Development of a portable small gas flow transfer standard based on laminar flow technology

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Abstract

Small gas flow measurement is widely applied in aerospace, environmental monitoring, automotive, medical and other fields. To calibrate the small gas flow, a portable transfer standard device based on laminar flow technology is developed, which includes a gas conditioner, laminar flow elements, a pressure sensor, a temperature sensor and a flow computer. The measurement range of the device is (1~10000) mL/min with a relative expanded uncertainty of $U \leq 0.3\%$, $k = 2$. The device has the capacity to compensate the medium temperature influencing on the flow rate. It can be utilized to calibrate the gas flow whose pressure does not exceed 0.6 MPa. With a compact dimension and weighing 27kg, the device is easy to be carried. The consistency of the measurement results of the device under different temperature and pressure conditions is studied, and it is verified that the device can be utilized as a transfer standard for both in-laboratory calibration and on-site calibration for small gas flow.

1. Introduction

All papers will be edited, but not peer reviewed, and prepared in pdf format for publication on the MSA website. The papers will be accessible to MSA members and conference attendees. Authors should limit the total length of paper to 6 pages. Small gas flow measurement is widely applied in aerospace, environmental monitoring, medical biology, automobile manufacturing and other industries. In the field of aerospace, small flow is utilized to evaluate the performance of the engine or critical components. In the test of small and medium-sized aero-engines, the measurement range of small gas flow covers a range of tens of grams per second to tenths of grams per second, and the medium pressure is measured [1]. For the air monitoring systems, where the gas sampling flow rate is often less than 1 L/min, a stable and accurate gas flow measurement is the basis for the accuracy of gas analysis. In the field of medical biology, mass spectrometers are widely used in research and production as a general tool, in which the accuracy of small gas flow parameters has a crucial impact on the transmission of ions [2]. For automobile engines, the new type of reciprocating HCCI engine improves thermal efficiency and reduces emissions through inter-cycle combustion control, which is inseparable from the control of micro-flow of intake air between cycles [3]. Obviously, the small gas flow measurement has become a basis in many fields.

With the continuous research on small gas flow measurement technology, based on the needs of scientific research and production, many countries have developed various small gas flow standards according to their needs. Active piston flow standard, pVTt flow standard, MT gas flow standard, etc. are well introduced as the primary standards[4].

Due to the complexity of small gas flow measurement, especially in the measurement of medium and high-pressure small flow, the gas flow is greatly influenced by the ambient temperature and gas pressure, therefore it is difficult to have an accurate and stable standard. In China, small gas flow standards are mainly imported [5]: such as the Molbloc-L, CalTrak -XL, and so on.

A laminar flow meter is a differential pressure-based flow measurement device consisting of laminar flow elements and a differential pressure sensor. The laminar flow elements ensure that the fluid passing through the flowmeter is in a laminar state, in which case the mathematical model of the volume flow it produces can be expressed by the *Hagen-Poiseuille* equation [6] .

$$Q = \frac{\pi r^4}{8\eta L}\Delta p \qquad (1)$$

Where,
Q —— volume flow;
Δp —— the pressure difference between the inlet and outlet of the laminar flow element
r —— radius r of the laminar flow element
L —— the length of the laminar flow element
η —— viscosity coefficient of fluid

As the critical part of the flow device, the laminar flow elements accuracy directly determines the measurement uncertainty of the device. Much research shows the improvement of the accuracy of laminar flow component. Fernando Lopez Pena [7] proposed to start with the differential pressure measurement method of laminar flow components, measure static pressure by adding a position, and provide static pressure through the pressure measuring port at the level of each chamber. pressure to reduce the linearization error. Chih - Cheng Feng[8] developed a laminar flow meter composed of single or multiple glass capillaries, the flow rate is as low as 1 mL/ min in, and the deviation reaches ±0.15%. Wang Xiaolu [9] proposed a rectangular gap type LFM with a laminar flow channel formed by a groove between two cubes, which can measure the pressure drop from developed laminar flow, avoid the effect of inlet and outlet, realize low pressure loss measurement, and improve the LFM Performance. Starting from the principle, Huang Haoqin[10] proposed a pressure-potential laminar flow sensing technology, using a cross-symmetrical double flow channel structure of laminar flow components to partially offset the local loss at the inlet and outlet of the capillary and the nonlinearity of the initial laminar flow. pressure loss, so that the differential pressure output has better linearity; Qingqing Wang[11] proposed the use of parallel pressure differential (PPD) laminar flow sensing technology to reduce nonlinear effects in traditional laminar flow elements (LFE) Waiting for new methods and technologies. However, since the accuracy of domestic laminar flow components is generally about 1% [12], which is not always qualified as a transfer standard.

