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DEVELOPMENT OF HIGH SPEED RESPONSE LAMINAR FLOW METER FOR AIR CONDITIONING

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ABSTRACT

In this paper, we developed a new laminar flow meter which is composed of a flute type cross-section laminar element. Since the element is light, cheap and has high efficient contact area, it can be used in a laminar flow meter to expand the application filed of the meter. At first, the flow characteristics of the flute type element are verified by computational fluid dynamics. Next, we developed a prototype laminar flow meter with the new laminar element. With the flow meter, the hydraulic diameter of the element is compensated from the steady characteristics experiments. Then, the unsteady flow characteristics of the flow meter are obtained using the unsteady flow generator we have developed. We confirmed that the developed flute type laminar flow meter can measure oscillatory flow up to 9 Hz and the new compensated hydraulic diameter is useful to analysis the unsteady flow characteristics with Womersley number.

Keywords: Air conditioning, Dynamical characteristics, Unsteady flow, Laminar flow meter, Flute type

INTRODUCTION

To achieve high cleaning level, prevent diffusion of chemical materials and avoid mutual interference in two or more sub systems, the room pressure must be precisely controlled in research facility. For this purpose, some valves are used to control the airflow rate which is supplied and exhausted to the room. So far, however, little information has emerged on the unsteady flow characteristics of airflow meters, because it is difficult to measure the unsteady flow rate. Since the density of gases is as a function of temperature and pressure, the measurement method of the unsteady flow rate is not well defined.

In the previous study, we developed quick response laminar flow sensor called QFS. The developed QFS can measure the airflow rate up to 6.0 [m^3/h]. The QFS consists of a large number of small-diameter metal channels to remain the airflow laminar flow has advantages, such as small pressure drop, linear

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relationship between flow rate and differential pressure, and suitable for bi-directional flow measurement. The flow meter was calibrated with generator of variable gas flows using an isothermal chamber, which can measure the unsteady airflow rate. We confirmed that the laminar flow meter can measure oscillatory flow up to 50 Hz experimentally.

When it comes to install the laminar flow meter in air conditioning system, the diameter of the duct is large and the airflow rate is large. Quite a large number of small-diameter flow channels are required to remain the airflow laminar flow. On the other hand, quite a large number of metal channels make it difficult to be used as a laminar element for air conditioning system because it becomes too heavy and the cost becomes high. Therefore, the application of this meter has been limited by the size, weight and cost of the laminar flow element.

In this research, we developed a laminar flow meter with new laminar element. Since the laminar element is made of paper and has flute type cross-section, it is light, moderate in price, and having high efficiency contact area against airflow. We analyze the theoretical characteristics of the flute type element in terms of computational fluid dynamics (CFD). Then we investigate both steady and unsteady characteristics of the flow meter experimentally.

NOMENCLATURE

A:	Cross-section area	[m^2]
b:	Width of channel	[m]
C_w :	Length of around	[m]
D:	Diameter of laminar element	[m]
d:	Diameter of tube	[m]
d_h :	Hydraulic diameter	[m]
G:	Mass flow	[kg/s]
h:	Circumference	[m]
L:	Length of laminar element	[m]
N:	Number of channel	[-]
P:	Pressure	[Pa]
Q:	Flow rate	[m^3/s]
R:	Gas constant	[J/(kg・K)]
t:	Time	[s]
V:	Volume of chamber	[m^3]
W_0:	Womersley number	[-]
θ:	Temperature	[K]
μ :	Viscosity	[Pa・s]
ν :	Kinetic viscosity	[m^2・s]
ω :	Angular frequency	[s^{-1}]
$\Delta P_{a,b}$:	Pressure drop	[Pa]

Subscripts

in:	Inlet
out:	Outlet
ref:	Target
c:	Chamber
f:	Flute

PRINCIPLE OF LAMINAR FLOW METER

We developed quick response laminar flow sensor called QFS in the previous study. Fig.1 and Fig.2 show the overview of QFS and schematic diagram of QFS respectively. The laminar element is made of circular metal tube.

The differential pressure across the laminar flow element is proportional to the airflow rate in accordance with the Hagen-Poiseuille law for laminar flow pressure drop. The flow rate for laminar flow meters can be expressed as

$$Q_s = \pi d^4 \Delta P / 128\mu \qquad (1)$$

If the flow rate of each tube is given as Qs, the total flow rate of the flow meter can be written as

$$Q = NQ_s \qquad (2)$$

The airflow rate is obtained by measuring the differential pressure across the laminar element.

