Analysis of flow characteristics and flow measurement accuracy of elbow under different conditions

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Abstract. In modern industry, flow rate is one of the three testing parameters, for pipes with elbows, the fluid in the measuring section can not reach the ideal flow state after the elbow. Therefore, there is a great error in the measurement of flow. The principle of ultrasonic flow measurement based on V method is introduced in this paper, the combination of experimental research and numerical simulation is adopted, the physical model of 90 degree bend pipe with the diameter of 219mm is established, and based on the finite volume method, with the condition of 75t/h, 98t/h and 136t/h. The flow measurement error at different measuring positions after the bend is studied by numerical simulation. The results show that the elbow with diameter of 219mm is under the above three working conditions, the relative error curve of flow measurement tends to be stable and the accuracy is less than 2% after the distance from 10D to the elbow. When other measurement conditions remain unchanged, the greater the flow of the working fluid in the tube, the higher the accuracy of the flow measurement will be at the same measuring position.

1. Introduction

The flow rate is one of the important parameters to reflect the operation status of industrial boilers. The accuracy of flow measurement is very important in thermal performance test, especially for the regulation of industrial boiler plays an important role[1-3].

The better measurement accuracy requires higher flow state of the measuring fluid. The better measurement accuracy requires higher flow state of the measuring fluid, however, the flow that after elbow measuring section can not reach the ideal state, which will cause large measuring error[4-6].
Many scholars at home and abroad have studied the flow of working substance in elbow. In 1927, Dean et al. analysed the flow state of refrigerant of circular cross-section in elbow and proposed the two flow phenomenon[7]; Kumar and Zheng et al explored the error of ultrasonic flowmeter, compared the velocity and path angle, receiving position of the transducer and inclination angle of measuring pipeline on impact of flow velocity measurement[8,9]. Chen Hong et al found that there is a very obvious vortex in the pipe elbow, and the effect of the space elbow on the flow measurement is greater than that of the plane elbow[10].

In this paper, we based on the ultrasonic flow measurement principle of V method, by using the method of combining numerical simulation with experiment, the accuracy of flow measurement at different positions of straight section after bend is analyzed under different working fluid flow rate. Firstly, the flow trace diagram of elbow pipe, longitudinal velocity profile of elbow, the conditions under different flow velocity and the same pipe diameters velocity contours on the middle section of different measuring positions after elbow Velocity distribution diagram on speed sampling line and velocity distribution diagram on speed sampling line are given. Analysis of the variation of working fluid flow in pipe at different measuring positions after bend. After that, the relative error is attained by comparing with the inlet velocity in the pipeline boundary condition. The relative error curve is used to judge the measurement accuracy at different positions of the pipe section, which provides theoretical support for practical engineering measurement.

2. Establishment of physical model and mesh generation

2.1. Establishment of physical model

In this paper, the bending spiral steel pipe with diameter D of 219mm, wall thickness of 5mm and bending radius of 90 degrees is taken as the research object, the corresponding physical model is established. Under three different flow conditions, 75t/h, 98t/h and 136t/h, working fluid flow law and relative error of flow at different positions after bend are analyzed. The pipe model is shown in Figure 1, among them, the length of the straight section before the elbow is 10D, the length of the straight section after the elbow is 20D, and the bending radius of the elbow is R=1.5D. The distance between the measuring sections is calculated by the ultrasonic flowmeter according to the material, diameter, wall thickness and water temperature of the pipe section, Take 131mm. The distance between the center line and the end of the elbow is P, which are 2D, 4D, 6D, 8D, 10D, 15D and 20D respectively. The computational domain is divided into structured grid using ICEM, in order to ensure the accuracy of the calculation results, the boundary layer mesh is added to the wall near the wall, and the grid is encrypted for the elbow part.