2. Design of a small gas flow standard based on laminar flow technology

The laminar flow device consists of laminar flow elements, a differential pressure sensor, a high-stability flow conditioner and valves. The device design is shown in Figure 1.

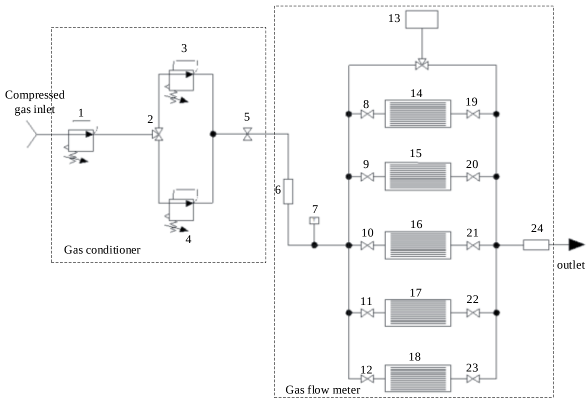

Figure 1: Schematic of laminar flow standard

1-pressure regulator;
2-3 way solenoid valve;
3&4-precision pressure regulator;
5- solenoid valve;
6&24-filter 0.5μm;
7-temperature sensor;
8 to 12- solenoid valve;
13-differential pressure sensor;
14 to 18- laminar flow element;
19 to 23-solenoid valve

Through the inlet compressed gas is supplied to the system, consisting of gas conditioner and gas flow meter, where pressure regulators, solenoid valves, filters, temperature sensor, pressure sensor and laminar flow elements are engaged to generate reference gas flow. The outlet of the system is connected to the device under calibrated. The gas pressure and flow are manually adjusted by pressure regulators to generate certain pressure and flow rate. The gas flow meter, consisting of five laminar flow meter, differential pressure sensor and temperature sensor, is used as a standard meter with a measuring range of 1 to 10 000 ml/min.

The laminar flow elements, Model 10s manufactured by CME, and differential pressure sensor, Model 6000-100G manufactured by Paroscientific, are adapted. An enclosure in which the gas flow meter is integrated has a dimension of 520×370×210 mm and a weight of 27kg, so that it can be transported in a trolley case to perform calibration in laboratory or on-site.

Figure 2: The completed development of the laminar flow device

3. Verification test of laminar flow device in different status

To verify the consistency of the measurement results of the device in different status, its flow rate is compared by a piston flow standard device, SIERRA SL-500, with measurement range of 5 sccm - 50 slpm and an expanded uncertainty of

$U_{rel} = 0.26\%, k = 2$. The test framework is shown in Figure 3.

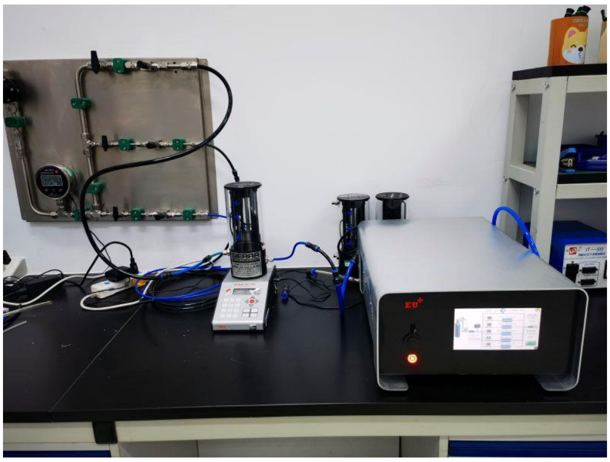

Figure 3: Comparison test site of laminar flow device and piston device

The pipeline of the comparison system connects the gas source which is high-purity nitrogen, pressure regulators, needle valve, piston standard device and laminar flow device in series [13]. The medium gas temperature is 15°C, and pressures is adjusted at 0.1MPa, 0.2MPa, 0.3MPa and 0.4MPa[14]. The test result data is obtained. Then the medium gas temperature is adjusted to 20°C and 30°C respectively and similar test at different pressure is performed. The results are shown in table 1.

