Research on the Method of Improving the Flow Field Quality in the Elbow of the Water Flow Standard Device Based on the CFD Numerical Calculation Method

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Abstract. To solve the problems of secondary flow, turbulent vortex, and instability of the flow field in the elbow of the water flow standard device, some 3D geometric models of the elbow were established, and the flow field numeral calculations of the elbows were carried out based on the 3D models. The study shows that appropriately increasing the turning angle and the number of deflectors has a significant effect on improving the flow field quality in the elbow. While it is not obvious that the effect of increasing the thickness of the deflector on the flow field quality, and which may increase the requirements for the power source of the standard device. It is concluded that the elbow with a 135°turning angle and 2 pieces deflectors may be the optimal choice.

1. Introduction

Flow measurement is an important part of metrology science. Flow measurement and test technology have played an important role in trade settlement, energy measurement, process control, environmental protection, medicine, and health. To ensure the quality of flowmeters, the flow standard devices with different working media, different ranges, and different accuracy levels have been established in scientific research and technical institutions and various flow meter manufacturers. Flow stability is an important performance index of flow standard devices, which is the basis for the flow standard devices to replace the instantaneously changing flow with the average flow over some time. Limited by the installation space and the height of the piping arrangement, the fluid in the standard device will inevitably pass through Elbows with different angles. When the fluid flows through the elbows, water hammer, vortex and secondary flow will occur, which not only causes energy loss but also affect the velocity distribution and flow stability of the pipeline. This paper introduces a CFD numerical calculation method to study the flow characteristics of fluid passing through the elbows. By increasing the turning angle and installing deflectors, the method of reducing vortex and secondary flow has been researched to improve the flow stability of the standard device.

2. Numerical Calculation Methods and Research Status at Home and Abroad

Fluid mechanics is an important branch of mechanics, which mainly studies fluid flow characteristics and interaction forces between fluids. With the advancement of computer and microelectronic...
technology, computational fluid dynamics (CFD) has gradually developed into an indispensable and important method for studying fluid flow.

Many scholars have applied numerical simulation combined with experimental research to study fluid flow. Zhou Oujie of Chongqing University used Fluent software to numerically simulate the wind field at a suspension bridge in the western mountainous area and simultaneously use the instrument to measure the field environment [1]. Li Haiyang of Shanghai Institute of Metrology and Testing Technology proposed a method for CFD numerical calculation and calibration of the S-type pitot tube coefficient [2]. Meanwhile, some scholars also have applied numerical calculation methods to study how to improve the unstable flow field at the elbows of the flow standard device. For example, Yu Fei of Xi'an Jiaotong University proposed that at the 90 ° rectangular section elbow of the pulverized coal pipeline of the thermal power plant, if a deflector is installed, the optimal arrangement is the center angle of the deflector θ ≥ 60 ° and then the deflector should be arranged in the back of the elbow, which the ratio of the divided two parts of the flow channel is between 1:1 and 1:1.25[3].Yu Changli et al. of Harbin Institute of Technology (Weihai) proposed that the non-uniform arrangement of multiple deflectors in the elbow of the circulating water tank can significantly improve the secondary flow in the elbow. However, there is no research on improving the flow field in the elbow by changing the number of deflectors, the angle of the elbow, and the thickness of deflectors [4].

3. Establishment of Calculation Model and Grid Meshing

3.1. Establishment of 3D Geometric Model of Elbow

The basic 3D geometric model of the 90 ° elbow for the study of the flow field in the elbow is shown in Figure 1. The model is based on the pipe at the elbow of the DN50 high-accuracy water flow standard device of Shanghai Metrology and Testing Technology Research Institute. The pipe has a circular cross-section with 50mm diameter; the length of the front straight pipe is 575mm, the length of the rear straight pipe is 275mm, and the turning angle is 90 °.

