flow velocity distributions will be destroyed and not keep uniform, which will affect the measurement accuracy of the ultrasonic flowmeters. Kumar[11] experimentally studied the indication error of ultrasonic flowmeters when the pipe is inclined at a small angle (6°,12°). The results show that the indication error increases with the increase of the pipe slope. In this section, experiment studies are carried out to show the difference of measurement accuracy for the ultrasonic flowmeter horizontal installation and vertical installation. The measurement points in this work are shown in Figure 2, involving two positions on the vertical pipe (respectively H=7D and H= 14.5D away from the header).

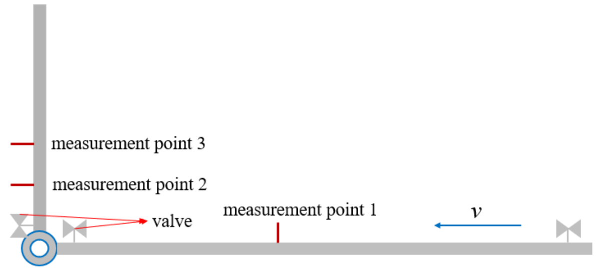


Figure 2. Structure diagram of the measuring points

The indication error and repeatability results from the tests are shown in Table 1. The flow velocity of each test is controlled at about 2.1 m/s. From Table 1, the indication error obtained from different positions of the vertical pipe are quite different. For the measurement point of H=7D, the average error and the value of repeatability are larger than those in the measurement point of H=14.5D and horizontal point. The reason is that the fluid passes through the header at a 90° angle, resulting in the disturbance of flow field, leading to the increase of measurement error. An error deviation of horizontal installation and vertical installation (H=14.5D) exits, and the absolute value of the average error difference between the two is 2.3 %. The test results are similar to those in literature [11], indicating that the pipe changes from horizontal position to vertical position, the measurement error of the ultrasonic flowmeter increases.

Table 1. Test results of different pipe slopes

	Actual flowrate (m^3/h)	**Flowrate of flowmeter(m^3/h)**	**Error (%)**	**Average error (%)**	**Repeatability (%)**
Horizontal	978.932	966.075	-1.31	-1.2	0.2
	980.595	970.437	-1.03		
	971.907	959.725	-1.25		
Vertical (H=7D)	946.230	975.575	3.10	3.7	0.6
	946.174	986.925	4.31		
	946.339	980.188	3.58		
Vertical (H=14.5D)	946.205	955.625	1.00	1.1	0.2
	942.713	954.500	1.25		
	947.363	956.500	0.96		

2.2 Effects of valve opening

The valve is a typical disturbance, which will strongly change the flow field distributions inside the pipe, affecting the measurement accuracy of flowrate. In order to investigate the influences of valve opening on the measurement error, the test device as shown in Figure 1 was adopted for experiment study. The ball valve opening was selected as 15%, 25%, 50%, 60% and 100%. The ultrasonic flowmeter is installed at L=5D and L=12.5D downstream of the ball valve (the distance between the header and the ball valve is 2D, L=H-2D).

Figure 3 shows the relationship between the opening of the ball valve and the flowrate in the pipeline. It shows that the variation tendency is not linear, when the opening drops to about 50%, the flowrate begins to decrease significantly.

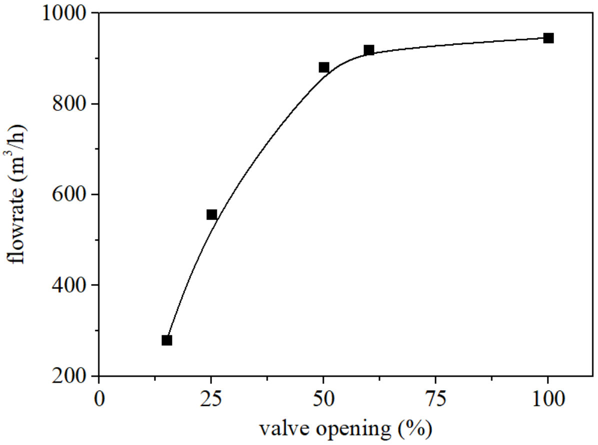


Figure 3. Relationship between the valve opening and flowrate

Figure 4 shows the indication error of each measurement for different valve openings. When the valve opening is higher than 50%, a good repeatability result is shown. When the valve opening decreases from 100% to 50%, the average error at L=12.5D has little change, while the error at L=5D decreases significantly. When the valve opening is lower than 50%, the error deviation of multiple measurements is quite large. As the opening degree decreases from 25% to 15%, the repeatability of test result is getting worse (for the 25% opening, the error ranges from -3.6% to 3.6%; for the 15% opening, the error ranges from -11.6% to 3.1%).