Table 1: Results of comparison between laminar flow device and SL-500.

Medium temp (℃)	**Flow measurement(L/min) with different inlet pressure**				**Pressure difference(kPa) with different inlet pressure**			
	0.1 MPa	**0.2 MPa**	**0.3 MPa**	**0.4 MPa**	**0.1 MPa**	**0.2 MPa**	**0.3 MPa**	**0.4 MPa**
15	19.863	20.062	19.541	19.411	4.6181	4.6264	4.6271	4.5843
	10.892	11.112	10.529	10.623	2.4697	2.4352	2.4140	2.4580
	5.267	4.716	4.428	4.135	1.1218	1.0073	1.0115	0.9349
	1.756	2.382	2.764	2.531	0.3806	0.5019	0.6102	0.5674
20	20.237	19.617	19.621	19.731	4.6540	4.5354	4.5561	4.5809
	11.009	10.794	10.348	10.651	2.4770	2.4532	2.3484	2.4325
	4.707	4.691	4.268	4.346	1.0260	1.0411	0.9556	0.9742
	2.407	2.467	2.628	2.208	0.5210	0.5495	0.5792	0.4929
30	20.931	20.042	20.332	20.171	4.6705	4.4926	4.5651	4.5345
	11.412	11.421	11.711	11.062	2.4911	2.5220	2.5786	2.4580
	5.067	5.063	4.594	4.267	1.0852	1.0935	0.9942	0.9184
	2.527	2.426	2.250	2.298	0.5343	0.5150	0.4813	0.4923

In equation (1), for the same laminar flow element, both the radius r and the length L are fixed. For pure nitrogen as the medium, the change of the fluid viscosity coefficient can be ignored , take $\boldsymbol{k} = \frac{\pi r^4}{8\eta L}$, equation (1) can be simplified as [15] :

$$Q = k \times \Delta p \qquad (2)$$

Based on equation (2), the flow rate Q of the laminar flow device is proportional to the differential pressure Δp between the inlet and outlet of the laminar flow element, and Δp directly reflects Q. The coefficient k can be determined by the calibration of the high-precision flow device. To avoid systematic errors, the measured value of the piston flow standard and the differential pressure Δp is utilized to analyze the experiment result.

(1)under the same pressure , the influence of temperature on the linear flow of laminar flow is shown in Figure 4 to 7.