![Figure 1. Physical model of pipe with bend radius of 1.5D](image)

2.2. Mesh generation and boundary conditions

The mesh is divided by ICEM, and the mesh of the elbow is encrypted, the local diagram of grid of the elbow is shown in Figure 2, the Schematic diagram of grid of the elbow is shown in Figure 3. The grid is imported into Fluent for numerical calculation, the inlet boundary condition is set as velocity inlet,
the outlet is free outflow, the wall roughness is taken as 0.19. The pipeline is in turbulent state, RNG model is chosen as the calculation model, SIMPLE algorithm is used for pressure and velocity coupling, the flow medium is water, the convergence residual is defined as $1e^{-06}$.

\[\left\{ \begin{array}{c}
\frac{\partial}{\partial x_j} (\rho u_{i,j}) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g \\
\frac{\partial}{\partial y_j} (\rho u_{i,j}) = -\frac{\partial p}{\partial y_i} + \frac{\partial \tau_{ij}}{\partial y_i} + \rho g \\
\frac{\partial}{\partial z_j} (\rho u_{i,j}) = -\frac{\partial p}{\partial z_i} + \frac{\partial \tau_{ij}}{\partial z_i} + \rho g
\end{array} \right. \] (2)

$\tau_{ij}$ represents deviatoric stress tensor.

3) Constitutive equation, See form (3):

\[ X = \tau_{ij} = \left[ \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) \right] - \frac{2}{3} \mu u_i \delta_{ij} \]
\[ Y = \tau_{ij} = \left[ \mu \left( \frac{\partial u_i}{\partial y_j} + \frac{\partial u_j}{\partial y_i} \right) \right] - \frac{2}{3} \mu u_i \delta_{ij} \]
\[ Z = \tau_{ij} = \left[ \mu \left( \frac{\partial u_i}{\partial z_j} + \frac{\partial u_j}{\partial z_i} \right) \right] - \frac{2}{3} \mu u_i \delta_{ij} \] (3)

The $\mu$ refers to the kinetic viscosity coefficient, the $\delta_i$ is a Krone Neck symbol, $\delta_{ij} = \begin{cases} 1, & i = j \\ 0, & i \neq j \end{cases}$.

4. Analysis of flow law in elbow

The trace diagram of fluid flow in 219mm bend under 75t/h flow condition is on the Figure 4. The longitudinal velocity contour map of 219mm bend under 75t/h flow condition is on the Figure 5. When the working fluid in the pipeline passes through the elbow, the flow trace changed obviously. Refrigerant of elbow block rotate upward under the influence of pipe wall, which makes the
refrigerant of elbow inner wall rotates downward. It can clearly see the refrigerant after elbow is deflected to a certain extent, which caused the spoiler effect of elbow.

As shown in Figure 5, the velocity of the working fluid is uniformly distributed before the elbow. There is a thin boundary layer near the wall, and the velocity increases from 0 to the main flow velocity on the boundary layer. Through the elbow, due to the interaction of the inertia of the working medium and the molecular viscosity, the velocity near the elbow is increased, and the velocity near the elbow is reduced, and the obvious spoiler area is formed after the elbow, which affects the flow within a long distance after the elbow. The flow of working fluid gradually tends to be stable after 10 times the pipe diameter.

![Figure 4. Flow pathline under 75t/h working conditions in 219mm pipe](image)

![Figure 5. Longitudinal-sectional velocity contour under 75t/h working conditions in 219mm pipe](image)

The velocity contour map at the middle section of the 219mm elbow at different measuring positions after the elbow under the 75t/h condition is shown on Figure 6. As shown in the diagram, when the flow rate of the pipe is 75t/h, the velocity contours at different positions are approximately symmetrical along the center line. The outer circumference of the cross section has a boundary layer around 3mm, and the velocity increases from 0 to about 0.57m/s. After the elbow, the velocity curve at 2D is concave, and the upper part of the pipe is small and the lower part is large.
Figure 6. Velocity contour in measuring period of middle cross section in 75 t/h working condition

The point of low velocity of the elbow is after 4D at the bottom of the pipe, velocity curve begin to concave from the starting point of the trend, and along with the increase of the distance measuring section and elbow, the concave trend of pipe on the bottom of the concave trend is more and more obvious, the pipe upper concave gradually weakened, refrigerant velocity increases with increasing distance of the measuring section and elbow room. After the elbow, the concave at the upper part of 10D has gradually weakened to the weakest, but the concave degree is more and more big. At the elbow 20D, there are two symmetrical vortices on the left and right sides of the pipe.

