The application of numerical calculation method in determining the coefficient of S-type Pitot tube

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Abstract. In this paper, the coefficient of S-type Pitot tube is obtained by using numerical calculation method with the help of the computational fluid dynamics (CFD) software. The process includes designing the three-dimensional geometric models of the S-type Pitot tube being calibrated and the low speed wind tunnel used in calibrating the Pitot, meshing the 3D geometric model, setting calculation model and boundary conditions, solving mesh by using hydrodynamic equations, and obtaining the coefficient of the Pitot tube by post-processing of the calculation results. However, in order to verify the validity of the method, a real flow test of calibrating the K coefficient of S-type Pitot tube was carried out in a low speed wind tunnel. The result shows that all the Pitot tube coefficients at different velocity points have errors of less than 1.5% except for the minimum flow velocity point, which indicates the effectiveness of the numerical method.

1. Introduction
The Pitot tube is a kind of instrument for measuring fluid velocity, which is widely used in aerospace, environmental monitoring, energy management and other industries. Especially in the field of environmental monitoring, although the technology of flow measurement has made great progress and various flowmeters emerge in endlessly, the Pitot tube is still the best choice for the measurement of gas velocity in flue gas with changeable flow field, complex gas composition and large particles. According to “The determination of particulates and sampling methods of gaseous pollutants from exhaust gas of stationary source” published by the State Bureau of Environmental Protection of China, Pitot-type flow velocity measurement equipment is still the main equipment used in the actual measurement method of exhaust from fixed pollution sources. This paper introduces a method of calibrating Pitot tube coefficient by numerical calculation, which provides a new choice for acquiring the coefficient of Pitot tube both in use and newly developed.

2. The principle of Pitot tube flow velocity measurement and real flow test calibration method

2.1. The principle of flow velocity measurement with Pitot tube
Based on Bernoulli equation the gas flow velocity can be measured by Pitot tube. Due to the text length constraints, the main research object of this paper is the basic S-type Pitot tube. Other geometry types,
such as L-type, diamond-shaped and spherical-shaped Pitot tube are similar in obtaining calibration coefficients by numerical calculation, which will not be repeated. The appearance of S-type Pitot tube is shown in Figure 1. It is welded by two back-to-back metal pipes. In the front of each metal pipe has a 180 degree back-to-back opening. The hole towards the gas flow direction when measuring the velocity is called total pressure hole; while the hole back to the gas flow direction is called static pressure hole.

When using the Pitot to measure the gas flow velocity, the total pressure hole is directly towards the gas flow direction, while in the back the static pressure hole is opposite to the gas flow direction (that is to say, the connection between the total pressure hole and the static pressure hole is parallel to the direction of the mainstream gas flow). Then, measure the pressure between the two holes with the differential pressure gauge. At last, combining the current gas density and Pitot coefficient, the gas flow velocity at the edge of the steady flow field in front of the total pressure hole of Pitot tube can be calculated. The above calculation process is shown in formula (1).

\[ v = K \cdot \sqrt{2\Delta p / \rho} \]  

Where:
- \( v \) is the gas flow velocity at the edge of the steady flow field in front of the total pressure hole of Pitot tube (the gas flow velocity at the maximum velocity gradient between the stable basin and the unstable basin);
- \( \Delta p \) is the differential pressure between the total pressure hole and the static pressure hole;
- \( \rho \) is the measured gas density;
- \( K \) is the coefficient of Pitot tube.