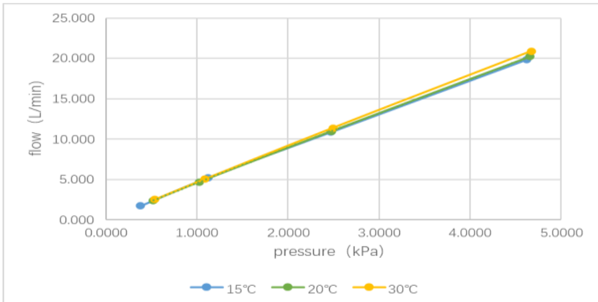

Figure 4： Tempreture influence on Q and Δp under inlet pressure 0.1 MPa

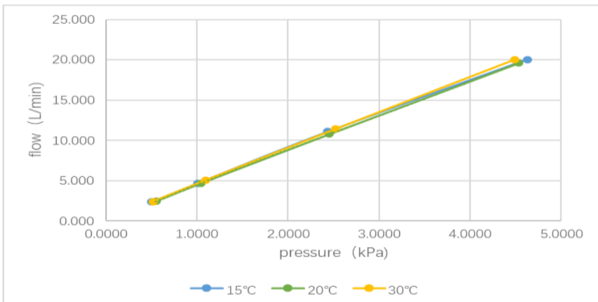

Figure 5： Tempreture influence on Q and Δp under inlet pressure 0.2 MPa

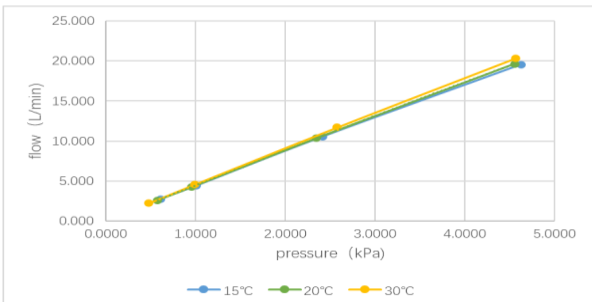

Figure 6： Tempreture influence on Q and Δp under inlet pressure 0.3 MPa

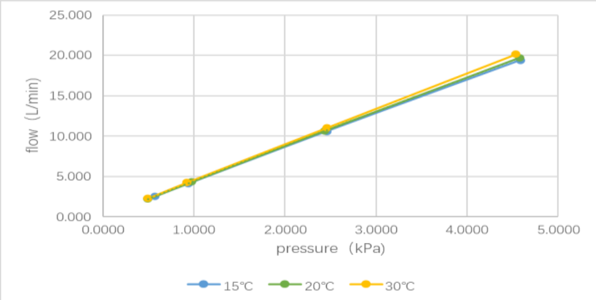

Figure 7: Tempreture influence on Q and Δp under inlet pressure 0.3 MPa

(2) at the same temperature, the influence of pressure on the linear flow of laminar flow is shown in Figure 8 to 10.

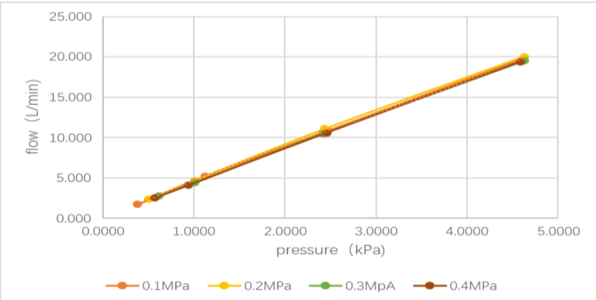

Figure 8: Inlet pressure influence on Q and Δp at 15 ℃

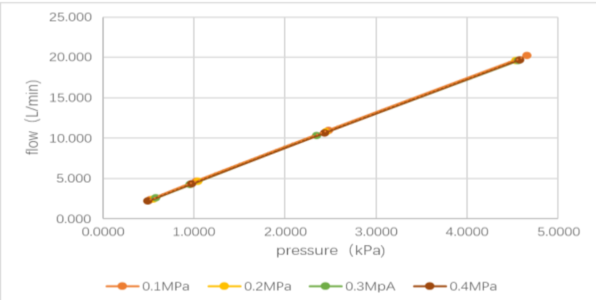

Figure 9: Inlet pressure influence on Q and Δp at 20 ℃

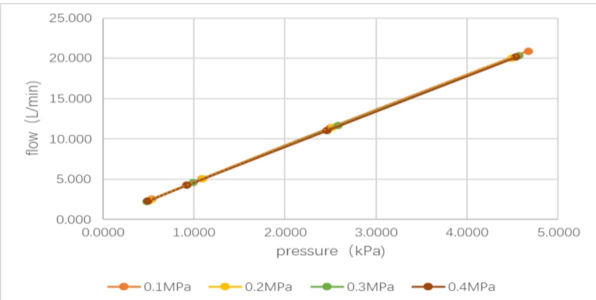

Figure 10: Inlet pressure influence on Q and Δp at 30 ℃

The above three charts show that at the same temperature the four flow lines under different inlet pressures highly overlap, indicating that the pressure change has little effect on the flow rate and differential pressure. It verifies that the device can be applied to calibrate flow meter under different medium pressure.

The change of the medium temperature has a linear effect on the flow rate of the laminar flow device. During the same measurement, the flow linearity of the laminar flow device is stable, and the change of inlet pressure of the LFE has little effect on the flow linearity of the laminar flow device, and the amount of influence is between 0.005-0.1. In the follow-up test, the medium temperature is measured, and the pressure change is limited, therefore the impact on the measurement result can be reduced to a lower level, and the k value can be corrected by the empirical quadratic function of the LFM model [16].

4. Quantitative traceability of laminar flow device

The development of the laminar flow device must have a traceability to the primary standard. Since the minimum measurement point of the flow benchmark of NIM is 5.28 mg/s [17], the device was calibrated in the Shanghai Institute of Measurement and Testing Technology (SIMT) where SIERRA SL-800 piston standard with a measurement range of 5 sccm - 50 slpm, an expanded uncertainty of $U_{rel}=0.19\%, k=2$ was used as the standard device. The medium is nitrogen, and the medium temperature is 21.9 ℃. The measurement results and the expanded uncertainty are shown in Table 2 and the comparison charts are shown in Figure 11 to 13.

