Experiment Research on Detecting the Small Throat Diameter Flowmeter for Critical Flow by Using a Bell-type Facility

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Abstract: This article introduces the detection method of the small throat diameter sonic nozzle by using a bell-type gas flow standard facility and its advantages. The related experiment researches have been done. It also describes the structure styles and the working principles. Meanwhile, it assesses the uncertainty of the outflow coefficient C for the small throat diameter sonic nozzle detected in this method. The feasibility of the detection method has been verified through the experiment data analysis.

Keywords: Bell-type gas flow standard facility, Small throat diameter sonic nozzle, Outflow coefficient, Uncertainty analysis

1. Introduction

Now critical flow meter (commonly known as sonic nozzle) are commonly used as standard meter by many municipal metrology departments to detect domestic gas meter, the diameter of nozzle throat is small with (0.016~6) m^3/h flow range and 0.35% accuracy. Combining with temperature and pressure accuracies, the accuracy of detection device for gas meter in standard meter method is level 0.5. At present, the PVTt method is used for many of sonic nozzles, generally the throat diameter is big with (20~1000) m^3/h flow range, conforming to the requirement of ISO9300 that the Reynold number should be over 2.5×10^4[1]. For this kind of small flow nozzle, through error analysis and investigation, it is believed that it can be calibrated by widely used bell-type gas flow standard facility.
The maximal accuracy of bell-type gas flow standard facility can reach up to level 0.1. The accuracies of many existing bell-type gas flow standard facilities are level 0.2, if improving its stability, inserting high accuracy temperature sensor and pressure sensors inside the bell body and exit to correct gas temperature and pressure, it is possible to increase bell accuracy up to within level 0.15, then, through error analysis and calculation, it can be realized to use the level 0.15 bell to test level 0.35 critical flow meter.

2. Structure and Measurement Method of Bell-type Detection Device

2.1 Structure of Detection Device

The following schematic diagram(figure 1) represents detection of small throat diameter sonic nozzle conducted by bell-type gas flow standard facility. The device consists of bell (incl. pressure compensation mechanism, vacuum pump etc), high accuracy temperature and pressure sensors, nozzle (to be tested) and test pipe, as well as computer data collection system etc.

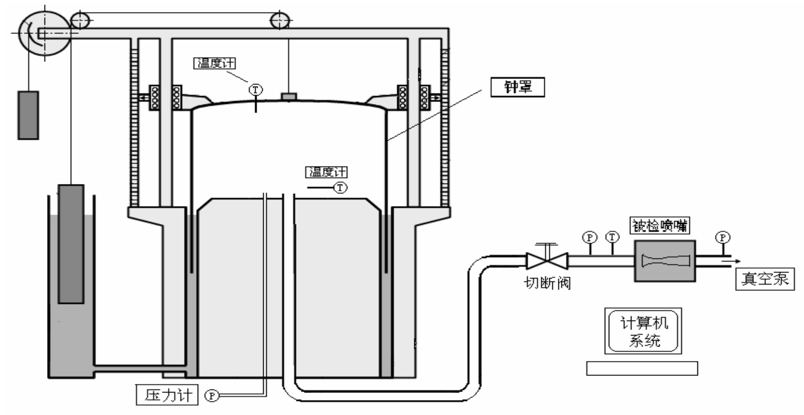

Fig. 1 Schematic diagram of detection

The bell is used to provide standard flow and stable gas source with pressure fluctuation less than 10Pa, pressure inside the bell is small between 2kPa~5kPa; the temperature transmitter is mounted both at the upper and lower ends of the bell to measure temperature value and difference inside the bell; the bell is lifted by being pulled outside the cylinder and naturally intake indoor air; Pressure difference developed by vacuum pump is up to 0~-70kPa which meets the requirement of back pressure ratio of the nozzle; both high accuracy pressure and temperature transmitters are installed in front of nozzle, pressure transmitter is installed at the downstream of the nozzle to monitor back pressure ratio.

