Optimization of Key Parameters of Two-way Inner and Outer Tube Differential Pressure Flowmeter

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Abstract. In view of the existing insufficient research on the parameters of the key structure of the two-way inner and outer tube differential pressure flowmeter, on the basis of the structure of the two-way inner and outer tube differential pressure flowmeter, the front and rear cone angles are respectively set. The study of the length of the thin tube for the bidirectional inner and outer tube differential pressure flowmeter was added. For the three structural parameters of the front cone angle $\alpha$, the rear cone angle $\beta$, and the length of the thin tube $l$, nine sets of orthogonal tests were designed, which is different from the previous ones. The pressure loss ratio is proposed as the main evaluation index, and the simulation is performed by using FLUENT. By analyzing the results, the optimal combination is selected. Through simulation, the optimal model has good performance in measurement accuracy and pressure loss.

1. Introduction
At present, among the flow measurement of various industrial productions, the pressure difference type flowmeter has a low price and has a lot of experience. After a long period of research, the accuracy is getting higher and higher, so the application is very extensive [1]. The two-way inner and outer tube pressure difference flowmeter has the advantages of small disturbance to the fluid and large pressure difference signal[2]. In this paper, a new evaluation index of pressure loss difference is proposed. On these basis, the front and rear cone angles and the length of the thin tube are optimized to make the measurement more accurate and the disturbance to the fluid smaller.

2. Model structure and theoretical basis
The pipe for the throttle is selected to select the pipe diameter of the DN32. According to previous studies, the equivalent diameter ratio is optimal at around 0.7, and the diameter of the tube of the throttle member is 18 mm and 12.6 mm, respectively. The basic structure and three-dimensional model of the inner and outer tube differential pressure flowmeter are shown in Figs. 1 and 2.
The theoretical basis of asymmetric bidirectional internal and external tube differential pressure flowmeters is derived from the continuous equation and the Bernoulli Equation [3]. When the fluid passes through the throttle, in the I-I plane, the external flow channel compresses the throttle, the flow rate increases, the pressure decreases, the internal flow fluid diffuses, the flow velocity decreases, and the pressure increases; in the II-II plane, The inner and outer runners are relatively stable, and the flow velocity and pressure tend to be stable. In the III-III plane, contrary to the I-I plane, the outer runner diffuses, the flow rate decreases, the pressure increases, and the inner runner fluid compresses and the flow rate increases. The pressure is reduced. As a result, the largest pressure difference will be formed inside and outside the II-II section:

Similar to the measurement formula of the traditional differential pressure flowmeter [4]:

\[ Q = \frac{C \rho A}{\sqrt{1 - \lambda^2}} \sqrt{2 \frac{\Delta P}{\rho}} \]  

where \( C \) is the outflow coefficient, \( A \) is the cross-sectional area of the flow channel, and \( \lambda \) is the equivalent diameter ratio, \( \rho \) is the density of the measured fluid, and \( \Delta P \) is the pressure difference between the internal and external measuring points.

As shown in Fig. 1, in the figure, \( A \) is the cross-sectional area of the flow channel, \( V \) is the average flow velocity of the inlet, and \( P \) is the outlet pressure. When \( m \) is 1 in \( A_{mn}V_{mn}P_{mn} \), it represents the parameter of I-I section. When \( m \) is 2, it represents the parameter of II-II section. When \( m \) is 3, it represents the section III-III parameter. When \( n \) is 1, it represents the external channel parameter, \( n \) when it is 2, it represents the internal flow channel parameter. \( \alpha \) and \( \beta \) are the front and rear cone angles, respectively. According to the Bernoulli equation, the outer flow path and the inner flow path are respectively:

\[ Z_1 + \frac{P_{11}}{\gamma} + \frac{V_{11}^2}{2g} = Z_2 + \frac{P_{21}}{\gamma} + \frac{V_{21}^2}{2g} + h_1 = Z_3 + \frac{P_{31}}{\gamma} + \frac{V_{31}^2}{2g} + h_2 \]  

\[ Z_1 + \frac{P_{12}}{\gamma} + \frac{V_{12}^2}{2g} = Z_2 + \frac{P_{22}}{\gamma} + \frac{V_{22}^2}{2g} + h_1 = Z_3 + \frac{P_{32}}{\gamma} + \frac{V_{32}^2}{2g} + h_2 \]

where \( Z_1, Z_2 \) and \( Z_3 \) are the positional potentials, and \( h_{11}, h_{21}, h_{32}, h_{32} \) are the head losses. A head loss includes the pipeline loss \( h_i \) and local loss \( h_\beta[5] \). The losses along the outer and inner runners are:

\[ h_{i1} = \frac{8 \mu L}{\pi} \left[ R^4 - r^4 - \frac{(R^2 - r^2)}{\ln(R/r)} \right] \rho g \frac{Q_{v1}}{Q_{v1}} \]  

\[ Q = \frac{C \rho A}{\sqrt{1 - \lambda^2}} \sqrt{2 \frac{\Delta P}{\rho}} \]
where $L$ is the path traveled by the fluid, $R$ and $r$ are the hydraulic radii of the inner and outer runners, $Q_1$ and $Q_2$ are water flows, and $\mu$ is the dynamic viscosity coefficient.