In the case of the airflow in circular tube, the dimensionless number called Womersley number expresses the oscillatory flow frequency in relation to viscous effects.

$$W_0 = d\sqrt{\omega / \nu} \qquad (3)$$

This number is an index for the unsteady flow response of laminar flow meters. When the Womersley number is small(2.5 or less), it means the frequency of pulsations is sufficiently low that a parabolic velocity profile has time to develop during each cycle, and the flow will be very nearly in phase with the pressure gradient, the flow meter responses well at this frequency. It is known that when the frequency of oscillatory flow becomes higher, a phase-lead characteristics can be observed with laminar flow meters. The tube diameter of developed QFS is approximately 0.6 [mm]. So, it can measure the oscillatory flow at a frequency of approximately 40 Hz.

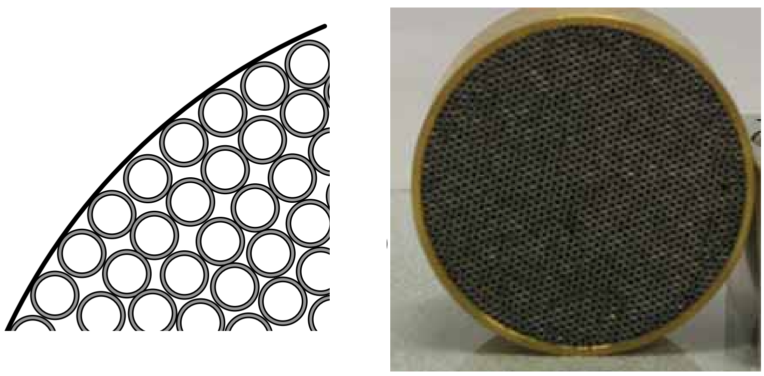


Fig. 1. Cross section of QFS(circular tube)

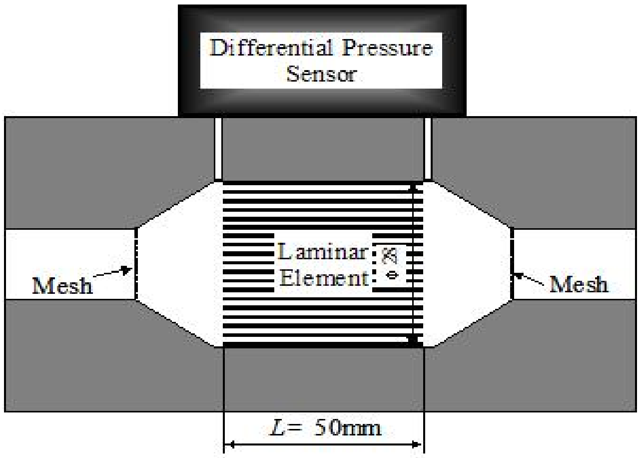


Fig.2 Schematic diagram of QFS

FLUTE TYPE LAMINAR FLOW METER

We can measure an unsteady airflow rate up to 6.0 [m^3/h] with QFS. The maximum airflow rate is limited by the size and the number of small-diameter metal tube of laminar element.

On the other hand, comparing with the developed QFS, the diameter of the duct and the intended airflow are too large in the fields of air conditioning system. If the QFS is used in air conditioning system, quite a large number of small-diameter flow channels are required. But, the large numbers of metal tube make it difficult to be used as a laminar element for air conditioning system because it becomes too heavy and the cost becomes high.

From these reason, we propose new flute type laminar element instead of the circular tube type. The flute type cross section elements are shown in Fig.3. The flute type cross section standard product used at catalytic fin and corrugated board, and its sinusoidal cross sections have high efficiency contact area to air flow.