At the same opening, the maximum value of error difference is larger as the measurement point is closer to the valve. For example, when the opening is 15%, the measurement error ranges from -11.6% to 3.1% for L=5D, while the error ranges from -2.1% to 0.9% for L=12.5D.

It is concluded that the change of valve opening will significantly affect the measurement accuracy of ultrasonic flowmeters. When the valve opening is lower than 50%, the indication error increases and the repeatability is getting worse, which cannot meet the requirements of the maximum allowable error and repeatability of the Verification Regulation of Ultrasonic Flowmeter [14].

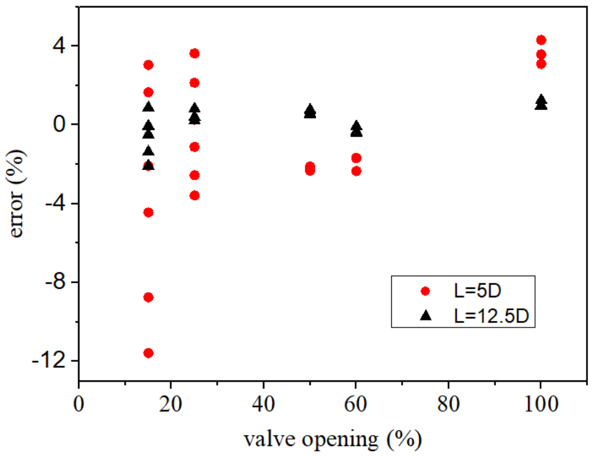


Figure 4. Measurement error under different valve openings

3. Numerical simulation

3.1 Modelling

The CFD method is applying to study the flow filed changing when the pipeline is affected by the disturbances. Firstly, the test facility shown in Figure 1 is appropriately simplified, and constructed to a 3-D model by the SolidWorks, as shown in Figure 5. The mesh is generated by the Gambit. The tetrahedral grid is applied for mesh construction of header, while the other domain is divided by hexahedral mesh. The meshes approaching the pipe wall and ball valve are refined. Approximately 600000 grids cells are contained in the meshes.

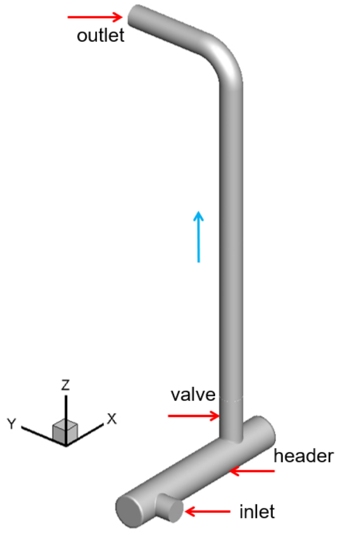


Figure 5. 3-D structure of the test device

The standard *k*-*ε* model is selected as the turbulence model. The governing equations include the Reynolds time-averaged Navier-Stokes equations, the *k* equation and the *ε* equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho \bar{u}_i)}{\partial x_i}=0 \qquad (1)$$

$$\frac{\partial(\rho\bar{u}_i)}{\partial t}+\frac{\partial(\rho\bar{u}_i\bar{u}_j)}{\partial x_j}=-\frac{\partial\bar{p}}{\partial x_i}+\frac{\partial}{\partial x_j}(\frac{\partial\bar{u}_i}{x_j}-\rho\overline{u_i^{'}}\overline{u_j^{'}})+F_i \qquad (2)$$

$$\frac{\partial(\rho k)}{\partial t}+\rho u_j\frac{\partial\bar{u}_i}{\partial x_j}=\frac{\partial}{\partial x_i}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right)+ \qquad (3)$$

$$\mu_t\frac{\partial\bar{u}_j}{\partial x_i}(\frac{\partial\bar{u}_i}{x_j}+\frac{\partial\bar{u}_j}{\partial x_i})-\rho\varepsilon$$

$$\frac{\partial(\rho\varepsilon)}{\partial t}+\rho u_j\frac{\partial\varepsilon}{\partial x_j}=\frac{\partial}{\partial x_i}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x_j}\right)+ \qquad (4)$$

$$\frac{c_1\varepsilon}{k}\mu_t\frac{\partial\bar{u}_j}{\partial x_i}(\frac{\partial\bar{u}_i}{x_j}+\frac{\partial\bar{u}_j}{\partial x_i})-\rho C_2\frac{\varepsilon^2}{k}$$

where ρ is the fluid density, t is the time, p is the hydrostatic pressure, u_i is the velocity component in the i direction, x_i is the coordinate component, F_i is the volume force in the i direction, μ is the viscosity coefficient, μ_t is the turbulent viscosity, σ_ε represents the turbulent Prandtl number of ε, and c_1 and C_2 are empirical constants.