Table 2: Traceability data of small gas flow standard device

Flow range /mL/min	*flow point /mL/min*	*Indication error (%)*	*Repeatability*	*Expanded uncertainty*
(1-10)	5	-0.24	0.14	U_{rel}=0.34% , k=2
	10	0.18	0.12	
(10-100)	10	0.22	0.03	U_{rel}=0.26% , k=2
	20	0.13	0.02	
	50	-0.16	0.03	
	100	0.36	0.05	
(100-1000)	100	0.37	0.01	U_{rel}=0.26% , k=2
	200	0.66	0.05	
	500	0.52	0.02	
	1000	0.76	0.04	
(1000-10000)	1000	-0.03	0.07	U_{rel}=0.26% , k=2
	2000	-0.01	0.04	
	5000	0.05	0.04	
	10000	-0.14	0.01	

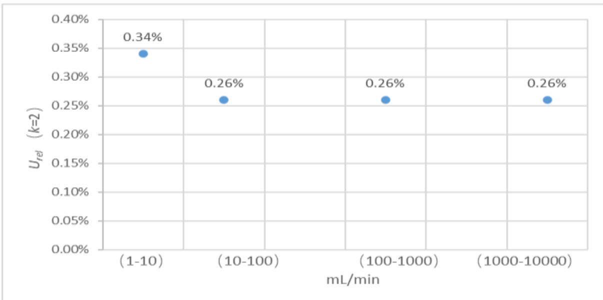

Figure 11: Comparison of expanded uncertainty of each channel

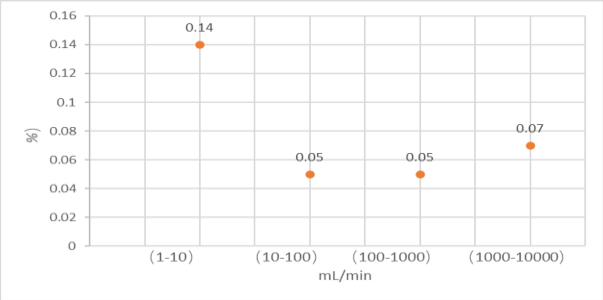

Figure 12: Comparison of maximum repeatability of each channel

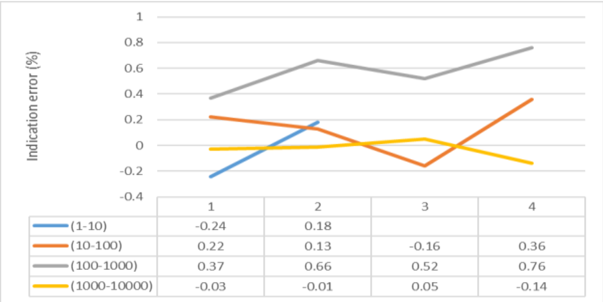

Figure 13: Error trend of each channel

By comparing Figure 11 to Figure 13, it is found that the repeatability and uncertainty of the (1-10) mL/min channel are large, and the error curve is not ideal. This might be due to that small flow rate is close to the measurement limit of the piston standard device, and the repeatability of the laminar flow element itself or the pressure channel control is not stable enough, which finally affects the measurement uncertainty of the channel. The error curves of the remaining three flow channels basically tend to be stable, and the expanded uncertainty is 0.26%, *k*=2. And the measurement repeatability is better than 0.07%.

5. Conclusion and further research

As a transfer standard, the gas flow standard device developed based on laminar flow meter is feasible for the small flow, and it has an expanded uncertainty of $U_{rel} = 0.34\%, k = 2$ for the range of 1-10 ml/min, and an expanded uncertainty of $U_{rel} = 0.26\%, k = 2$ for the range of 10-10 000 ml/min.

When it is used to measure the gas flow under the pressure no more than 0.4MPa, the laminar flow device can maintain the consistency of its measurement.

The medium temperature and inlet pressure changes have a certain influence on the linearity of the laminar flow device, but when compressed nitrogen is used as the medium, the temperature and pressure changes are small, which can ensure the consistency of the flow measurement of the laminar flow device.

The gas medium used in the device is nitrogen from compressed gas cylinders. Furthermore, the performance of the laminar flow device with medium of clean air or other gases will be studied so that it will be applied for different on-site calibration.

6. Acknowledgement

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