2.2 Principle of Measurement

Flow path with minimal orifice diameter of sonic nozzle is called nozzle throat. When pressure ratio of the upstream and downstream of nozzle, i.e., back pressure ratio reaches up to critical pressure ratio, the critical flow state is formed at nozzle throat, and gas flow reaches up to maximal speed (sonic speed). Gas mass flow passing through the nozzle also reaches up to maximal value q_m. At this time the q_m only relates to stagnation pressure and temperature at nozzle inlet without subject to downstream state change.

Theoretical mass flow of the nozzle is calculated according to the measured nozzle upstream stagnant pressure and stagnant temperature, and nozzle outflow coefficient C can be calculated from standard flow (i.e., actual mass flow of the nozzle) supplied by bell.

2.3 Math Model

2.3.1 Bell Flow Model

In stable working condition, gas mass flow at bell exit is equal to that at tested nozzle. The tested nozzle flow can be obtained by calculating the bell flow at that moment.

The mass flow at bell exit is shown in Eq.(1):

$$q_m = q_V \rho = \frac{V}{t} \rho \qquad (1)$$

where

q_m : mass flow of bell; kg/s

q_v : volume flow of bell; m^3/s

ρ : density of air inside the bell; kg/ m^3

V : standard volume of bel; m^3

t : time counted by timer; s

2.3.2 Nozzle Flow Model

Formula for mass flow of critical Venturi nozzle is shown in Eq.(2):

$$q_m = \frac{A_* C C_* P_0}{\sqrt{R_M T_0}} \tag{2}$$

Where

q_m : mass flow of nozzle; kg/s
A_* : throat area of nozzle;m^2
C : outflow coefficient
C_* : critical flow function
P_0 : stagnant absolute air-pressure in front of nozzle;Pa
T_0 : stagnant absolute air-temperature in front of nozzle;K
R_M : gas constant（J/（kg×K））, For air, R_M =287.1

For ideal state, C=1. During calibration, accumulated nozzle flow is obtained by carrying out real time continuous collection of stagnant pressure and stagnant temperature in front of nozzle (at this moment, both stagnant pressure and stagnant temperature are treated as functions of the time).

Set the calibration time t= t_0 seconds, then, the ideal mass flow of the nozzle is shown in Eq.(3):

$$q_{mi} = \frac{\int_{t=0}^{t_0} \frac{A_* C_* P_0(t)}{\sqrt{R_M T_0(t)}} dt}{t_0} \tag{3}$$

At this moment, integration time must strictly synchronize with the both upper and lower photoelectric switches of calibrated volume of the bell.

The application condition of sonic nozzle is that nozzle throat reaches up the sonic speed, i.e., the maximal flow when back pressure ratio is satisfied.

Under ideal conditions, the calculation formula of critical pressure ratio can be derived theoretically as shown in Eq.(4) [2]:

$$\left(\frac{P_1}{P_0}\right) = \left(\frac{2}{k+1}\right)^{\frac{k}{k-1}} \tag{4}$$

Where

P_0—stagnant pressure at upstream inlet of the nozzle
P_1—pressure at downstream outlet of the nozzle
k —gas isentropic index, for perfect gas, k is equal to specific-heat-capacity. For air, k=1.4.

2.3.3 Nozzle Outflow Coefficient Model

Outflow coefficient is the ratio of actual mass flow got by Eq.(1) to theoretical mass flow calculated by Eq.(3). The calculation formula of outflow coefficient is shown in Eq.(5):

$$C = \frac{q_m}{q_{mi}} = \frac{\frac{V}{t_0}\rho}{\frac{\int_{t=0}^{t_0} \frac{A_* C_* P_0(t)}{\sqrt{R_M T_0(t)}} dt}{t_0}} = \frac{V\rho}{\int_{t=0}^{t_0} \frac{A_* C_* P_0(t)}{\sqrt{R_M T_0(t)}} dt} \tag{5}$$

3. Uncertainty Assessment

Measurement uncertainty of outflow coefficient C in this method is mainly from the following aspects:

3.1 Uncertainty of Throat Cross-section Area

Because throat cross-section area A is the same as the value taken in calibration during the use of sonic nozzle, it can be regarded as a constant and its uncertainty can be omitted.

