



Research and Realization of Mutual-Verification Method between Critical Flow Sonic Nozzle Gas Flow Standard Device and Bell Prover Gas Flow Standard Device

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Abstract

Starting from the demand of solving the reliable calibration mode of gas flow standard device, the concept of synchronous mutual-verification of flow standard device is presented in this paper. On this basis, the two system mutual-verification device of positive pressure critical flow sonic nozzle gas flow device and inlet type bell prover gas flow device is established, and advanced control system circuit design is adopted to realize the two system automatic control. The high precision roots flowmeter is used as the mutual-verification instrument. The uncertainty ($k = 2$) of the two sets of flow devices is 0.28% and 0.16% respectively. Under the mutual-verification mode, judgment value E_n is 0.19 and 0.07 (0.45 MPa and 0.63 MPa) respectively, it shows that the measurement results of the two sets of devices have good consistency and reliability. Therefore, the effectiveness of mutual-verification method is verified, and it also have certain significance for the traceability of the value in the field of gas flowmeter measurement.

1. Introduction

The process of flow measurement is a dynamic and complex measurement process. Compared with liquid, gas has larger molecular spacing, smaller attraction between molecules, and better expansibility and compressibility, that is, the pressure, volume and temperature of gas are closely related. Therefore, due to the influence of compressibility and thermal expansion, there are many factors to be considered in the gas flow standard device. Gas flow standard device is a complex standard device in flow measurement. Since the flow is a derived quantity composed of the length, quality and time of the base physical quantity, all the primary standard devices can be traced to these base quantities, rather than to the physical measuring devices. As a result, the quantity values given by each standard device are often different due to the complexity of traceability, and the secondary or working standard devices are more difficult to converge because of the extension of its traceability chain [1].

It is an important way to qualitatively analyse and quantitatively evaluate the flow value difference

between different flow standard devices, and ensure the long term stability of the flow value to compare each flow standard device with an appropriate method [2,3]. Its essence is to discover and improve the problems of the traceability device through a scientific evaluation based on data, and finally make the flow value tend to be consistent. It can be seen, since the development of gas flow measurement, that the single application of high pressure gas flow standard devices and bell prover device gas flow devices at home and abroad mostly adopts the methods of regular period verification and asynchronous measurement comparison to ensure the accuracy and reliability of the gas flow standard device [4]. In this paper, the concept of synchronous mutual-verification for two systems is proposed for the demand for a reliable verification method for gas flow standard devices, and the gas flow standard devices of synchronous mutual-verification for two systems is realized, which can effectively verify the accuracy and reliability of different gas flow standard devices.

2. Theoretical feasibility of device



2.1 Theoretical feasibility of mutual-verification

The working principle of positive pressure critical flow sonic nozzle gas flow device measuring flowmeter is shown below:

$$Q_{Nv} = \frac{A_* C_* C_d p_0 T}{p Z} \sqrt{\frac{R}{M T_0}} \quad (1)$$

where Q_{Nv} is cumulative volumetric flow of tested flowmeter in actual condition, R is gas constant of air, T_0 is absolute stagnation temperature at nozzle upstream, A_* is area of cross section at nozzle throat, C_* is the critical flow function of actual air, C_d is the discharge coefficient of nozzle, p_0 is absolute stagnation pressure at nozzle upstream, p is pressure of tested flowmeter, T is temperature of tested flowmeter, Z is compression factor of air at tested flowmeter.

The working principle of bell prover gas flow device measuring flowmeter is shown below:

$$Q_{Bv} = V_{20} \frac{p_s T_m Z_m}{p_m T_s} [1 + 2\alpha_B (\theta - 20)] \quad (2)$$

where Q_{Bv} is cumulative volumetric flow of tested flowmeter in actual condition, p_s is absolute pressure of air at bell prover, p_m is absolute pressure at tested flowmeter, T_s is thermodynamic temperature of air at bell prover outlet, T_m is thermodynamic temperature of air at tested flowmeter, Z_m is compression factor of air at tested flowmeter, V_{20} is bell prover standard volume at 20 °C, α_B is linear expansion coefficient of bell prover body material, θ is air temperature in bell prover body.

The high pressure gas flow through mutual-verification flowmeter, the positive pressure nozzle gas flow device, bell prover device gas flow device in sequence. When the flow rate is stable, according to Equation 1 and Equation 2, the process parameters of positive pressure nozzle gas flow device and bell prover gas flow device and the tested flowmeter are synchronously collected. After correction and calculation, the flow standard value of positive pressure nozzle gas flow device, flowmeter flow value and bell prover gas flow device flow standard value can be obtained. Two errors of the tested flowmeter respectively relative to two devices can be obtained. Since the gas flows through two devices and the mutual-verification flowmeter in a certain order, by comparing and judging the difference between two errors, it shows

that two-device mutual-verification mode is feasible in the measurement principle. And the mode can be used to verify the accuracy and reliability of two sets of gas flow devices.

