Laminar Flow Element Type Flow Meter with Straight Glass Capillary

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Abstract: Center for Measurement Standards (CMS) developed a laminar flow element (LFE) type flow meter as a transfer standard. This LFE consists of a single straight glass capillary or multiple straight glass capillaries connected in parallel. Two gauges and one thermometer measured the inlet/outlet pressure and inlet temperature, respectively, and the differential pressure was restricted from 2 kPa to 100 kPa. The glass capillaries were manufactured by laser machining, resulting in consistent inner diameter and straight flow path. Characteristics of glass material also prevented the capillary from bending during installation. By means of regression, the turndown ratio of this LFE flow meter could be higher than 20 and the residual would be still within 0.11 %. The reproducibility within 0.03 % indicated that this LFE flow meter can be used as a transfer standard. Measurement with dry air demonstrated that these four LFE meter could span the flow rate at (0.8 to 986) μmol/s within the deviation of ±0.15 %. (1 μmol/s could be converted as 1.3 cm^3/min at 0 ℃ and 101.325 kPa) Additional measurement with nitrogen demonstrated the feasibility of measurement with multiple gases.

Keyword: Straight glass capillary, laminar flow element

1. Introduction

This article describe Center for Measurement Standards (CMS) developed the laminar flow element (LFE) flow meter for gas flow below 985 μmol/s, i.e. converted flowrate below 1280 sccm at 0 ℃ and 101.325 kPa as reference condition. The LFE comprise straight glass capillary, two pressure gauges and a thermometer. Two gauge measure the inlet and outlet pressure of the LFE and a thermometer monitor the inlet temperature. A Hydrodynamic model determines the flow rate from P_1, T_1, P_2 and gas properties.

This LFE flow meter could be a portable transfer standard. Flow comparisons between laboratories are used to demonstrate equivalence, validate uncertainty analyses, and support fair trade. Critical flow venturis (CFVs) are used as gas flow transfer standards. As the flow below 1 L/min, CFVs become difficult to manufacture. The requirement for ISO 9300 nozzle shape and small throat in this range is challenging for workshops. On the other hand, LFE type flow meter performs best at low flow rates. Consequently, CMS chose LFE flow meter as a transfer standard model.

Wright et al.[1] listed some features of transfer standards, and compared the difference of CFVs and LFE, gave a suggestion that reproducibility shall below 0.05 %. With the use of long curved capillaries, Berg[2,3] developed a LFE flow meter and the physical model to predict the flow rate based on pressure and temperature measurement. The meter was then used as a transfer standard [4]. The difficulty lies in bending the long capillary and maintaining the curvature precisely at the same time. Constrained by the resource and capability of workshops, straight capillary was adopted.

Spanning the described flow rage required four flow elements design (see Table. 1). Each flow element comprised either a single capillary or an array of parallel capillaries, and the value for inner diameter ID was chosen to minimize the deviations shown in Fig. 1. Fig. 2 showed results for Nitrogen and air flowing through the LFE. With the use of gas properties correctly, CMS LFE flow meter could keep the deviation of flow rate within ±0.15 %.

The spec for this LFE flow meter included the turndown ratio higher than 20, and total length of the meter less than 30 cm. The reproducibility and repeatability of this LFE was evaluated. A means of expending the flow rate were studied. The physical model[2] was then modified with regression to meet the expected spec.

Table. 1 Characteristic of the four Laminar Flow Element flow meter

		Laminar flow element				
		CMS-0.1-50-1	CMS-0.2-100-1	CMS-0.25-125-3	CMS-0.3-150-7	
Range of flow rate (dry air)	$\dot{n}$	0.8 to 15.5	4 to 57.7	26.5 to 237	77.5 to 986	μmol/s
Capillary inner diameter	*ID*	100	200	252	300	μm
Capillary length	*L*	50	100	125	150	mm
capillaries in parallel	*N*	1	1	3	7	-