The local head loss of the outer and inner runners is:

$$h_{t1} = \zeta_1 \frac{V_{21}^2}{2g} + \zeta_2 \frac{V_{31}^2}{2g} = \frac{\lambda_1 (K_1^2 - 1) V^2}{2g \sin \alpha} + \frac{\lambda_2 (K_1^2 - 1) V^2}{2g K_1^2 \sin \beta} + k_1 \left(1 - \frac{1}{K_1} \right) \frac{V^2}{2g}$$

$$h_{t2} = \zeta_3 \frac{V_{22}^2}{2g} + \zeta_4 \frac{V_{32}^2}{2g} = \frac{\lambda_3 (1 - K_2^2) V^2}{2g \sin \alpha} + \frac{\lambda_4 (1 - K_2^2) K_2^2 V^2}{2g \sin \beta} + k_2 \left(1 - K_2 \right) \frac{K_2^2 V^2}{2g}$$

where $\lambda_1, \lambda_2, \lambda_3, \lambda_4$ are the resistance coefficients along the path, $k_1$ and $k_2$ are the coefficients related to the front and rear cone angles, $K_1$ and $K_2$ are the compression ratios of the water flow channel. In addition to the aspect ratio associated with the head loss and local head loss along the path, there are also the length of the throttle and the front and rear cone angles $\alpha$ and $\beta$. This is the optimal level combination to look for in this article.

3. Experimental Design and Flow Field Simulation

3.1. Experimental design

According to the analysis, the main parameters affecting the pressure loss difference are the length $l$ of the throttle tube, the front cone angle $\alpha$, and the rear cone angle $\beta$. Three parameters are selected for each of the three levels. The length of the thin tube is divided into three levels of 0mm, 5mm and 10mm. The front cone angle $\alpha$ is selected from three levels of 5°, 25° and 45°, and the rear cone angle $\beta$ is also selected from three levels of 5°, 25° and 45°. The test is a three-factor three-level, so the selected orthogonal table $L_9(3^4)$ is suitable [6]. There are nine groups of tests, and the specific design of the test design is shown in Table 1.

| Test number | Front cone angle $\alpha$/° | Rear cone angle $\beta$/° | Thin tube length/mm |
|-------------|-----------------------------|--------------------------|---------------------|
| 1           | 5                           | 5                        | 0                   |
| 2           | 5                           | 25                       | 5                   |
| 3           | 5                           | 45                       | 10                  |
| 4           | 25                          | 5                        | 10                  |
| 5           | 25                          | 25                       | 0                   |
| 6           | 25                          | 45                       | 5                   |
| 7           | 45                          | 5                        | 5                   |
| 8           | 45                          | 25                       | 10                  |
| 9           | 45                          | 45                       | 0                   |

3.2. Flow field simulation

The three groups of experiments were modelled by three-dimensional software, and the flow field simulation was simulated by ANSYS FLUENT with the RNG $k$-$\varepsilon$ model. The unstructured tetrahedral meshes were used [7], and the number of grids was about 13000. The simulation medium was selected from liquid water at room temperature of 20°C and the incompressible fluid. The diameter $D$ of the
pipe was 27.2 mm for the inner diameter of the DN32 PVC pipe, the simulated inlet flow rate was 2 m/s, and the outlet condition was outflow. Two pressure taps are respectively set at a distance of 1D before and after the throttle member, and two other pressure tapping points are set at the center of the throttle member and the center of the outer flow passage. When modeling, set the symmetry plane to facilitate observation of the pressure cloud map. The symmetry plane pressure cloud diagram of Experiment 2 is shown in Figure 3.

4. Simulation results and data analysis
Each group of experiments was simulated, the relative pressures of the four pressure points were recorded, and the pressure difference between the front and back points was calculated. The pressure difference between the internal and external points was measured. The pressure loss ratio of the traditional evaluation index was the internal and external pressure difference signal and the front and rear pressure. The ratio of losses[8]. The original intention of using the pressure loss ratio as the evaluation index is to select the structural parameters with the inner and outer pressure difference as large as possible and the pressure loss before and after as small as possible [9], but the internal and external pressure difference and the front and rear pressure loss cannot be avoided, but their ratio is small. But it is a big situation. Therefore, the pressure loss has certain loopholes in this evaluation index. The pressure loss difference is the difference between the internal and external pressure difference signals and the pressure loss before and after. This index is more scientific and reasonable than the pressure loss ratio. All the measurement parameters and calculation results are shown in Table 2.