2.2 Description of devices

The device consists of positive pressure critical flow sonic nozzle gas flow device and inlet type bell prover gas flow device, and mutual-verification connection pipe line. The device structure is shown in Figure 1. The positive pressure nozzle gas flow device is mainly composed of the high pressure air source part, pressure stabilizing and regulating equipment, measurement pipes, nozzle group, etc. The inlet type bell prover gas flow device is mainly composed of the bell prover body, the liquid tank, and the pressure compensation mechanism, supporting mechanism, lifting mechanism, guiding mechanism, lifting transmission equipment, gas heat exchanger balance system, etc.

The positive pressure air source can provide the high pressure gas required for the experiment of the positive pressure critical sonic nozzle gas flow device and the inlet type bell prover device gas flow device. It consists of screw air compressor unit, freeze air dryer unit, two-stage pressure stabilization unit, two-stage pressure-regulating unit. There are three screw air compressors, and each air compressor is equipped with auxiliary devices such as oil-water separator, filter, dryer, safety control system, etc., which can provide a maximum air production capacity of 1.3 MPa and 7.8 m³/min. There are three freeze air dryers, and the nominal inlet flow rate of each air dryers is 10.5 m³/min, and the maximum working pressure is 1.3 MPa. The two-stage pressure stabilization tanks are consisted of three sets of primary and secondary pressure stabilization tanks, and the volume of the primary stabilization tank is 15 m³, and the maximum pressure resistance is 5 MPa, and the secondary pressure stabilization tanks is 5 m³, and the maximum pressure resistance is 1.72 MPa. The pressure-regulating unit consists of three sets of primary and secondary pressure regulating valves are arranged in series. To reduce the impact of temperature fluctuation, in order to ensure the temperature is further constant, one heat exchanger is set before entering the flow device to ensure that the temperature is close to the laboratory temperature. The air into the devices are finally maintained at the requirement pressure and temperature range for tested.

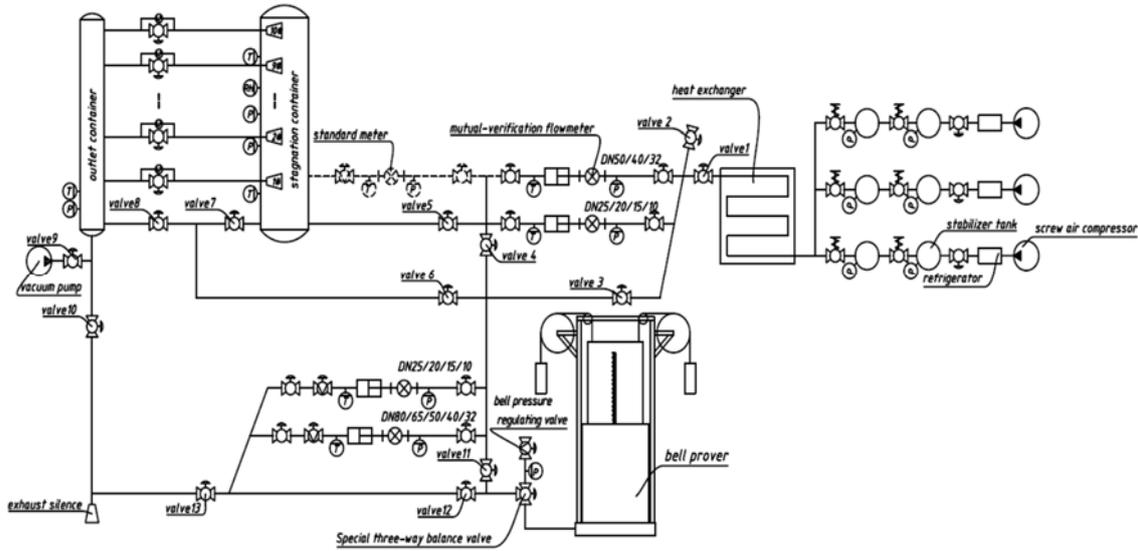


Figure 1: Schematic diagram of gas flow device of mutual-verification

2.3 Realization of device control system

The advanced control system circuit design is adopted. In the non mutual-verification mode, the control system of the positive pressure critical sonic nozzle gas flow device and the inlet type bell prover device can operate independently. when entering mutual-verification mode, the host computer can control data acquisition control unit of two sets of devices. Data acquisition control unit of two sets of devices are mainly composed of data acquisition control module, PLC, counting time module and relay, etc. Host computer performs system selection and switching through the multiple-selection control switch. Data acquisition modules mainly includes Advantech ADAM4017+, Advantech ADAM 4024, Advantech ADAM 4050, Advantech ADAM 4520. PLC is S7 200 SMART-ST30. Counting time module is mainly realized by standard crystal oscillator, dual-channel decimal timing chip 74LS390 and auxiliary circuits.