It can be seen from Figure 7 that when the flow rate is 98t/h, the velocity contour map is similar to that of Figure 6, and the distribution of the velocity contour along the centerline is symmetrical in different positions. The outer circumference of the cross section has a boundary layer of about 3mm, and the velocity increases from 0 to about 0.81 m/s. At the position of 2D, the velocity curve also shows a "concave" distribution, the upper part of the pipeline is small, and the lower part is large. However, compared with the 75t/h, the downward depression degree of the 98t/h velocity contour map is obviously deeper. At the bottom of the 4D, there is also a point of lower velocity, the speed curve is also beginning to show the trend from the starting point of the concave, and along with the increase of the distance measuring section and the pipe elbow, the concave upward trend is more and more obvious, but compared with 75t/h, the concave degree was significantly smaller. At the position of 10D, the concavity of the upper part of the pipe is no longer present, and there are obvious two symmetrical vortices at 20D. With the Figure 6 comparison, it is found that the fluctuation of the working fluid flow rate of 98t/h is more severe than that of 75t/h.

Figure 7. Velocity contour in measuring period of middle cross section in 98 t/h working condition

Figure 8. Velocity contour in measuring period of middle cross section in 136 t/h working condition
Can be seen from Figure 8, when the pipe flow is 136t/h, the speed variation contour and flow rate are similar to that of 75t/h and 98t/h, which is approximate symmetrical type distribution in different locations along the center line. The boundary layer cross section of the outer circumference is about 2mm, the speed change gradually from 0 to 1.05m/s. The velocity curve shows a concave distribution after 2D, the depression degree if deeper than that of Figure 6 and Figure 7. The depression point at 4D behind the elbow has reached the 3/4 pipe diameter. Accordingly, the concave curve at the bottom of the pipe appears later, from Figure 8 can be inferred, The location of the center line velocity contours is between 8D and 10D behind the elbow. Two symmetrical vortices are also observed at 20D after the elbow.

5. Measurement error analysis
In this paper, the data collection in this paper is based on the measurement principle of ultrasonic flowmeter using the V method (reflection method), two sampling line speed is in center section of the pipeline, which is symmetric with the central section of measurement section. Because the two sampling lines have similar positions, the velocity distribution is basically the same. In order to show the velocity distribution results more clearly, This paper only analyzes the sampling line near the elbow, named the No. 1 sampling line. 1000 points are selected equally on the sampling line, and the average speed of 1000 points is considered as the sampling line line average speed, at the same time, output the speed curve of each sampling point on the sampling line.

Figure 9 is the velocity curve of the 75t/h bend at the 1 sampling line at different measuring positions. Figure 10 is the velocity curve of the 98t/h bend at the 1 sampling line at different measuring positions. Figure 11 is the velocity curve of the 136t/h bend at the 1 sampling line at different measuring positions.

![Figure 9. Sampling linear velocity diagram in measuring section for 75t/h pipe](image)

![Figure 10. Sampling linear velocity diagram in measuring section for 98t/h pipe](image)