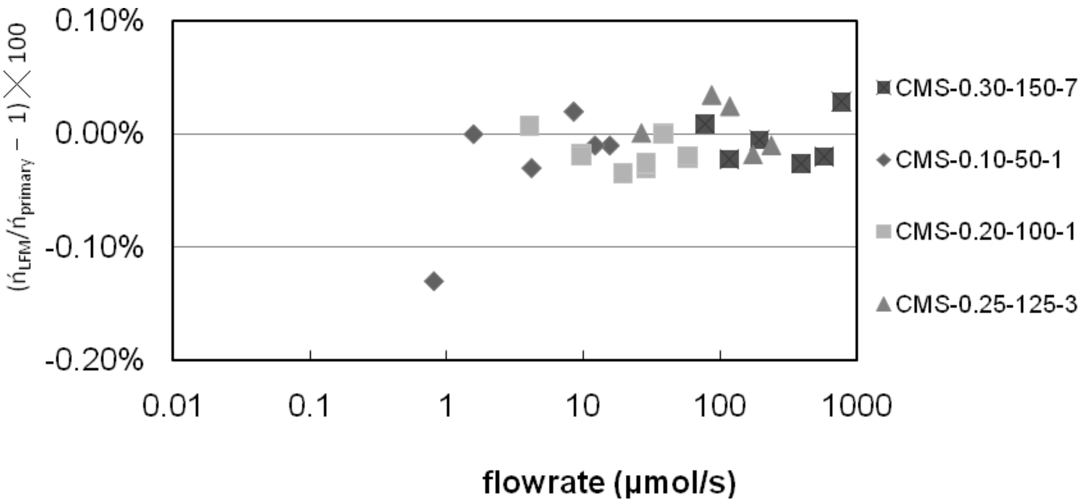


FIG. 1 Deviations of the flowrate indicated the difference between four flow elements (see Table. 1) and Piston Prover as a primary standard through dry air gas flow.

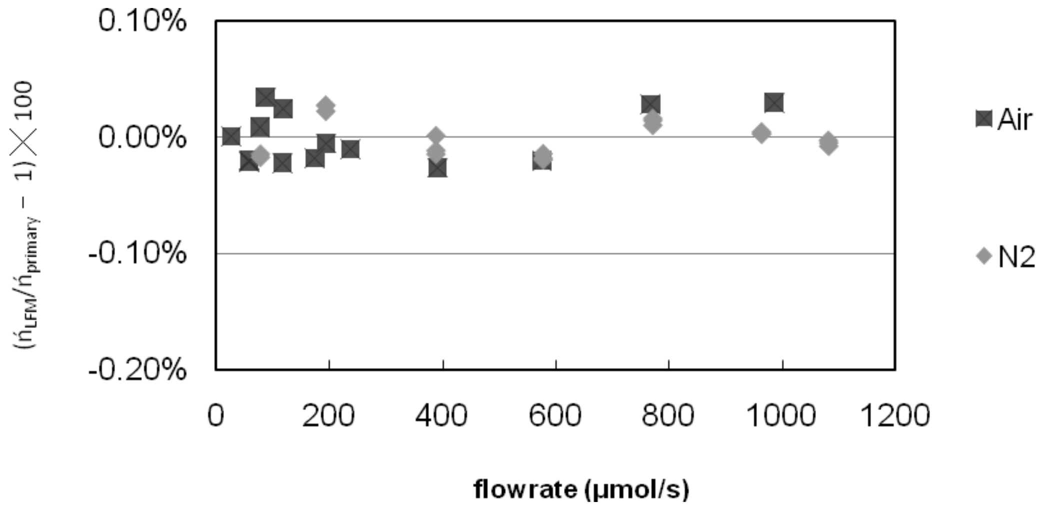


Fig. 2 Normalized deviations of the indicated flowrate in the CMS-0.30-150-7 from that measured with the Piston Prover primary standard.

