Research of large diameter gas flow rate measurement method

P. CHEN[1], M. CHEN[2], M. ZHAO[3]

1. Shenyang Xingya Metrology and Calibration Technology Co., LTD.110143 China

2. Liaoning Institute of Measurement, Shenyang 110004, China

3. Shenyang Xingya Metrology and Calibration Technology Co., LTD.110143 China

Zhaomiyue2000@163.com

Abstract

To solve the hard problem of large diameter Pitot Pipe flow meter source tracing and parameter obtaining, we propose the similarity principle, which means making one (set) model that has same geometric structure but scaling down of the actual applied flow meter (prototype for short). We calibrate the model with gas flow standard facility, determine the mathematical formula and characteristic parameters of flow calculation, then applied on prototype. Base on DN4000 pipe air flow rate measurement project, we design a differential pressure flow meter based on the principle of Pitot static tubes for prototype. Models of DN1200, DN800 and DN400 are made at the same time. In order to verify the correctness and feasibility of the solution, this project is carried on in two steps. In first step, we make the models of DN600, DN300 and DN150, then test them with gas low standard facility, figure out the relationship of parameter of different diameter. In second step, we test the models of the flow meter actually in used. Base on the two groups of test results, we can find out the parameter of the flow meter actually in used. This essay is a phase summary of step one. The result shows that the Pitot tube flow meter with same geometric structure and similarity ratio is 2, their flow coefficient difference would not be larger than 5%.

Key words: Flow rate measurement of large diameter pipe, Pitot tube flow meter, similarity principle, prototype, model.

1. Introduction

Since the rapid development of science, technology and industry, the pipe diameter and flow rate of air flow meter applied in urban environment protection, natural gas, steam, motor set, petroleum, electric, metallurgy, aerospace and military is getting larger and larger. Differential pressure flow meter based on Pitot static pressure tube principle is widely applied in these areas. The largest measure diameter can be up to 9 meter, which is far beyond the capacity of present gas flow rate standard facilities. This problem makes it very difficult to trace source and get parameters. Therefore, we propose the similarity principle, which means making one (set) model that has same geometric structure but scaling down of the actual applied flow meter (prototype for short). We calibrate the model with gas flow standard facility, determine the mathematical formula and characteristic parameters of flow calculation, then applied on prototype.

2. Similarity Principle

Many mechanics questions could hardly be solved by mathematics method. It has to be experiment method. However in many situation we can not make experiment directly to the object. For example, airplane is too big to do fly research directly in wind tunnel, while insect is too small too do the research. Scientists make the research by using models which are scaling down or up. In order to make the data of models could be applied on the original object exactly, the model and original object must fulfill the conditions below:

(1) Geometric similarity: model has the same geometric shape of original object, different size but proportional.

(2) Kinematic similarity: fluid in model and original object has same velocity, direction and differential pressure.

(3) Dynamic similarity: medium in model and original object has same component, temperature, viscosity and density

When all the conditions above are fulfilled, the two flow phenomena can be called similarity in mechanics. Geometric similarity is premise of kinematic similarity and dynamic similarity, dynamic similarity is main factor of kinematic similarity, kinematic similarity is characterization of geometric similarity and dynamic similarity. None of these is dispensable.

We take the instance of DN4000 pipe flow rate measurement as an example.

Figure 1 is actual DN4000mm pipeline, the average flow velocity of area 1 is v_1, flow area is S_1, density of the medium is ρ_1; the average flow velocity of area 2 is v_2, density of the medium is ρ_2, a flow meter has been installed at area 2. The block area formed by the flow meter is Z, thus flow area at area 2 is $S_2 = S_1 - Z$.