The dynamic mesh technology is used to realize the switch of the ball valve in the pipeline. The rotating speed of the ball valve is coded by the user-defined function (UDF). The boundary conditions of the pipe inlet and pipe outlet are velocity inlet and outflow, respectively. The connection surface between the bodies is set as interface. 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.

3.1 Simulation results

3.1.1 Valve fully open

Contours of the axial velocity at L=5D and L=12.5D when the valve is fully open are shown in Figure 6, which are compared with those in horizontal pipeline. For horizontal pipeline, the axial velocity increases gradually from the wall to the centre of the pipe, and is evenly distributed. For vertical pipeline, though the valve is fully open, the axial velocity distribution in the cross-section is uneven. The reason is that the flow field is disturbed when the fluid flows through the header and enters the vertical pipe. As the distance to the valve increases, the distribution of the flow field is gradually uniform.

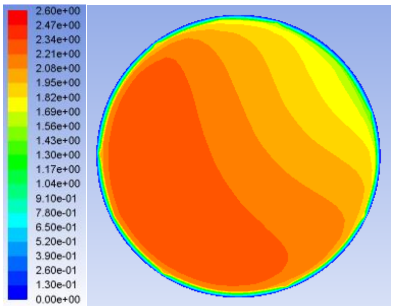
For the fully developed flow in a smooth circular pipe, the axial velocity of the fluid on the cross-section is logarithmically distributed when it is in a turbulent flow (Re>10^5). The theoretical velocity at the distance r to the centre can be expressed by Equation (5), where the coefficient n is determined by the Planck's Equation (6)[15]. The flowrate can be obtained by integrating the velocity on the cross-section surface (Equation (7)). However, when the flow field is distorted by the disturbance, as shown in Figure 6(a), 6(b), the calculation method of Equations (5) ~ (7) should be modified.

$$v(r)=v_{\max}(1-r/R)^{1/n} \qquad (5)$$

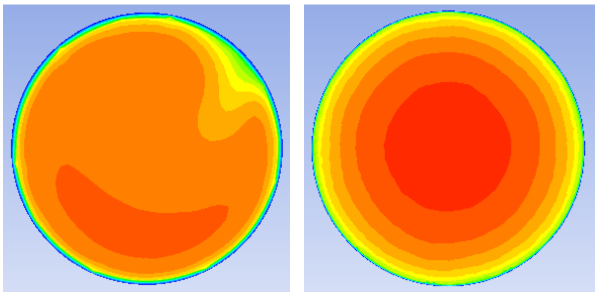
$$n=2\lg(Re/n)-0.8 \qquad (6)$$

$$q=\int_0^R\int_0^R v(r)drdr \qquad (7)$$

Where R is the radius of the pipe, $v_{\max}$ is the maximum velocity, n is the coefficient, and q is the flowrate.



(a) L=5D



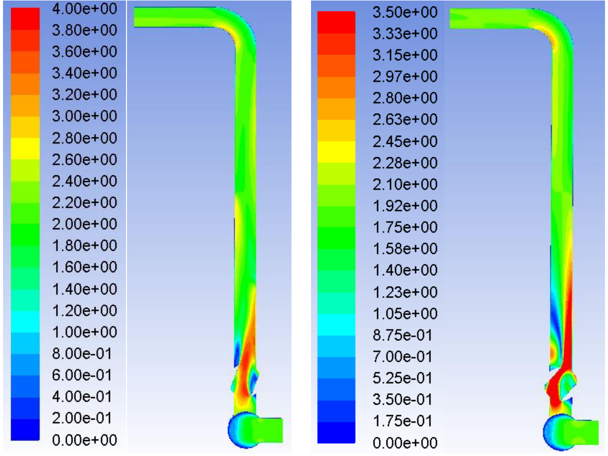
(b) L=12.5D (c) Horizontal

Figure 6. Axial velocity distribution downstream of the valve when it is fully open (m/s)

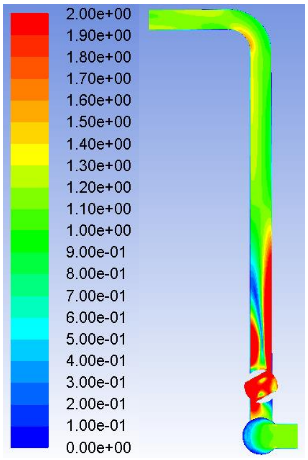
3.1.2 Different valve opening

Figure 7 shows the contour of the axial velocity distribution of the fluid at different valve openings. When the fluid passes through the valve, its velocity increases due to the reduced flow area. The fluid flow pattern changes significantly downstream of the valve. An obvious boundary is shown between the high velocity zone and the low velocity zone. As the distance to the valve increases, the axial velocity gradually tends to be uniformly distributed. It can be seen that a greater impact is shown on the flow field of the pipe when it is closer to the valve.