2.4 Mutual-verification mode

In mutual-verification mode, the control system synchronously collects real-time parameters of the mutual-verification flowmeter and two devices. Referring to Figure 1, the air flow sequence in this mode is screw air compressors, refrigerators, stabilizer tanks, filters, pressure regulating valve group, valve 1, valve 5, stagnation container, nozzles, outlet container, valve 8, valve 6, valve 11, special three-way balance valve, bell prover.

2.5 Device uncertainty

For the positive pressure critical flow sonic nozzle gas flow device, since the uncertainty components of A^* , C^* , R , M and Z are very small, the measurement uncertainty of A^* , C^* , R , M and Z is ignored. The combined standard uncertainty of instantaneous flow rate is shown below:

$$u_{Q_{NV}} = \sqrt{u_{C_d'}^2 + u_t^2 + \frac{1}{4}u_{T_0}^2 + u_T^2 + u_{p_0}^2 + u_p^2 + u_{p_{ipe}}^2 + u_{N_{\Delta p}}^2 + u_{N_{\Delta T}}^2} \quad (3)$$

where $u_{C_d'}$ is the standard uncertainty of nozzle discharge coefficient, u_t is the standard uncertainty of the timer, u_{T_0} is the standard uncertainty of stagnation temperature, u_{p_0} is the standard uncertainty of the stagnation pressure, u_p is the standard uncertainty of pressure measurement at tested flowmeter, u_T is the uncertainty of temperature measurement at tested flowmeter, $u_{p_{ipe}}$ is the uncertainty of pipe capacitance effect, $u_{N_{\Delta p}}$ is the standard uncertainty of pressure fluctuations, $u_{N_{\Delta T}}$ is the standard uncertainty of temperature fluctuations.

For the inlet type bell prover gas flow device, the combined standard uncertainty of flow is shown below [5]:

$$u_{Q_{BV}} = \sqrt{u_{B_V}^2 + u_{B_S}^2 + u_{T_m}^2 + u_{T_S}^2 + u_{p_m}^2 + u_T^2 + u_{p_{ipe}}^2 + u_{B_{\Delta p}}^2 + u_{B_{\Delta T}}^2 + u_{B_{\Delta p_0}}^2 + u_{B_{\Delta T_0}}^2} \quad (4)$$



where u_{BV} is the standard uncertainty of bell prover volumetric flow; u_t is the standard uncertainty of time, u_{Tm} is the standard uncertainty of temperature at tested flowmeter, u_{ps} is the standard uncertainty of pressure at the bell prover, u_{pm} is the standard uncertainty of pressure measurement at tested flowmeter, u_{TS} is the standard uncertainty of temperature measurement at bell prover, u_{pipe} is the standard uncertainty of pipe capacity effect, $u_{B\Delta p}$ is the standard uncertainty of pressure fluctuation, $u_{B\Delta T}$ is the uncertainty of temperature fluctuation, $u_{B\Delta p0}$ is the standard uncertainty of bell prover pressure fluctuation, $u_{B\Delta T0}$ is the standard uncertainty of temperature fluctuation of bell prover device.

All standard uncertainties of input variables are listed in Table 1 and Table 2.

Table 1: Uncertainty estimation of positive pressure sonic nozzle gas flow device

Symbol of input variables	Standard uncertainties of input variables %	Index
$u(C_d')$	0.1055	1
u_t	1.6×10^{-9}	1
u_{T0}	0.017	0.25
u_T	0.017	1
u_{p0}	0.0375	0.5
u_p	0.0375	0.5

Table 3: Test results and data of mutual-verification mode (nozzle device)

Flow rate m ³ /h	Measuring time s	Stagnation temperature °C	Stagnation vessel pressure kPa	Temperature of tested meter °C	Absolute pressure of tested meter kPa	Normal conditions volume L	humidity %RH	Pulse of tested meter	Factor K L ⁻¹	Average Factor K L ⁻¹	Repeatability %
16.26	53.5013	20.95	451.053	21.35	452.550	241.584	25.1	4911	20.3283	20.3252	0.38
	53.4801	20.90	451.501	21.28	452.531	241.708	25.5	4912	20.3221		
	53.4812	20.94	451.461	21.28	452.536	241.672	25.6	4912	20.3251		
16.27	38.5110	21.03	631.392	21.56	634.166	174.074	28.0	3550	20.3936	20.3935	0.008
	38.5480	21.13	631.386	21.51	634.199	174.170	27.9	3551	20.3881		
	38.5400	21.14	631.363	21.52	634.211	174.127	27.9	3552	20.3989		

u_{pipe}	0.018	0.5
$u_{N\Delta p}$	0.012	1
$u_{N\Delta T}$	0.07	1
$u_{QNv} = 0.14\%$		