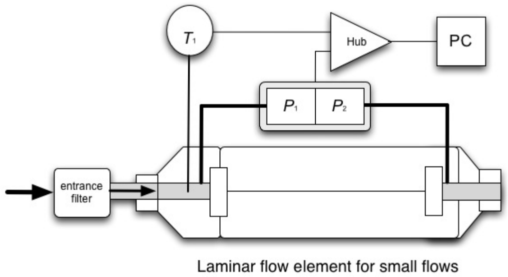
2. Principal and experiment

2.1 Materials and apparatuses

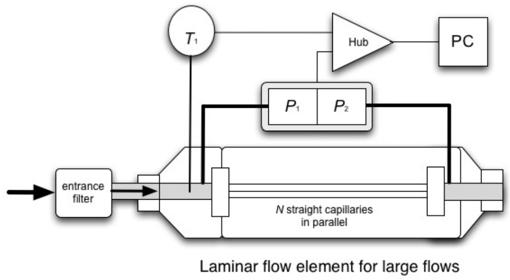
The flow meter used a single straight capillary or multiple straight glass capillaries connected in parallel as the LFE. The pressure and temperature were measured to determine the flow rate. The pressure gage used in this study was mensor CPG 2500 (two channels) with a full range of 300 kPa absolute pressure and 1 Pa resolution. The 3-wire Pt 100 type thermometer was custom-made with a resolution of 0.01 ℃.

The differential pressure of the LFE used was designed to be within the range of 2 kPa to 100 kPa. These pressure gauges were tared at zero flow rate before conducting the experiments. This is especially important when the pressure difference is down to 2 kPa where each 1 Pa variation in the differential pressure measurement would cause 0.05 % difference in flow rate calculation, and, as a result zero-drifting effect becomes significant.

Fig. 3 illustrated the CMS's LFE flow meter system at small flowrate and large flowrate. When the flowrate at the range of (0.02 to 3) μmol/s, CMS used single capillary as shown in Fig. 3(a) (i.e. CMS-0.1-50-1, CMS-0.2-100-1 listed in Table.1). When the flowrate was larger then 0.87 μmol/s, CMS installed parallel capillaries to expand the usage of flowrate as shown in Fig.3 (b) (i.e. CMS-0.25-125-3, CMS-0.3-150-7 listed in Table.1).



(a) at the range of (0.02 to 3) μmol/s



(b) at the range of (0.87 to 50) μmol/s

***Fig. 3** Illustration of LFE flow meter system with capillary*

P_1, T_1, and P_2 were installed on stainless steel block which set gas reservoirs. Capillary would be installed in another stainless steel block as a holder. At this paper, we analyzed three different kinds of capillaries. Glass capillary was fabricated by precision laser machining with inner diameter uniformity of 2 μm. PEEKsil capillary was polymer-sheathed fused silica tubing with an inner diameter uniformity of 5 μm. Stainless steel capillary was machine cut and polished at each end, and finalized the tubing preparation process with diameter uniformity of 25 μm.

2.2 Hydrodynamic model

The physical model to predict flow rate Q was adopted from Berg et al.[3] with the omission of the compensation for centrifugal effect, as shown below.

$$\dot{n}=\frac{\pi R^4}{16}\cdot\frac{(P_1^2-P_2^2)}{L\cdot \mathrm{R_{gas}}\eta(T,0)}\left[1+Cs\right] \qquad (1)$$

$$Q_{\mathrm{actual}}=\dot{n}\cdot\left(\frac{\mathrm{R_{gas}}\cdot T_1}{P_1}\right)\cdot Z_1 \qquad (2)$$

$$\frac{P_1}{Z_1\mathrm{R_{gas}}T}=\frac{P_{\mathrm{r}}}{Z_r\mathrm{R_{gas}}T_{\mathrm{r}}} \qquad (3)$$

$$Q_r=\dot{n}\cdot\left(\frac{\mathrm{R_{gas}}\cdot T_{\mathrm{r}}}{P_{\mathrm{r}}}\right)\cdot Z_{\mathrm{r}} \qquad (4)$$

$$Re=\frac{2\times Q_{\mathrm{actual}}\times\rho(T,P_1)}{\pi\cdot R\cdot\mu(T,0)} \qquad (5)$$

Where P_1 is the upstream pressure, P_2 is the downstream pressure, P_r is the reference pressure at 101.325 kPa, T_1 is the inlet temperature, T_r is the reference temperature at 273.15 K, L is the total length of capillary, R is the capillary radius, $\mathrm{R_{gas}}$ is the universal gas constant, η is the gas viscosity, μ is the gas dynamic viscosity, Cs is the corrections include gas's non ideality, slip at capillary walls, entrance effect, gas expansion on the velocity distribution, and thermal effect within the capillary. Q_r is the flow rate at reference condition at 273.15 K, 101.325 kPa; Q_{actual} is the flow rate at P_1 and T_1; Z_1 is the compressibility factor at P_1 and T_1; Z_r *is* the compressibility factor at reference condition of P_r and T_r. The gas could be dry air, nitrogen at different evaluations. The flow rate Q_{r} would be obtained by substituting equations (1), (2) and (3) into (4), and Re is Reynolds number.