2.2. Real flow test Method for Pitot Tube Coefficient

At present, the general calibration method of Pitot tube in China is JJG518-1998 "Verification Regulation of Pitot tube" issued by the former National Bureau of Quality and Technical Supervision [1]. A standard pitot tube is needed in the calibration process. The standard Pitot tube and the calibrated Pitot tube are installed on both sides of the low speed wind tunnel, and the total pressure holes of the two Pitots should be located in the same cross-section in the wind tunnel. It is assumed that the gas flow velocity at the standard L-type Pitot tube is the same as that at the S-type Pitot tube being calibrated, and the coefficient of the Pitot tube under test can be obtained by formula (2):

\[ K_i = K_0 \cdot \sqrt{P_{\text{0i}} / P_{\text{0i}}} \]  

Where:
- \( P_{\text{0i}} \) is the differential pressure value of L-type standard Pitot tube;
- \( P_{\text{0i}} \) is the differential pressure value of S-type Pitot tube being calibrated;
- \( K_0 \) is the coefficient of L-type standard Pitot;
- \( K_i \) is the coefficient of S-type Pitot tube being calibrated;
Then five velocity points at which calibrate the S-type Pitot tube are selected in the range of 5-25m/s according to the regulation, and the measurement at each velocity point should be conducted three times. Finally, data processing can be carried out according to the regulation requirements.

3. The calibration method of Pitot tube based on CFD numerical calculation

Although the traditional Pitot tube calibration method has been widely used in industrial production practice, there are still some problems, such as long calibration cycle, high cost of equipment operation, complex methods and steps. This paper will introduce how to obtain Pitot coefficient by CFD numerical calculation, which provides a simple, efficient and inexpensive method, and also provides coefficient reference for new geometric form of Pitot tube and has a broad application prospects and economic value.

3.1. The CFD numerical calculation method and research situation at home and abroad

Computational Fluid Dynamics (CFD) is a new interdisciplinary science based on computer and fluid mechanics. By solving the basic hydrodynamic equations with the help of computer, the actual flow state of the fluid can be visualized accurately. It is widely used in the simulation and analysis of large complex flow, multi-phase flow and variable boundary conditions. Many scholars have used CFD numerical method to simulate actual flow including analysis the influence of contraction curve on the flow field in the working section of the annular wind tunnel, the influence of blade inlet position on the performance of marine centrifugal pump, the role of critical flow Venturi nozzle in micro gas flow standard device, and so on [2, 3]. However, up to now, no researchers have applied the numerical simulation method to calibrate the flow meters such as Pitot tube and anemometer. In this paper, the method of numerical calculation is applied to acquire the K coefficient of S-type Pitot tube [4].

3.2. Three-dimensional geometric model of S-type Pitot tube and calibration wind tunnel

The 3D geometric model of S-type Pitot tube is designed as shown in Figure 2, and is marked as S Pitot60 so as to distinguish from another Pitot tube in the behind of the paper. The important parameters are as follows: the distance between the total pressure hole and the static pressure hole is 60 mm, the inner diameter of the hole is 6 mm, the wall thickness of the pressure hole is 2 mm, the curvature radius of the central axis of the pressure hole is 25 mm, the bending radian is 90 degrees, the length of the tube after the pressure hole is 75 mm, the diameter of the support rod is 26 mm, and the length is 400 mm (extending to the wall of the geometric model of the wind tunnel).

![Figure 2. 3D geometry model of S-type Pitot tube.](image)

The geometric model of the test wind tunnel is shown in Figure 3, which is designed with reference to the wind tunnel used in the real flow test (the geometric parameters are not identical). It is the bicubic contraction curve and circular shrinkage cross-section in the contraction section of the wind tunnel, which entrance cross-section diameter is 800 mm, and exit cross-section diameter is 500 mm. The contraction section is followed by the working section and the diffusion section, with a length of 6000 mm. The calibrated S-type Pitot tube is placed at 3000mm distance from the inlet of the wind tunnel with keeping the total pressure hole toward the direction of gas flow direction and the connection between the total pressure hole and the static pressure hole coinciding with the central axis of the wind tunnel.
3.3. Mesh processing and Boundary conditions setting