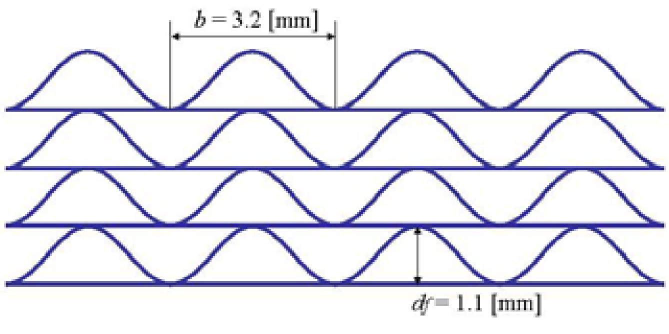


Fig. 3. Sinusoidal cross section (Flute type)

ANALYSIS WITH CFD, SCRYU/TETRA

The flow characteristic of the flute type is analyzed by CFD (computational fluid dynamics) software because the flute type cross section is not circular cross section. SCRYU/Tetra CFD software is used because it is the outstanding general purpose calculation hydrodynamics code. The height, width and length of the flute type are 1.1[mm], 3.2[mm] and 90[mm]. The inlet condition is that velocity to the z direction is constant. The outlet condition is that pressure is atmospheric pressure. Assuming that the flute type laminar element is used in air duct which diameter is 300[mm], the number of channel is approximately 34,000 and the flow rate is 500[m^3/h].

Fig.4 shows the simulation result of z direction velocity at the centre of cross section. The inlet velocity 2.8[m/s] is accelerated about 4.3[m/s]. This acceleration region is called inlet length. In this case, the inlet length is about 10[mm]. The velocity after the inlet length is constant value. The flow in the outlet is fully developed flow. Fig. 5 shows velocity distribution to the z direction on flute type cross section. The velocity near the both edges is slow. It means that resistance to the flow near the both edges is large. In general, the cross-section shape of the pipeline is not circular, like as rectangular, triangular and oval shape, the hydraulic diameter is effectively used in analysis of steady and unsteady characteristics. The hydraulic diameter is obtained by Eq. (4).

$$d_h = 4\frac{A}{C_w} \tag{4}$$

A is the cross-section area and C_w is length of around. If the cross-section shape has sharp edges, the flow rate at the sharp edges is too small. But, the length of it is considered as around length. Then there is possibility obtained hydraulic diameter is smaller than actual hydraulic diameter. The flute type has also two edges. So it is necessary to examine hydraulic diameter of the flute type by simulation and experiment.

Fig.6 shows the simulation result of pressure drop at a flow rate of 500[m^3/h] and the linear approximation that is obtained by assuming the pressure drop at fully developed flow. The difference pressure drop ΔP_b exists in the entrance region. To investigate the effect of them, the simulation has been conducted when the flow rate is 100 to 1500[m^3/h]. Table.1 shows the ratio of ΔP_b to ΔP_a versus the flow rates. Assuming that a maximum flow rate is practically up to 1500[m^3/h], the ratio is no more than 4%.