![Figure 1. The basic 3D geometric model of the 90 ° elbow.](image)

Assuming that there is one droplet in the elbow with a unit mass m of 0.2D (D refers diameter of the pipe) away from the inner pipe wall, the centripetal force is \( F_{in} \) and its velocity is \( V_{in} \); while the other droplet in the elbow with a unit mass m of 0.2D away from the outer pipe wall and the centripetal force is \( F_{out} \), and its velocity is \( V_{out} \). Then the centripetal force of the inner droplet is \( F_{in} = mV_{in}^2/1.2D \); the centripetal force of the outer droplet is \( F_{out} = mV_{out}^2/1.8D \). Considering the boundary layer effect of the flow in the pipeline and the symmetry of the flow, it is approximated that \( V_{in} = V_{out} \); then the centripetal force of the outer droplet is significantly smaller than the centripetal force of the inner droplet. The macroscopic expression is that the fluid gathers toward the outer pipe wall of the elbow, and the flow field is uneven.

To improve the flow field quality of the elbow, the following two methods were used for the basic model: 1) Change the turning angle of the elbow to 135 °, and reduce the turning radius difference between the droplet of the inside and outside pipe. 2) Adding deflectors in the elbow to reduce flow accumulation. Figure 2 shows the 3D geometric models of 112.5 ° and 135 ° elbow. Figure 3 shows the 3D geometric models with 2 and 5 deflectors of 0.5mm (uniformly arranged) installed in the 135 ° elbow.
3.2. Grid Meshing

All the above-mentioned 3D geometric models of elbows were imported into the mesh generation software. Considering the timeliness of mesh generation and fitness of near-wall, an unstructured mesh was used in the entire calculation domain. Meanwhile, to analyze the flow field near the deflector, the grid near the deflector was locally refined. Besides, the setting of the maximum grid computing element should be based on reasonable and efficient principles. After several trial calculations, a maximum element was 2.0 mm³, and the tetrahedron-based mixed grid generated by the Robust(Octree) method was used. The first height of the wall boundary layer was 0.6mm, the growth rate was 1.3, and the total thickness of the wall boundary layer 5.42mm, the total number of grids was about 5.5 million. After grid generation, multiple iterations were used to improve the quality of the grid to ensure that there were no negative volume grids which would cause false numerical calculations. Also, the grid independence was verified for the grids of all different geometric models. Figure 4 shows the grid of the 90° elbow (excluding the deflector) at the central cross-section plane in the vertical direction. Figure 5 is the grid of a 135° elbow with 5 deflectors of 0.5mm at the central cross-section plane and the detail features of the grids of the deflectors.
3.3. Parameter Setting of Numerical Calculation
The water flow in the pipe studied in this paper belongs to the steady flow of incompressible fluid. The governing equations were the mass conservation and momentum conservation equation of the Cartesian coordinate system. Since the computer used had up to 32 cores, the highly accurate Realizable k-e two-equation turbulence model was chosen. The solver type was selected as the pressure-based Steady flow. For liquid medium, the influence of gravity was considered. For calculation convenience, no heat exchange, adiabatic and single-phase flow condition was considered. For the viscous model, a k-e two-equation model with enhanced wall treatment was selected. For the 90° elbow, the inlet boundary condition was set as 10kg/s mass flow inlet, 2000pa static pressure, and the flow direction was the same as the pipe axis. The turbulence definition was based on turbulence intensity and equivalent hydraulic diameter. The inlet Turbulence Intensity was defined as 1%, and the equivalent hydraulic diameter was 50mm. Defined the exit boundary condition as a free-flow exit. All wall surfaces and defectors were set as Stationary wall. The velocity and pressure coupling method was SIMPLE; the gradient difference method was the Green-Gauss Cell-Based method, and the pressure difference method was the Standard method. The default value was selected for each relaxation factor when solving the iterative equation. Calculate the initial value from the inlet, and then initialize the calculation domain. Set the number of iteration steps to 1000, and the convergence occurs at about 300 Iteration.