3.2. Uncertainty of Standard Facility

The uncertainty of the device is 0.15%FS according to calibration certificate of bell-type gas flow standard facility. Assuming it is normally distributed, k=2, its referenced standard uncertainty is shown in Eq.(6):

$$u_1=\frac{0.15\%}{2}=0.075\% \quad (6)$$

3.3. Gas Constant Uncertainty of Air

Calculation formula of converted gas constant of wet air is shown in Eq.(7):

$$R=\frac{287.1}{1-0.3778\dfrac{\varphi_0 p_{sv}}{p_0}} \quad (7)$$

Where

φ_0 : relative humidity of air

p_{sv} : saturated vapor pressure of air; Pa

Because gas constant uncertainty of air is mainly from humidity measurement, when measurement uncertainty of atmospheric relative humidity is 4%, the corresponding uncertainty of gas constant calculation of air is 0.03% [2]. Assuming it is uniformly distributed, k= $\sqrt{3}$, thus its referenced standard uncertainty is shown in Eq.(8):

$$u_2=\frac{0.03\%}{\sqrt{3}}=0.017\% \quad (8)$$

3.4. Uncertainty of Critical Flow Function

Critical flow function C※ is:

$$C_*=\sqrt{k}\left(\frac{2}{k+1}\right)^{\frac{k+1}{2(k-1)}} \quad (9)$$

$$k=\frac{c_p}{c_V}=\frac{\rho_{a0}c_{pa}+\rho_{V0}c_{pv}}{\rho_{a0}c_{va}+\rho_{a0}c_{Vv}}=\frac{\rho_{a0}c_{pa}+\varphi_0\rho_{s0}c_{pv}}{\rho_{a0}c_{Va}+\varphi_0\rho_{s0}c_{Vv}} \quad (10)$$

Where

c_{pa}, c_{pv} : specific constant pressure heat capacities of dry air and water vapor respectively

$$c_{pa}=1004J/(kg\cdot K), c_{pV}=1863J/(kg\cdot K) \quad (11)$$

c_{Va}, c_{Vv} : specific constant volume heat capacities of dry air and water vapor respectively

$$c_{Va}=717J/(kg\cdot K), c_{Vv}=1402J/(kg\cdot K) \quad (12)$$

ρ_{s0} : saturated air density in front of sonic nozzle, kg/ m^3

ρ_{V0}, ρ_{a0} : Vapor density and dry air density in front of sonic nozzle, kg/ m^3

Atmospheric relative humidity is the most main factor affecting the calculation of critical flow function, when measured uncertainty of atmospheric relative humidity is 4%; the corresponding uncertainty of critical flow function calculation is 0.002% [2] . Assuming it is uniformly distributed, k= $\sqrt{3}$, then its referenced standard uncertainty is shown in Eq.(13):

$$\mathrm{u}_3 = \frac{0.002\%}{\sqrt{3}} = 0.001\% \qquad (13)$$

3.5. Uncertainty of Temperature Measurement

Allowable error of temperature sensor used in the facility is ±0.2℃, for measured temperature value at 20℃. Assuming it is uniformly distributed, k= $\sqrt{3}$, its referenced standard uncertainty is shown in Eq.(14):

$$u_{41} = \frac{0.2}{293.15\sqrt{3}} = 0.039\% \qquad (14)$$

The maximal temperature change during one-time calibration would not exceed Δt =0.1℃, for measured temperature value at 20℃. Assuming it is uniformly distributed, k= $\sqrt{3}$, its referenced standard uncertainty is shown in Eq.(15):

$$u_{42} = \frac{0.1}{293.15\sqrt{3}} = 0.020\% \qquad (15)$$

After combination, the standard uncertainty induced by temperature measurement is shown in Eq.(16):

$$u_4 = \sqrt{u_{41}^{\ 2} + u_{42}^{\ 2}} = 0.044\% \qquad (16)$$

3.6. Uncertainty of Pressure Measurement

The accuracy of the pressure sensor adopted is 0.075% according to pressure sensor calibration certificate. Assuming it is uniformly distributed, k= $\sqrt{3}$, its referenced standard uncertainty is shown in Eq.(17):