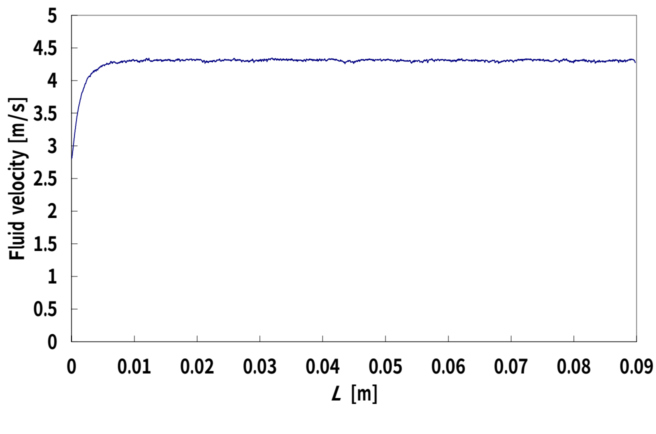


Fig. 4. Fluid velocity at the center of the cross section

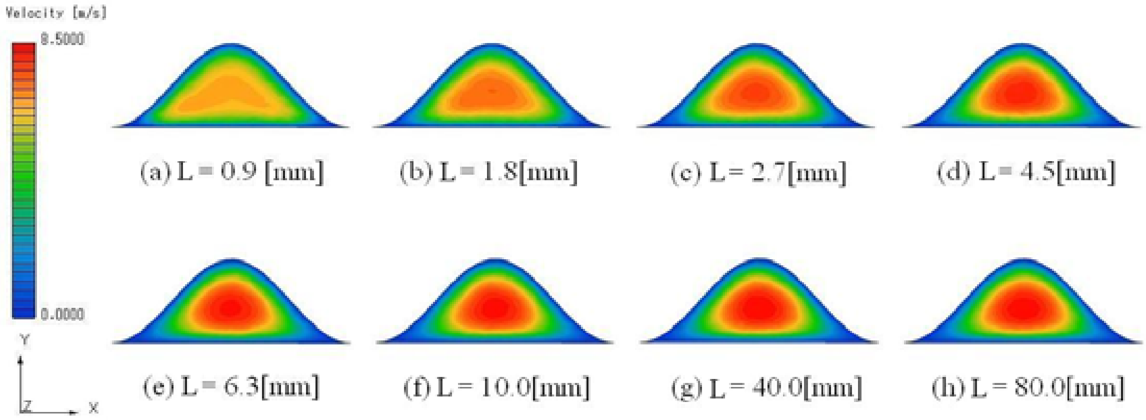
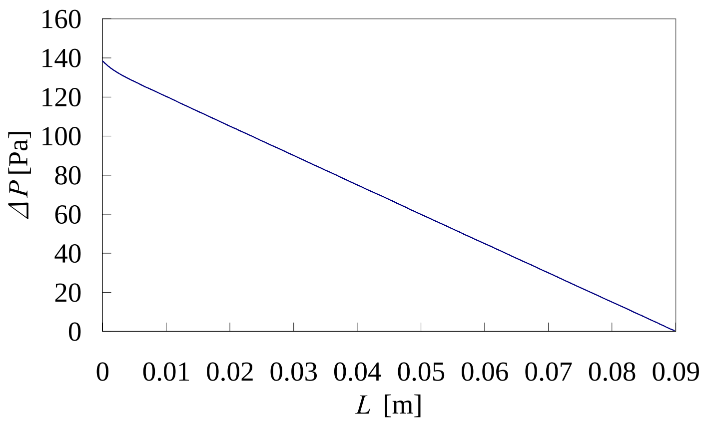
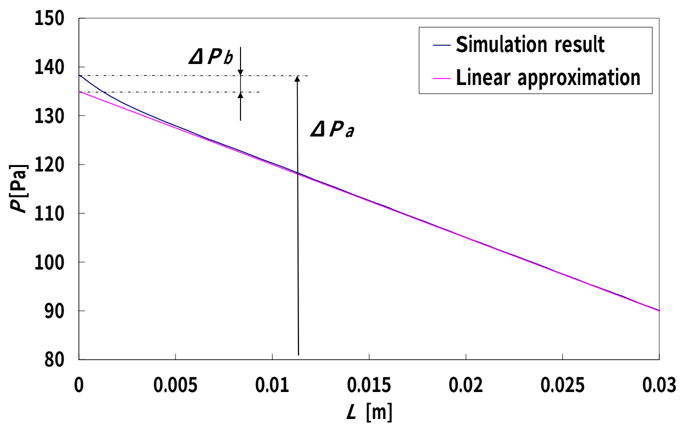


Fig. 5. Velocity distribution on cross section



(a) Overall view



(b) Magnified view

Fig. 6. Pressure drop along the direction of channel

TABLE 1. The Ratio of ΔP_b to ΔP_a

Flow rate[m^3/h]	Ratio %
100	0.671
500	2.399
1000	3.247
1500	3.643

STEADY FLOW CHARACTERISTICS OF NEW FLOW METER

Steady flow characteristics of the laminar flow meter using flute-type element were measured by experiment. Fig.7 shows the cross section of new flow meter called FQFS. The outer diameter of FQFS is 60[mm]. The experiments were conducted for three element lengths 90[mm], 190[mm] and 290[mm], respectively.

Fig.8 shows the experimental apparatus for steady characteristics measurement. The working fluid is dry air. The FQFS is calibrated by a dry flow meter is arranged in the downstream side. Substituting the differential pressure across the laminar element into Eq. (1), we can obtain the air flow rate.

At first, the flow rates are calculated with the hydraulic diameter d_h = 1.01. The experimental results are shown in Fig.9. Q_{ref} is flow rate of standard flow meter. Good linearity can be observed for all elements. However, the experimental results are considerably different with the results from hydraulic diameter d_h.

Therefore, it became clear from the experiments that the hydraulic diameter must be compensated. We employed a new hydraulic diameter which will best fit to the experimental data using the root mean square error given as Eq. (5).

$$RMSE = \sqrt{\sum_{i=1}^{n} (Q_{ref} - Q_i)^2 / n} \tag{5}$$

The new hydraulic diameter d_h` =1.31 is obtained. Fig.10. shows the result of it.