Table 2: Uncertainty estimation of inlet type bell prover gas flow device

Symbol of input variables	Standard uncertainties of input variables %	Index
u_{BV}	0.012	1
u_t	1.6×10^{-9}	1
u_{Ts}	0.017	1
u_{Tm}	0.017	1
u_{ps}	0.0375	1
u_{pm}	0.0375	1
u_{pipe}	0	1
$u_{B\Delta p}$	0.009	1
$u_{B\Delta p0}$	0	1
$u_{B\Delta T}$	0.004	1
$u_{B\Delta T0}$	0.006	
$u_{QBv} = 0.061\%$		

3. Experimental tests

The high-precision DN50 Roots flowmeter is used as the tested mutual-verification flowmeter. The collected process parameter information of two devices and mutual-verification flowmeter are shown in Table 3 and Table 4 [6].

Table 4: Test results and data of mutual-verification mode(bell prover device)

Flow rate m ³ /h	Measuring time s	Bell prover normal conditions volume L	Bell prover pressure kPa	Bell prover temperature °C	Absolute pressure of tested meter kPa	Temperature of tested meter °C	Pulse of tested meter	Factor K L ⁻¹	Average Factor K L ⁻¹	Repeat ability %
16.269	53.5013	241.777	104.708	21.03	452.550	21.35	4911	20.3121	20.3184	0.57
	53.4801	241.729	104.708	21.03	452.531	21.28	4912	20.3202		
	53.4812	241.701	104.709	21.10	452.536	21.28	4912	20.3230		
16.27	38.5110	174.144	104.709	21.15	634.166	21.56	3550	20.3854	20.3871	0.24
	38.5480	174.154	104.708	21.21	634.199	21.51	3551	20.3901		
	38.5400	174.234	104.707	21.10	634.211	21.52	3552	20.3864		

The Factor K under 0.45 MPa and 0.63 MPa in Table 3 and Table 4 are listed in Table 5. Through calculation, the relative error of the Factor K results under the mutual-verification model is 0.033% and 0.031%, respectively.

The equation for calculating verification consistency result is:

$$En = \frac{Er}{\sqrt{U_1^2 + U_2^2}} \quad (5)$$

where U_1 is the expanded uncertainty of the Factor K measurement result of the mutual-verification flowmeter on the nozzle device, U_2 is the expanded uncertainty of the Factor K measurement result of the mutual-verification flowmeter on the bell prover device, En is the judgment value, En less than 1 indicate good verification consistency of the measurement result.

Table 5: Relative errors of measurement results under the mode of mutual-verification of two-devices

pressure (MPa)	Factor K (nozzle device) (1/L)	Factor K (bell prover device) (1/L)	Relative error Er (%)
0.45	20.3252	20.3184	0.033
0.63	20.3935	20.3871	0.031

The expanded uncertainty ($k=2$) of the two sets of devices is 0.28% and 0.16%, respectively. Combined with the repeatability in Table 3 and Table 4 and Er in Table 5, it can be calculated that En respectively are 0.19 and 0.07 (under 0.45 MPa

and 0.63 MPa), both less than 1. Therefore, the measurement results of the two sets of devices are in good agreement, which also verifies and illustrates the accuracy and reliability of the two sets of devices.

The mutual-verification is carried out on the positive pressure sonic nozzle gas flow device and the bell prover gas flow device. For the $En < 1$, it is concluded that the measurement of the positive pressure sonic nozzle gas flow device and the bell prover gas flow device has a good consistency and a high degree of reliability.

4 Conclusion

This paper starts from improving the accuracy and reliability of the gas flow standard device. The concept of mutual-verification is put forward, and the calculation formula for judging the consistency result is given. At the beginning of flow device design, the realization of mutual-verification function and devices layout have been considered. The positive pressure critical flow sonic nozzle gas flow standard device and the inlet type bell prover gas flow device are established, and each device can operate independently and can also perform under the mutual-verification mode. Finally, through the experimental test, it is concluded that the two sets of gas flow standard devices have good consistency and high reliability, which verifies the effectiveness of the mutual inspection of the two systems. It is of certain significance to the traceability of quantity value in the field of gas flow measurement.



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