$$u_{51} = \frac{0.075\%}{\sqrt{3}} = 0.043\% \qquad (17)$$

The maximal pressure change during one-time calibration would not exceed ΔP=0.02kPa, and pressure average value is 101.813kPa. Assuming it is uniformly distributed, k= $\sqrt{3}$, its referenced standard uncertainty is shown in Eq.(18):

$$u_{52} = \frac{0.02}{101.813\sqrt{3}} = 0.011\% \qquad (18)$$

After combination, the standard uncertainty induced by pressure measurement is shown in Eq.(19):

$$u_5 = \sqrt{u_{51}{}^2 + u_{52}{}^2} = 0.044\% \qquad (19)$$

3.7. Uncertainty Induced by Repeatability

Taking the sonic nozzle (No: 4-3-68)as an example(the Reynold number is less than 2.5×10^4), under the same measurement conditions, repeatedly carry out measurement six times with 0.519 back pressure ratio(then reach the critical pressure ratio). Measurement results respectively are 0.957、0.958、0.957、0.957、0.958、0.958. The repeatability obtained by Bessel formula is shown in Eq.(20):

$$u_6 = 0.057\% \qquad (20)$$

Schedule of each uncertainty component is indicated as Table 1:

Table. 1 Schedule of Measurement Uncertainty Component

number	symbol	source of uncertainty	distribution	blanketing factor	standard uncertainty $u_i(x)/\%$
1	u_1	bell-type standard facility	normal	2	0.075
2	u_2	gas constant of air	uniform	$\sqrt{3}$	0.017
3	u_3	critical flow function	uniform	$\sqrt{3}$	0.001
4	u_4	temperature measurement	uniform	$\sqrt{3}$	0.044
5	u_5	pressure measurement	uniform	$\sqrt{3}$	0.044
6	u_6	repeatability			0.057

The above component is independent with each other, thus the combined standard uncertainty from calculation is shown in Eq.(21):

$$u_c = \sqrt{u_1^2 + u_2^2 + u_3^2 + u_4^2 + u_5^2 + u_6^2} = 0.12\% \qquad (21)$$

Let k=2, then expanded uncertainty of the outflow coefficient for sonic nozzle detected by the bell device is shown in Eq.(22):

$$U=0.24\%,\ k=2 \qquad (22)$$

4. Advantages of Bell-type Gas Flow Standard Facility

4.1

Because all bells are equipped with balance mechanism to keep pressure constant inside the bell during bell dropping. Generally, the pressure fluctuation inside the bell during dropping could be controlled to less than 10Pa, thus pressure source with high stability is provided. In order to further control pressure inside bell, install high accuracy pressure sensors at top of the bell and at the exit to measure the upper and lower pressures inside the bell, take their average value as P.

4.2

At early stage, the bell is mainly used to test domestic or industrial gas meter, its required ambient temperature is (20±2) ℃, for a constant temperature laboratory, it certainly meets the requirements. The bell calibration duration is short and temperature fluctuation is very small, less than 0.1℃. In order to further control the temperature, install high accuracy (allowable error is ±0.2℃) temperature sensors at both the top of the bell and at the exit to measure the upper and lower temperature inside the bell, take their average value as T.

4.3

The total volume of the bell is changing during test, but calibrated scale volume V is constant and unchanged, because pressure fluctuation is small, gas compression coefficient remains unchanged, V could be regarded as unchanged. Use high accuracy timer to count time t with accuracy up to 1×10^{-5}s, the calculated flow value Q=V/t is stable and reliable.

4.4

Bell constant volume is photoelectric synchronous and the volume is stable. Pressure difference is small after flow is stable; create negative pressure with negative pressure pump to meet test requirements of back pressure ratio of the nozzle. And during the test, critical pressure ratio is easily gained.

4.5

PVTt method is to measure change in temperature and pressure parameter values of the calibrated container before and after calibration and calculate the entered gas flow. Because the negative pressure is low due to tank absorbing before calibration, the temperature reduces; during calibration, the pressure rises up gradually, and work is done externally, and temperature rises. So, change of both temperature and pressure in the tank before and after calibration is very big, and temperature difference and gradient inside the tank is also big, with significant impact on measurement result. During calibration of the bell, work is not done externally on the gas inside the bell, it could be regarded as constant pressure and constant temperature, the bell is sealed by white oil and humidity inside the bell is also constant, therefore, the influence factors is stable and the measurement parameter is reliable.