In Figure 7, the change of valve opening has an obvious influence on the flow field. With the decrease of the valve opening, the critical distance of the flow velocity approaching a uniform distribution increases, and the stratification of high velocity and low velocity is more obvious.



（a）75% opening （b）50% opening



（c）25% opening

Figure 7. Contour of the axial velocity distributions (m/s)

3.1.3 Error calculation model based on simulation

In this section, an error calculation model based on the numerical simulation is proposed, in order to study the influence of flow field changing on the measurement accuracy of ultrasonic flowmeters. For the ultrasonic flowmeter of single beam measurement principle, the measurement error at position *D* can be calculated according to Equation (8), v_A^D is the surface average velocity at position *D*, and v_A^∞ is the surface average velocity for the stable flow. The value of v_A^D can be calculated according to Equation (9), which is related to the linear average velocity and the correction factor *K*. It can be considered that the flow field at the pipe outlet is in a stable state (if the distance between the disturbance and pipe outlet is long enough). Hence, the v_A^∞ can be replaced by the value of v_A^{out}. Therefore, the correction factor *K* can be expressed according to Equation (10). By Equation (8) ~ (10), the error at position *D* can be obtained.

$$\xi=(v_A^D\cdot S-v_A^\infty\cdot S)/(v_A^\infty\cdot S) \qquad (8)$$

$$v_A^D=v_L^D\cdot K \qquad (9)$$

$$K=v_A^\infty/v_L^\infty\approx v_A^{out}/v_L^{out} \qquad (10)$$

where ξ is the error, v is the velocity, S is the cross-section area, K is the correction factor, the subscript A represents the certain surface, and the subscript L represents the certain line.

To verify the error calculation model, the calculation results are compared with those from experiments. Firstly, the liner average velocity v_L^D at L=5D and L= 12.5D are extracted from Figure 8. The v_L^∞ is the linear average velocity at the position of 50D downstream of the DN400 diameter pipeline. Then, according to the error calculation model, the errors obtained from simulation results could be calculated, which are compared with those in Figure 4. As shown in Figure 8, the simulation results are in good agreement with the experimental results.

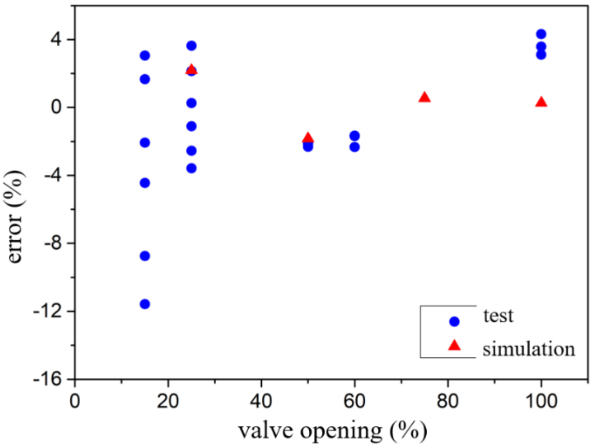


Figure 8. Comparisons of simulations and test results

4. Conclusions

In this work, experiments and CFD numerical simulation are used to study the influence of pipe slope and valve opening of ball valve on the measurement accuracy of ultrasonic flowmeters. The following conclusions are drawn from experiments: (1) measurement errors obtained on the horizontal installation pipe are different from that obtained on the vertical installation pipe, and the absolute value of error deviation is 2.3%. (2) The change of valve opening degree will significantly affect the measurement accuracy of ultrasonic flowmeters. With the decrease of opening degree, the variation range of indication error increases, and the repeatability is difficult to meet the requirements. (3) At the same opening of the valve, the variation range of indication error becomes larger when the measurement point is closer to the valve.

Through numerical calculation, the following conclusions are obtained: (1) The flow velocity in vertical pipe is asymmetrical distributed, which is different from that in horizontal pipe. (2) The flow field at the downstream of the valve has obvious distortion.

With the decrease of the valve opening, the critical distance of the flow velocity approaching a uniform distribution increases. (3) An error calculation model based on numerical simulation is proposed, which is in good agreement with the experimental results.

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