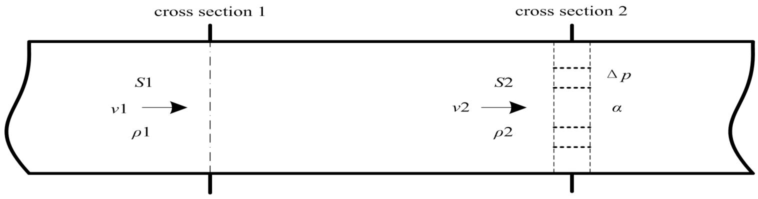

Figure 1. actual DN4000 mm pipeline

Base on continuity principle:

$$S_1 v_1 \rho_1 = (S_1 - Z) v_2 \rho_2 \tag{1}$$

Base on Pitot tube velocity measurement principle:

$$v = \alpha \sqrt{\frac{2\Delta p}{\rho}} \tag{2}$$

Put formula (2) into formula (1) we have:

$$v_1 \rho_1 = \left(1 - \frac{Z}{S_1}\right) \alpha \sqrt{2\Delta p \cdot \rho_2} \tag{3}$$

We set $\beta = \frac{Z}{S_1}$, named blockage area ratio, put it into formula (3):

$$v_1 \rho_1 = (1 - \beta) \alpha \sqrt{2\Delta p \cdot \rho_2} \tag{4}$$

Same as above, for model we have:

$$v_1' \rho_1' = (1 - \beta') \alpha' \sqrt{2\Delta p' \cdot \rho_2'} \tag{5}$$

Formula (4) divided by formula (5) on both side, we have:

$$\frac{v_1 \rho_1}{v_1' \rho_1'} = \frac{(1 - \beta) \alpha \sqrt{2\Delta p \cdot \rho_2}}{(1 - \beta') \alpha' \sqrt{2\Delta p' \cdot \rho_2'}} \tag{6}$$

Since geometric similarity, we have $(1-\beta) = (1-\beta')$; since movement similarity, we have $v_1 = v_1', \Delta p = \Delta p'$; since dynamic similarity, we have $\rho_1 = \rho_1', \rho_2 = \rho_2'$. Thus $\alpha = \alpha'$.

3. Actual Example

Base on actual situation of DN4000 industry air pipeline, we design a sensor shown in Figure 2. Three models which are DN600, DN300 and DN150 are made shown in Figure 3.

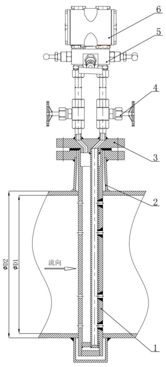

Figure 2. sensor structure

Figure 3. DN150, DN300 and DN600 models

Models conditions shown in Table 1.:

Table 1. models specific

Nominal diameter	Actual diameter （mm）	Self-contained pipeline length （mm）	Block area ratio
DN600	614.0	510	22.40%
DN300	307.1	600	22.39%
DN150	153.1	500	22.45%

According to ISO 3966 and ISO 5167, *α,* the calculation factor of Pitot pipe, is determined by the relationship below:

$$\alpha = 7.90848\frac{q_v}{(1-\varepsilon)D^2}\sqrt{\frac{\rho}{\Delta p}} \tag{7}$$

Where $(1-\varepsilon)$ is a compressibility correction factor, in a compressible fluid at low Mach numbers, it can be determined by the relationship below:

$$1-\varepsilon \approx \sqrt{1-\frac{1}{2\gamma}\frac{\Delta p}{p}+\frac{\gamma+1}{6\gamma^2}\left(\frac{\Delta p}{p}\right)^2} \tag{8}$$

Where γ is ratio of specific heat capacities, we set it as 1.4, if there is no special note.

ρ can be calculated by CIPM wet air density formula:

$$\rho = 3.483744\times\frac{p}{ZT}(1-0.3780x_v) \tag{9}$$

4. Data analysis

We tested three models with air flow standard facilities. The equipment used in the research includes standard meter method air flow rate standard facility, diameter ranging from DN300 to DN1200, maximum flow rate is 45000 m^3/h, uncertainty U_{rel}=0.5% (k=2); Negative pressure critical flow Venturi nozzle method air flow rate standard facility, diameter ranging from DN15 to DN300, maximum flow rate is 10000 m^3/h, uncertainty U_{rel}=0.33% (k=2); 0.1 class pressure transmitter, maximum range is 106kPa; 0.1 class differential pressure transmitter, maximum range is 2500Pa; temperature transmitter, measure ranging from 0 ℃ to 50 ℃, U=0.1℃ (k=2).