5. Experimental Result

Experimental subject: sonic Venturi nozzle, submitted by Dandong Dongfa Gas Measurement and Control Instrument Co., Ltd.; Calibrator: bell-type gas flow standard facility.

When submitting, attach a copy of result data of PVTt-based gas flow standard facility (expanded uncertainty U_1: 0.1%, k=2) by another calibration authority (Shanghai Research Institute of Industrial Automation), compare the experimental result(converted into standard condition)using bell-type gas flow standard facility (expanded uncertainty U_2 : 0.15%, k=2) with it, the result is indicated as Table 2:

Table. 2 comparison with experimental results

nozzle number	PVTt-based gas flow standard facility （P=101.32kPa,T=293.15K）		bell-type gas flow standard facility （P=101.32kPa,T=293.15K）	
	actual flow X_1 （m^3/h）	outflow coefficient C	actual flow X_2 （m^3/h）	Outflow coefficient C
4-3-68	0.8156	0.960	0.8161	0.958

Using uncertainty verification method, take the result data obtained by gas flow standard facility in PVTt method by another calibration authority (Shanghai Research Institute of Industrial Automation) as comparison reference value, then:

$$|X_1 - X_2| = |0.8156 - 0.8161| = 0.001, \quad \sqrt{U_1^2 + U_2^2} = \sqrt{0.1\%^2 + 0.15\%^2} = 0.002 \quad (23)$$

Thus $$|X_1 - X_2| < \sqrt{U_1^2 + U_2^2} \quad (24)$$

From Eq.(23) and Eq.(24), It is known that using bell-type gas flow standard facility to calibrate small throat diameter sonic nozzle flow value is scientific and the data is real and believable. For sonic nozzle with small flow, its Reynold number is less than the application scope of ISO9300 and the back pressure ratio calculated conventionally does not reach up to sonic value[1]. Take the sonic nozzle with prescribed minimum of the application scope(Reynold number is equal to 2.5×10^4)as test. Decrease gradually in back pressure ratio and analyze the change in outflow coefficient. Experimental subject: sonic Venturi nozzle, attach a copy of result data of PVTt-based gas flow standard facility by National Institute of Metrology: nozzle flow is $3.964m^3/h$, outflow coefficient is 0.978.
The result is indicated as Table 3(converted into standard condition):

Table. 3 change of back pressure ratio test

calibrating sonic nozzle by bell-type gas flow standard facility (P=101.32 kPa ,T=293.15 K)		
back pressure ratio	flow（m^3/h）	outflow coefficient
0.753	3.947	0.974
0.734	3.961	0.978
0.733	3.968	0.979
0.701	3.964	0.979
0.604	3.968	0.980
0.515	3.964	0.979
0.482	3.964	0.979

It is shown that for sonic nozzle of small flow with 2.5×10^4 Reynold number, when the back pressure ratio reaches up to 0.733, the flow comes to the maximum and outflow coefficient is stable. The result is identical to the calibration data supplied by National Institute of Metrology.

6. Conclusion

It can be concluded from above experiment research and analysis as followed:

- It is proved that calibrating small diameter sonic nozzle by bell is feasible and it could be considered to develop and utilize. The patent is pending for the structure of device.
- Calibration data with this method is identical to the data calibrated with PVTt method by authoritative organization, and it is within the range of design accuracy of nozzle. Verification result is satisfactory.
- For sonic nozzle with Reynold number smaller than 2.5×10^4, the change regularity will be studied in the future through further experiment.

References

[1] Pere.,MT, Dong-wei Wang. Flow Measurement by improved sonic nozzle. Modern measurement and test. 1996.(3)

[2] Wang Chi, Li Fang, Dong-wei Wang. Analysis of some problems in calibration of sonic nozzle. Modern measurement and test. 2002.(01)