Import the 3D geometric model of wind tunnel with S-Pitot tube into the mesh generation software. Because of the complexity of the 3D geometric model of S-type Pitot tube, in order to ensure the consistency and conformity between the volume mesh and the actual S-type Pitot tube, and to reduce the difficulty of mesh generation, unstructured mesh is used in the whole computational domain. Then in order to fully describe the flow field around the total pressure hole and the static pressure hole, it is necessary to refine the head mesh of Pitot tube. In addition, it is noteworthy that the global mesh parameters and the maximum computational element size in the fluid domain need to be set reasonably. The bigger the number of the mesh is and the smaller the maximum computational element size is, the bigger number of the total mesh in the computational domain is and the more accurate the flow field description is, but the longer the calculation time is. Conversely, the smaller of the mesh number means that the flow field description is relatively rough, but the calculation time is short and the calculation result is easy to converge. Therefore, through several trial calculations, the maximum computational element size of the model is 32 mm$^3$; the initial height of the first layer of the prism on the Pitot tube is 0.02 mm, the height ratio of the prism is 1.2; and the number of layers is 14. Finally, about 27 million computational mesh is generated. The mesh of the central cross-section of the computational fluid field and its partial enlargement around the S-type Pitot tube are shown in Figure 4a and Figure 4b.

![Figure 4](image4.png)

(a) (b)

**Figure 4.** a. The mesh of the central cross-section of the computational fluid field. b. Partial enlargement around the S-type Pitot tube.

In addition, the mesh independence verification is also carried out under the same boundary conditions (where setting the inlet boundary condition of mass-flow-inlet with 3.6 kg/s mass flowrate and the outlet boundary condition of outflow). When the number of mesh reaches 21 million, there is no effect on the final computational result of K coefficient of Pitot tube with continuing to increase the number of mesh or further refine the Pitot head mesh. The computational result of K coefficient of mesh independence verification is shown as Figure 5.

![Figure 5](image5.png)

**Figure 5.** The result of mesh independence verification.
After the mesh checking, it is imported to fluid numerical simulation software to be solved based on hydrodynamic equations. As the maximum velocity of the actual gas flow is less than 100m/s, which belongs to the category of low speed incompressible flow, the solver is setting as a pressure-based steady-state solver, and the gravity effect is usually neglected for the gas medium. In the selection of viscous model, considering the influence of near-wall prism and turbulence, the k-ε two-equation viscous model with enhanced wall-treatment is selected. In the computational domain, the air is chosen as the single medium, and the inlet boundary condition is set as the mass flow inlet, which is helpful to the uniform distribution of the inlet flow field. According to the requirement of flow point setting in real flow test, the inlet mass flowrate is set to be 1.2 kg/s, 2.4 kg/s, 3.6 kg/s, 4.8 kg/s and 6.0 kg/s, respectively, corresponding to gas flow velocity of 5 m/s, 10 m/s, 15 m/s, 20 m/s and 25 m/s. The flow direction of the medium is set as the Z-axis of the wind tunnel. In the turbulence setting, choose “Intensity and Hydraulic Diameter” as the specification method, and set the inlet turbulence intensity at 1% with hydraulic diameter at 1600mm. The boundary condition of outlet is set as outflow. After case-initialization and there is no problem in case-check, iteration can be started. And to this case, convergence will emerge around 1700-step iteration.

4. Comparisons between numerical calculation result and real flow test

4.1. Numerical calculation result

The filled velocity contours of central cross section (y = 0) and its partial enlargement around the S-type Pitot tube in the fluid domain are shown as Figure 6a and Figure 6b.

![Figure 6a and Figure 6b](image)

**Figure 6. a.** The filled velocity contours of the central cross section (y = 0) in the fluid field. **b.** Partial enlargement around the S-type Pitot tube.

The data obtained in Figure 7 are brought into formula (1), then through simply deformation. The K coefficient of the calibrated Spitot is 0.8581 when the inlet mass flowrate is 3.6 kg/s, namely, the flow velocity in the stable flow field zone is 15 m/s.