2.3 ID conformability of capillary

$$\frac{\Delta Q}{Q_{\mathrm{nom}}}=\frac{Q_{\mathrm{nom+tolerance}}-Q_{\mathrm{nom}}}{Q_{\mathrm{nom}}} \qquad (6)$$

Where Q_{nom} is the nominal flow rate, $Q_{\mathrm{nom+tolerance}}$ is the nominal flow rate with maximum tolerance effect, $\triangle Q$ is the difference between Q_{nom} and $Q_{\mathrm{nom+tolerance}}$, all the flow rate in this equation were at reference condition.

From nominal inner diameter (ID_{nom}) and L, we could calculate Q_{nom}, which might deviate from the measured real flow due to intrinsic error resulted from the manufacturing tolerance of the capillary. Conversely, we could calculate the actual inner diameter (ID_{actual}) from the experiment data and compare with the nominal inner diameter (*ID)* to see how well the capillary conforms to its specification. $Q_{\mathrm{nom+tolerance}}$ could be calculated from the sum of ID_{nom} and tolerance. The ratio of $\triangle Q$ over Q_{nom} could show the error of flow rate with maximum tolerance induced.

$$MF = \frac{Q_{standard}}{Q_r} \qquad (7)$$

Where *MF* is Meter factor, $Q_{standard}$ is the working standard flowrate, Q_r is the calculated flow rate.

3. Results

3.1 LFE performance

The CMS LFE performance was shown in Fig. 1, and could apply in different kind of gas flow as shown in Fig. 2 within the flowrate deviation of ±0.15 %.

3.2 ID conformability of capillary

Table. 2 gave the manufacturer specifications and measurement performance of capillaries made with different materials. One can see that stainless steel capillary would potentially result in ± 72 % error in determining flow rate. On the other hand, PEEKsil and glass would possibly lead to ±14 % error. The range of ID_{actual} for each lot also showed glass capillary conforms to its spec best. Therefore, we would not recommend the use of the stainless steel capillary.

Table. 2 *Specifications and conformability of capillaries made with different materials*

Material	ID_{nom}(μm)	Tolerance(μm)	($\triangle Q$)/Q_{nom}(%)	ID_{actual}(μm)
PEEKsil B,C	150	±5	±14	152.7 - 154.0
PEEKsil D,E	150	±5	±14	151.4 - 151.9
Glass A,B,C,D	100	±3	±13	102.7 - 103.3
Glass A,B,C,D	252	±2	± 3	252.6 – 253.5
stainless	175	±25	± 72	188.4

3.2 Repeatability and reproducibility

The repeatability was evaluated by measuring flow rate from 1 sccm to 1000 sccm with LFM. Comparing the value of MF, the maximum variation of MF is within 0.02 %. The reproducibility was conducted in different days. The evaluation was done by measuring flow rates from 1 sccm to 1000 sccm with LFM. The MF variation would be within 0.03%.

3.3 Capillary performance

Glass and PEEKsil as the flow range from 20 sccm to 84.1 sccm with 200 μm (ID) × 100 mm (L) were compared. The performance of these two capillary fitted very well. Thus the PEEKsil were used for evaluating the case as below that glass capillary didn't fabricate.

The flow rate could be expanded by changing *L* and ID. Table. 3 compared the PEEKsil capillary of 150 μm (*ID*) but in different total length *L*. By changing *L* from 5 cm to 10 cm, we could double the flow rate. Another at *L/ID* = 500 as shown in Table. 3, changing a glass capillary from 100 μm (*ID*) × 50 mm (*L*) to 200 μm (*ID*) × 100 mm (*L*), which resulted in a expansion of flow rate. However, the total length of the meter less than 30 cm confined the L of capillary. Moreover, bundling multiple capillaries can easily expand the capacity of the flow meter.