| Test ID | Pressure of front point \( P_f \)/Pa | Pressure of rear point \( P_r \)/Pa | Pressure of inner point \( P_i \)/Pa | Pressure of outer point \( P_o \)/Pa | \( \Delta P_f = P_f - P_r \)/Pa | \( \Delta P_i = P_i - P_o \)/Pa | \( \Delta P = \Delta P_f - \Delta P_o \)/Pa |
|---------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|---------------------------------|---------------------------------|---------------------------------|
| 1       | 60.0666                           | 2110.894                          | -13.5472                          | -7860.6333                        | 2170.9606                        | 7847.0861                       | 5676.1255                       |
| 2       | 487.7056                          | 2098.6714                         | -4.7488                           | -6958.9761                        | 2586.377                         | 6954.2273                       | 4367.8503                       |
| 3       | 761.4759                          | -2646.1289                        | -15.0528                          | -6181.8521                        | 3407.6048                        | 6166.7993                       | 2759.1945                       |
| 4       | 828.038                           | -2189.9231                        | -2.6676                           | -7071.1963                        | 3017.9611                        | 7068.5287                       | 4050.5675                       |
| 5       | 2754.9976                         | -280.3122                         | 120.1933                          | -4863.2441                        | 3035.3098                        | 4983.4374                       | 1948.1276                       |
| 6       | 2101.8513                         | -1494.4583                        | 36.4986                           | -4966.9932                        | 3596.3096                        | 5003.492                        | 1407.1824                       |
| 7       | 1701.3268                         | -1353.7277                        | -50.1978                          | -6480.0381                        | 3055.0545                        | 6429.8403                       | 3374.7858                       |
| 8       | 1970.1716                         | -1332.1194                        | -43.9494                          | -6176.3115                        | 3302.291                         | 6132.3621                       | 2830.0711                       |
| 9       | 5734.3848                         | 1266.8462                         | 183.0813                          | -2134.8748                        | 4467.5386                        | 2317.9561                       | -2149.5825                      |

According to the data in Table 2, the most important parameters affecting the pressure loss difference are analyzed. The range calculation table of each factor is shown in Table 3, and the range \( R \) of each factor can be calculated [10].

It can be easy to learn that the magnitude of each factor is ranked as \( R(\beta) > R(\alpha) > R(L) \). Therefore, the factor that has the greatest influence on the pressure loss difference is the post-cone angle \( \beta \). According to Table 2, it can be analyzed that the optimal horizontal combination is 5° for the front cone angle, 5° for the rear cone angle, and 0mm for the length of the thin tube. The optimal level combination obtained is exactly the model of Test 1, which is a symmetrical structure, and there is no difference between forward measurement and reverse measurement. The pressure cloud image obtained by FLUENT simulation is shown in Fig. 4.
Table 3. Calculation table of each factor

|     | Front cone angle | Rear cone angle | Thin tube length |
|-----|------------------|-----------------|------------------|
| $T_1$ | 12803.1703       | 13101.4788      | 5474.6706        |
| $T_2$ | 7405.8775        | 9146.049        | 9149.8185        |
| $T_3$ | 4055.2744        | 2016.7944       | 9639.833         |

|     | $\bar{T}_1$     | $\bar{T}_2$     | $\bar{T}_3$     |
|-----|------------------|------------------|------------------|
|     | 4267.7234        | 4367.1596        | 1824.8902        |
|     | 2468.6258        | 3048.683         | 3049.9395        |
|     | 1351.7581        | 672.2648         | 3213.2777        |

$R$  | 2915.9653        | 3694.8943        | 1388.3875        

Figure 3. Pressure cloud diagram of test 2

Figure 4. Optimal structure simulation

According to the data in Table 2, it can be analyzed that the optimal horizontal combination is 5° for the front cone angle, 5° for the rear cone angle, and 0 for the length of the thin tube. The optimal level combination obtained is exactly the model of test 1. Through simulation verification, it is not difficult to find that the optimal horizontal combination of the inner runner and the outer runner has the largest pressure difference, and the pressure loss before and after the throttle is the smallest. The pressure loss difference is the largest and the expected effect is achieved. Moreover, the optimal structure is a front-back symmetrical structure, and there is no case where the forward measurement and the reverse measurement are different. The pressure cloud image obtained by FLUENT simulation is shown in Fig. 4.

5. Conclusion

This paper simply analyzes the loopholes of the pressure-loss ratio of the evaluation index of the internal and external tube pressure difference flowmeters, and proposes a more reasonable evaluation index-pressure loss difference. According to the experimental design and simulation, the optimal horizontal combination was selected. The front and rear cone angles of the optimal model are both 5° and the length of the thin tube is 0 mm. Through verification, the optimal level combination sought is in agreement with the simulation results. Compared with the previous flowmeter, it achieves more accurate measurement and less effect on fluid disturbance, and can adapt to more industrial occasions.

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