![Figure 7](image)

**Figure 7.** Static pressure of static and total pressure surface and velocity of selected point.

Using the same computational mesh, solver controls and coupling algorithm, the K coefficients of the calibrated S-type Pitot tube at other flowrate test points are shown in Figure 8.
4.2. Comparisons between numerical calculation result and real flow test

4.2.1. Comparison of the Same Pitot tube using different methods. Print the real S-type Pitot tube according to the above geometric model with the 3D printer, which is used in real flow test, and marked it as \((R)S_{\text{Pitot}60}\), shown in Figure 9. The L-type standard Pitot tube with the coefficient of 1.0008 is taken as the reference standard Pitot. According to JJG518-1998 "Verification Regulation for Pitot Tube", the real Pitot \((R)S_{\text{Pitot}60}\) is calibrated at 5 m/s, 10 m/s, 15 m/s, 20 m/s and 25 m/s, and the result is shown in Figure 10.

![Figure 9. The practicality of S-type Pitot tube printed by Formlabs 3D printer.](image)

![Figure 10. K coefficient of practicality \((R)S_{\text{Pitot}60}\) obtained by real flow test method.](image)

Through comparison, we find that the difference between numerical calculation result and wind tunnel real flow test result are about 1.5% at all flow velocity test point from 10 m/s to 25 m/s. Only for the flow velocity of 5 m/s, because of the uncertain changes of complex flow field, the difference is 2.03%. The reason can be attributed to the fact that the insertion of S-type Pitot tube in the wind tunnel has a great influence on the flow field around the Pitot in real flow test, but the Pitot tube's location in real flow test is not as accurate as that in numerical calculation.
4.2.2. Comparison of different Pitot tubes using different methods. In order to verify the universality of the above numerical calculation method to obtain the K coefficient of S-type Pitot tube, another Pitot tube with different geometrical forms is designed. The new design of Pitot tube is based on $S_{Pitot60}$ 3D geometric model: keep the total pressure hole parallel to the static pressure hole; shorten the distance $L$ between the total pressure hole and the static pressure hole to 40 mm; keep the other parameters remain unchanged; and name the new S-type Pitot tube 3D geometry as $S_{Pitot40}$. Then use the 3D printer to print the real Pitot tube of $S_{Pitot40}$, and name it as $(R)S_{Pitot40}$. The K coefficients of Pitot tube $S_{Pitot40}$ and $(R)S_{Pitot40}$ are still obtained by numerical calculation method and real flow test respectively at the five flowrate points of 1.2 kg/s, 2.4 kg/s, 3.6 kg/s, 4.8 kg/s and 6.0 kg/s, as shown in Figure 11.

![Figure 11. K Coefficient of $S_{Pitot40}$ and practicality $(R)S_{Pitot40}$ obtained by two different methods](image)

Comparing the K coefficient obtained by numerical calculation of $S_{Pitot40}$ and real flow test of $(R)S_{Pitot40}$, it was found that there was no significant difference between the two methods except the velocity point of 5 m/s. Considering the K coefficient of $S_{Pitot60}$ obtained by the two groups of measurement results, it is proved that the numerical calculation method is basically suitable for the calibration of S-type Pitot coefficient.

5. Conclusion
In this paper, a method based on computational fluid dynamics to obtain the coefficient of S-type Pitot tube is introduced. The 3D geometric model of the calibrated Pitot tube and low speed wind tunnel used in calibrating the Pitot was drawn, and the computational mesh was generated. Through solving the mesh with the hydrodynamic equations, the calibration coefficient of Pitot tube was obtained. In addition, the real S-type Pitot tube was printed with a 3D printer, and the real flow test of acquiring of the K coefficient of S-type Pitot tube was carried out to certify the validity of the numerical methods. The result shows that the K coefficient obtained by numerical calculation and real flow test at the measured velocity point other than the minimum velocity point has an acceptable error of no more than 1.5%. In the follow-up work, the influence of environmental conditions such as heat exchange will be considered in order to further reduce the relative error between the two calibration methods, so that the numerical method of calculate coefficient of Pitot tube can be better applied to industrial production practice.

Acknowledgments
This work was financially supported by the National Science and Technology Support Program Foundation (Grant NO. 2017YFF0205301).
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