4. Flow Field Quality Evaluation Index
To evaluate effect, such as changing the turning angle, the number of defectors and the thickness of the defectors, on reducing the vortex and secondary flow, improving the speed uniformity at the elbow and the flow field quality in the entire pipe, standard deviation of velocity on the central cross-section of the elbow and the pipe outlet, standard deviation of static pressure on the central cross-section of the elbow and the pipe outlet, turbulent viscosity on the central section, average static pressure and velocity on the outlet were selected as the index.

4.1. Standard Deviation of Velocity
The central cross-section of the elbow is shown as Figure 6, which is the vertical cross-section of the central part of the whole elbow. The standard deviation of the flow velocity at this plane can characterize the difference in the velocity of each point in the plane. The smaller the standard deviation of the velocity is, the better the velocity consistency of each point is, and the smaller the vortex and secondary flow is.

4.2. Average Turbulent Viscosity on Central Cross-section of the Elbow
The mean value of the turbulent viscosity on the central cross-section of the elbow can intuitively represent the size of the turbulence, the intensity of the secondary flow and the vorticity. The relative low turbulence viscosity value indicates that the turbulence in the central cross-section is small, the intensity of secondary flow and vortex near the pipe wall is low, and the flow consistency in the pipe is good.

4.3. Standard Deviation of Static Pressure
The standard deviation of the static pressure can characterize the difference in the pressure of each point in the planes. The smaller the value is, the better the static pressure consistency of the observed cross-
section is. Furthermore, it shows that there is less flow along the direction of the non-pipeline axis, and the chance of generation of secondary flow is smaller.

4.4. Average Static Pressure and Velocity on the Outlet
In the case of the same inlet pressure and mass flow rate, the lower the static pressure and the flow velocity on the outlet is, the greater the pressure loss is. This index is mainly used to evaluate the effect of the thickness of the deflectors on improving the flow in the elbow.

5. Numerical Calculation Results and Analysis

5.1. Choice of Turning Angle and Number of Deflectors
Select the empty elbow with two 0.5mm deflectors and with five 0.5mm deflectors as research objects, and all the three kinds of elbows should change their turning angle with 90°, 112.5°, and 135°. All these flow fields are shown in Figure 7. The velocity contours of the three different angles of empty elbows are shown in subfigures (a), (b), and (c); the velocity contours of two 0.5mm deflectors are shown in subfigures (d), (e), and (f); and the velocity contours with five 0.5mm deflectors are shown in subfigures (g), (h), (i). Use the parameter value extraction function in FLUENT post-processing to obtain the value of the parameter to be compared. The standard deviation of velocity on the central cross-section of the elbow and the pipe outlet were abbreviated as Std\textsubscript{v-mid} and Std\textsubscript{v-out}, the average turbulent viscosity on central cross-section of the elbow was abbreviated as Turbulent viscosity\textsubscript{aver-mid}, and the standard deviation of static pressure on the central cross-section of the elbow and the pipe outlet were abbreviated as Std\textsubscript{p-mid} and Std\textsubscript{p-out}. The above five indexes are used to quantitatively evaluate the quality improvement of the flow field, not only in the elbow but also in all pipe.

![Figure 7. The Velocity contours of 90°, 112.5°, 135° elbows with no deflector, 2 deflectors, and 5 deflectors](image)

Compare the flow field velocity contours of the above 9 different forms of elbows. The transverse analysis can obtain the influence of different angles on the secondary flow of the elbow, the stability of the outlet flow velocity and the stability of the flow field of the entire pipe, and the longitudinal analysis can obtain the influence of the number of deflectors on the above-mentioned flow field indexes. After
fluent post-processing, the numerical results of \( \text{Std}_v\text{-mid} \), \( \text{Std}_v\text{-out} \), and \( \text{Turbulent-viscosity}_{\text{aver-mid}} \) were obtained. The results are listed in Tables 1 to 3.