Test Data shown below:

Table 2. DN600 model tested with standard meter method air flow rate standard facility.

Velocity (m/s)	Pressure (kPa)	Temperature (℃)	Density (kg/m^3)	Differential pressure (Pa)	Flow rate coefficient α
9.6	99.820	25.2	1.157	203.958	0.5105
18.8	99.843	25.2	1.157	782.031	0.5116

25.5	99.859	25.2	1.157	1425.573	0.5147
31.3	99.871	25.5	1.156	2144.010	0.5150
33.3	99.879	25.6	1.156	2440.365	0.5143

Table 3. DN300 model tested with standard meter method air flow rate standard facility.

Velocity (m/s)	Pressure (kPa)	Temperature (℃)	Density (kg/m^3)	Differential pressure (Pa)	Flow rate coefficient α
7.4	99.448	25.0	1.153	110.886	0.5314
10.2	99.447	25.0	1.153	209.427	0.5338
18.9	99.526	25.0	1.154	717.761	0.5355
26.7	99.721	25.0	1.156	1448.646	0.5356
28.8	99.773	25.0	1.157	1692.760	0.5341
34.7	99.223	25.0	1.159	2453.073	0.5351

Table 4. DN300 model tested with Negative pressure critical flow Venturi nozzle method air flow rate standard facility

Velocity (m/s)	Pressure (kPa)	Temperature (℃)	Density (kg/m^3)	Differential pressure (Pa)	Flow rate coefficient α
7.4	100.067	24.6	1.167	108.333	0.5407
10.1	100.010	24.6	1.166	204.792	0.5403
18.9	100.027	24.8	1.166	716.927	0.5386
26.9	99.660	24.8	1.161	1442.344	0.5403
28.7	99.598	25.1	1.159	1643.802	0.5397

Table 5. DN150 model tested with Negative pressure critical flow Venturi nozzle method air flow rate standard facility

Velocity (m/s)	Pressure (kPa)	Temperature (℃)	Density (kg/m^3)	Differential pressure (Pa)	Flow rate coefficient α
7.4	100.182	25.3	1.160	97.552	0.5712
10.7	100.094	25.5	1.159	208.333	0.5619
19.9	99.755	25.6	1.154	740.781	0.5563
28.3	99.290	25.6	1.149	1480.625	0.5581
34.3	98.853	25.7	1.143	2149.375	0.5611
36.7	98.660	25.7	1.141	2448.802	0.5616

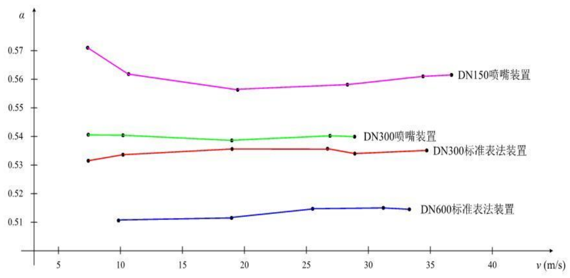

Figure 4. velocity-flow rate curve

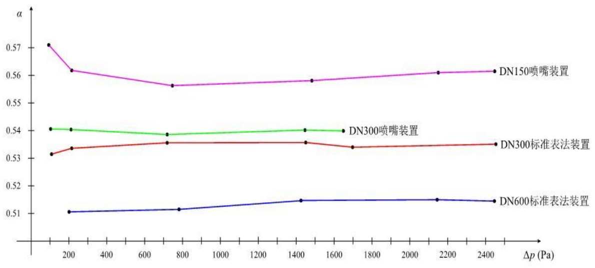

figure 5. differential pressure-flow rate curve

DN600 model was tested with standard meter method air flow rate standard facility; DN300 model was tested with standard meter method air flow rate standard facility and Negative pressure critical flow Venturi nozzle method air flow rate standard facility; DN150 model was tested with Negative pressure critical flow Venturi nozzle method air flow rate standard facility.