Table. 3 *Compare the same ID but different L on LFE of PEEKsil capillary(white), and L/ID = 500 with different L and ID for glass capillary(gray)*

ID(μm)	*L(mm)*	*L/ID*	*Re*	*△MF*100*	*Lentrance / L(%)*
150	*100*	*667*	*26 to 248*	*0.09*	*0.2 to 2.2*
150	*50*	*333*	*48 to 476*	*0.44*	*0.9 ro 8.6*
200	*100*	*500*	*37 to 365*	*0.09*	*0.1 to 4.4*
100	*50*	*500*	*16 to 164*	*0.18*	*0.2 to 2.1*

4. Discussion

4.1 suitable *L/ID* ratio

Table. 3 showed △*MF* is small while *L/ID* is more than or equal to 500. The reason might be because of maximum entrance length divided by length *L* is smaller than 8.6 %. At *ID* = 150 μm and L= 50 mm, entrance effect would be bigger than other condition as Table 2 shown. Therefore, the equation (4) could predict flow rate more correctly at *L/ID* ≥ 500, and the variation of meter factor would be small.

4.2 equivalent capillary radius

$$\sum_{1}^{n} Q_i \approx n \times Q_{\mathrm{eq}} \qquad (7)$$

$$R_{\mathrm{eq}} = \left(\frac{\sum_{1}^{n} R_i^{4}}{n} \right)^{\frac{1}{4}} \qquad (8)$$

Where Q_i is the flow rate at reference condition of *i*th capillary, Q_{eq} is equivalent flow rate at reference condition, $\sum_{1}^{n} Q_i$ is the summation of each capillary flow rate, R_{i} is capillary radius *of* *i*th capillary, R_{eq} is equivalent capillary radius.

As mentioned before, we could expand the flow rate by connected the capillary in parallel. In order to design holder, maximum flow rate, and choose suitable working standard in advance, equation (7) and (8) were adapted. The total flow rate would be estimated more accurately by equivalent flow rate than by summation of each capillary flow rate beforehand.

$$MF_e = \mathrm{a} + \mathrm{b} \cdot Q + \mathrm{c} \cdot Q^2 \qquad (9)$$

$$e = MF_e - MF \qquad (10)$$

Where *Q* is flow rate at reference condition, a, b, c, is the regression constant of the capillary, MF_e is estimated value of MF, *e* is residual.

The theory model[3] fits best at *Re* smaller than 500. The equations (1) to (4) can be used for curved capillary. However, for straight capillary in this study, some factors, such as entrance effect, might not be fully compensated. With 2nd order polynomial regression of *MF* and flow rate, equation (9) could fit the full flow region very well. Equation (10) showed the difference between regression *MF* and experiment *MF*. With these two equations, we could extend the turndown ratio higher than 20 and keep the residual within 0.11 % at the same time. (see Table.4) Moreover, Re greater than 500 could be used in LFE.

Table. 4 *polynomial regressions for all capillaries enlarge the predictable flow range and turndown ratio*

Material	*ID* (μm)	*L*(mm)	*Q*(μmol/s)	*e*	Turndown ratio
glass	200	100	1.54 to 64.7	0.10%	42
	252	53	3.85 to 76.2	0.08%	20
	100	50	0.85 to 43.5	0.06%	51

5. Conclusion

This LFE flow meter demonstrated the measurement capacity below 1000 μmol/s within deviation of ±0.15 %, turndown ratio higher than 20 and total length of flow meter less than 30 cm simultaneously. One thermometer and two pressure gauges measured the inlet temperature and inlet/outlet pressure, and the differential pressure was restricted from 2 kPa to 100 kPa. With the use of equivalent flow rate and 2nd order polynomial regression of MF and flow rate, the usable turndown ratio could be higher than 20, and the variation of residual is still below 0.11 %. By bundling multiple capillaries, the capacity of the flow meter would expand. Precision fabricated glass capillary were used for preventing bending during installation. The reproducibility is within 0.02 %, and repeatability is within 0.03 % showed LFE flow meter could be a transfer standard. The feasibility of multiple gas measurement was demonstrated, and the deviation of flowrate of air and nitrogen were both within 0.05%.

The future work would validate sensitivity of this LFE flow meter to temperature, back pressure, and performance under different gases, such as oxygen, hydrogen etc..

Reference

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