**Table 1. The numerical results of \( \text{Std}_v\text{-mid} \).**

| \( \text{Std}_v\text{-mid} \) | empty  | 2 deflectors | 5 deflectors |
|-------------------------------|--------|--------------|--------------|
| 90°                           | 1.3083 | 0.9851       | 0.9089       |
| 112.5°                        | 1.0811 | 0.8667       | 0.7800       |
| 135°                          | 0.8114 | 0.6683       | 0.6478       |

**Table 2. The numerical results of \( \text{Std}_v\text{-out} \).**

| \( \text{Std}_v\text{-out} \) | empty  | 2 deflectors | 5 deflectors |
|-------------------------------|--------|--------------|--------------|
| 90°                           | 1.1189 | 0.6694       | 0.8378       |
| 112.5°                        | 0.8773 | 0.7902       | 0.7388       |
| 135°                          | 0.5759 | 0.5651       | 0.5425       |

**Table 3. The numerical results of \( \text{Turbulent-viscosity}_{\text{aver-mid}} \).**

| \( \text{Turbulent-viscosity}_{\text{aver-mid}} \) | empty  | 2 deflectors | 5 deflectors |
|---------------------------------------------------|--------|--------------|--------------|
| 90°                                                | 1.9269 | 0.3911       | 0.2732       |
| 112.5°                                            | 0.1392 | 0.1594       | 0.0619       |
| 135°                                              | 0.0331 | 0.034        | 0.0442       |

The change trends of \( \text{Std}_p\text{-mid} \) and \( \text{Std}_p\text{-out} \) are basically the same as those of \( \text{Std}_v\text{-mid} \) and \( \text{Std}_v\text{-out} \), which are not listed here one by one. After comparing all the data, it is found that the flow field index of the 90° empty pipe is the worst. Increasing the turning angle has a significant effect on reducing turbulence. Regardless of the number of deflectors, the turbulent viscosity of the 135° elbow is more than 90% lower than that of the 90° elbow. In the case of simultaneously increasing the number of deflectors and the turning angle at the same time, the uniformity of the flow velocity and the static pressure of the central cross-section and the outlet are greatly improved, and in the optimal case, the index values are reduced by more than 50% compared with the worst values of 90° empty pipes. However, comparing the flow field index of a 135° elbow containing two deflectors or five deflectors, it can be found that even if the number of deflectors continues to increase from 2 to 5 deflectors, the improvement of index values are not particularly obvious. Therefore, it can be concluded from the above that, when considering reducing the secondary flow, improving the stability of the flow field of the elbow, improving the uniformity of the outlet flow velocity, and reducing the design difficulty and manufacturing cost simultaneously, it is the best choice thin the elbow of the flow standard device use 135° turning angle with 2 deflectors.

5.2. Choice of Thickness of Deflectors

After selecting the number of deflectors and the turning angle, this paper also analyzes the influence of the thickness of the deflectors on the flow field. The velocity contours of 135° elbow with 2 pieces of 0.5mm deflectors and 1mm deflectors are shown in Figure 8.
The StdP_out is the focus of the analysis, it is found when the inlet pressure was 2000pa, the StdP_out of the elbow with 2 pieces of 0.5mm deflectors was 350.275pa, while the value was -76.521pa at the outlet of the elbow with 2 pieces of 1mm deflectors. So it is concluded that thicker deflectors will cause greater pressure loss, which imposes higher requirements on the power source of the standard device; but the influence of different thicknesses of deflectors on the flow field and secondary flow in the elbow is not obvious. Therefore, it is considered that the 0.5mm deflector is more suitable for improving the flow field in the elbow of the flow standard device.

6. Conclusion
To solve the problems of secondary flow, turbulent vortex, and instability of the flow field in the elbow of the water flow standard device, some 3D geometric models of the elbow were established, and the flow field numeral calculations of the elbows were carried out based on the 3D models. Then the methods that might improve the flow field quality in the elbow were explored. Based on the results of the calculation, it is believed thin the elbow with a 135° turning angle and 2 pieces deflectors is the optimal choice. At the same time, using the 3D geometric model to perform numerical calculations of the flow field of a flow standard device, which is more practical than the traditional 2D geometric model.

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