From the date we can see that:

(1) Flow rate coefficient of DN150 is worse than DN600 model and DN300 model. Flow rate coefficient of DN150 model at minimum point is obvious larger than normal. The differential pressure of this point is less than same velocity point of DN300 model, but it is larger at other point. Thus the data of this point could be regarded as unreliable. After removing the unreliable data, the coefficient curve of three models are basically consistent.

(2) Also tested with standard meter method air flow rate standard facility, flow coefficient of DN600 model is approximate 4% less than it of DN300 model; flow coefficient of DN300 model got from standard meter method air flow rate standard facility is approximate 1.2% less than it got from Negative pressure critical flow Venturi nozzle method air flow rate standard facility; also tested with Negative pressure critical flow Venturi nozzle method air flow rate standard facility, flow coefficient of DN300 model is approximate 3.6% less than it of DN150 model.
The reason of these results might be:
(i) Block area is too large. According to ISO 3966, when the ratio of diameter of Pitot tube installed in pipe and diameter of the pipe is not larger than 0.02, the effect of velocity gradient and block area can be ignored. After correction of velocity gradient and block area, the ratio of Pitot tube diameter and pipeline diameter is maximum 0.04. However according to actual condition, regarding safety problem, we set the ratio as 0.18, and did not make correction to the measure result.
(ii) Effect of geometric parameter and processing technique. Self-contained pipeline length of DN150 model is longer than the other two models. Internal wall surface and flange end is finely processed. Self-contained pipeline length of DN600 model is relatively shorter, internal diameter is 614mm. Internal pipe wall surface is relatively rough, flange end is not well processed. The measured pipeline internal diameter is 600mm, 14mm shorter than self-contained pipeline length, which is not fulfilled the requirement, would affect the flow. Besides, the block area ratio of three models is not exactly same.
(iii) Effect of temperature and pressure of the tested medium. When we tested different models, the environment condition could not be same. The temperature, pressure and humidity would affect the density of medium. Density of medium would seriously affect the flow coefficient, especially by using Negative pressure critical flow Venturi nozzle method air flow rate standard facility.

5. **Conclusion**

By using similarity principle, we test models of different ratio with standard meter method air flow rate standard facility and Negative pressure critical flow Venturi nozzle method air flow rate standard facility. After analysis of the test result, conclusion summarized as below:
(1) For same Pitot tube flow meter, flow coefficient got from standard meter method air flow rate standard facility is less than it got from Negative pressure critical flow Venturi nozzle method air flow rate standard facility.
(2) The rougher Pitot internal wall surface is, the less flow coefficient is.
(3) There should be long enough self-contained pipeline length of Pitot pipe flow meter.
(4) The flow coefficient of Pitot pipe flow meters with same geometric structure, whose similarity ratio is 2, would not have a deviation larger than 5%.
The flow coefficient of Pitot tube flow meter is acquired by standard meter method air flow rate standard facility. When the diameter of flow meter is lager than diameter of facility, we can test the model under similarity principle, then apply the result to the actual flow meter. Since the different structure of Pitot tube flow meter, there are differences among flow meters even they have same structure and diameter. Thus more experiment and research is needed to find out the rules within.

Figure 6. DN400~DN1200 positive looped dual-turbine standard meter method air flow rate standard facility

Reference:

[1] Xinye Mao, Weijian Li, Larger diameter pipeline air flow rate calibration meter. Electrical Equipment. 2008.12:8-11

[2] DaiLiang Xie, Study on calibration method of discharge coefficient about annubar flowmeter.2010.8:90-96

[3] ISO 3966 Measurement of fluid flow in closed conduits —— Velocity area method using Pitot static tubes

[4] ISO 5167 Measurement of fluid flow by means of pressure differential devices inserted in circular cross-section conduits running full——Part 1:General principles and requirements

[5] JJG 640-2016 differential pressure flow meters