![Figure 11. Sampling linear velocity diagram in measuring section for 136t/h pipe](image)
As shown in Figure 9, Figure 10 and Figure 11, the sampling line velocity diagrams at different measuring positions are basically similar in three different operating conditions. The sampling line is basically axisymmetric, and there is a peak value and the two valley values in the middle of the sampling line speed curve at 2D after the elbow. The sampling line speed curve in both sides gradually increased from 0m/s to the mainstream speed. In the range from 2D to 10D, when the measuring section is farther away from the elbow, the peak value of the speed curve decreases gradually, and the valley value increases gradually. At 10D sampling line speed curve is flat, the sampling line slowly appear a small valley in 1D, which is consistent with the velocity contour map shown in Figure 6, Figure 7, Figure 8. Through the comparison of Figure 9, Figure 10, Figure 11, when the pipeline flow increases gradually, the sampling line speed curve fluctuation of the same position increases gradually after the elbow. For example with the elbow at 2D, the sampling line speed curve of 98t/h than 75t/h fluctuations, sampling line speed curve of 136t/h than 98t/h fluctuations. It can be seen from the speed chart of the sampling line, the difference between the cumulative value of the velocity in the measured segment of the pipe diameter of 75t/h condition in 2D and the cumulative value of the velocity in the measured segment in 10D is significantly higher than that in the 98t/h pipe diameter, the difference between the cumulative value of the velocity in the measured segment of the pipe diameter of 98t/h condition in 2D and the cumulative value of the velocity in the measured segment in 10D is significantly higher than that in the 136t/h pipe diameter, this can boldly conclude that under the same measuring position, The absolute value of relative error is larger under 75t/h condition, the measurement accuracy is low.

The flow error curve of three different measuring position under the condition of 219mm is shown on Figure 12.

![Figure 12. Flow error curve in different location under three condition of 219mm pipe](image)

The abscissa is the ratio between the center line and the elbow and the pipe diameter in the measuring section, representing different measuring positions. The vertical coordinate is the relative error between the measured flow calculated by the corrected average line velocity of the sampling line and the flow velocity calculated from the inlet velocity at the pipe boundary condition setting. Because pipeline is set to steady flow, the flow value calculated by the inlet velocity of the pipeline boundary condition can be regarded as the true value of the flow. Therefore, the relative error can be regarded as the relative error between the flow measurement and the true value.

As is shown on the Figure 12, under three conditions of 75t/h, 98t/h and 136t/h for the 219mm pipe, the relative error of flow measurement at different locations were negative, the measured values are less than the real value. Under the same working condition, the farther the test position is from the elbow, the smaller the absolute value of the relative error of the flow measurement is, and the greater the accuracy of the measurement. In the 75t/h condition, the relative error from 2D -6.8% to 20D -0.8% increased gradually, and in every measurement position, with the increase of pipeline flow, the
accuracy of flow measurement increases to a certain extent. When the pipe flow increases to 136t/h, the relative error from 2D -6.3% gradually increased to 20D -0.2%. The absolute value of relative error of flow is larger before 10D. Between 2% and 7%, the relative error curve of flow tends to be gentle after 10D. In the range of -2%, the flow measurement value after 10D can be more accurate.

6. Conclusion
In this paper, the principle of ultrasonic flow measurement based on V method, analyzed the law of fluid flow in the 219mm pipe under 75t/h, 98t/h, 136t/h three conditions after bending by using the numerical simulation method, gives the relative error variation of different measuring position of flow pipe, draws the following conclusion:

(1) The setting of upstream elbow causes the working fluid to produce local disturbance at the bend, which makes the flow velocity in the downstream pipe uneven and uniformly distributed, which has a great influence on the accuracy of the flow measurement using the ultrasonic channel flowmeter with V method.

(2) When the flow measurement is carried out by V method, the theoretical measurement values calculated by the velocity correction at different positions of the sampling line after the bend are smaller than the actual flow values.

(3) The elbow with diameter of 219mm is under the above three working conditions, the relative error of flow rate fluctuates from -6.8% to -0.2% in the measurement range of 2D to 20D, and the relative error is related to the measuring position of the 219mm elbow. In the range of 10D, the relative error fluctuates greatly, and the accuracy of flow measurement increases gradually with the increase of distance between measuring position and elbow. The relative error curve of flow measurement tends to be stable and the accuracy is less than 2% after the distance from 10D to the elbow.

(4) When the same other measuring conditions, measurement in the same position, refrigerant pipe flow is larger, the volatility of refrigerant velocity is large. The smaller the absolute value of the relative error between the theoretical measurement calculated after correction of the average velocity on the sampling line by ultrasonic flowmeter based on V method according to sound track arrangement method and the real value, the higher the accuracy of the flow measurement is.

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