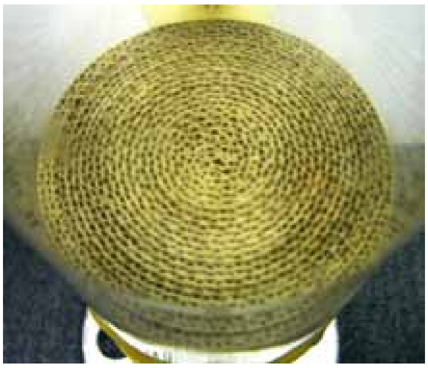


Fig. 7. Cross section of new FQFS (flute type)

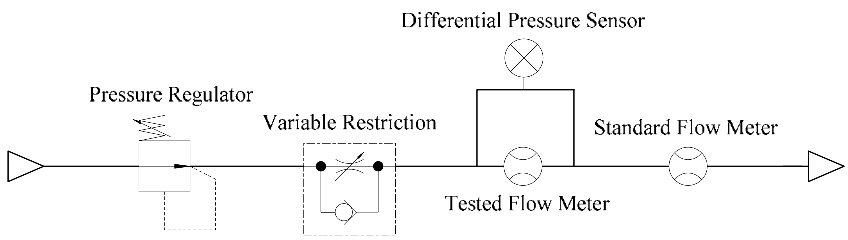


Fig. 8. Experimental apparatus for steady flow characteristic measurement

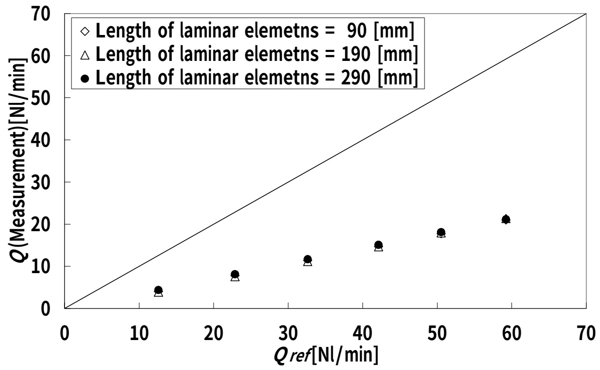


Fig. 9. Static characteristic of FQFS with d_h

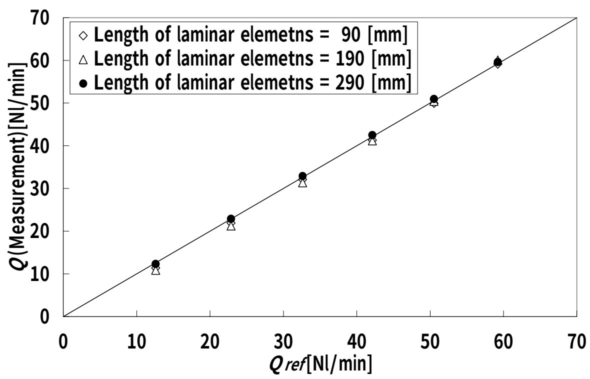


Fig. 10. Static characteristic of FQFS with d_h`

UNSTEADY FLOW CHARACTERISTICS OF NEW FLOW METER

Unsteady flow characteristics of new flow meter were tested were measured by experiment. Fig.10 shows the experimental apparatus for unsteady characteristics measurement. Sinusoidal inputs from 0.5 to 50 Hz were generated from the unsteady flow generator. The average flow rate of generated flow rate is 3.3×10^{-4}[m^3/s] and amplitude flow rate is 8.3×10^{-5} [m^3/s]. The sampling time is 1 [ms].

The results are summarized in a bode diagram as shown in Fig.11. The phase characteristics are good agreement with generated flow rate. The gain is not change up to 9[Hz]. When frequency rises than 9[Hz], the gain increased.

In addition, unsteady flow characteristics are examined from the viewpoint of Womersley number. For each hydraulic diameter d_h and d_h\`, the frequency that Womersley number became 2.5 is 14.7[Hz] and 8.7[Hz]. The new hydraulic diameter $d_h$\` agrees well with experimental results. Therefore, we confirmed that new hydraulic diameter is useful to analysis the unsteady flow characteristics with Womersley number.

The results show that the flute type element can be used as a laminar flow meter element for critical environment. In the application fields, the fluctuation of room pressure is caused by the manually door-opening and door-closing of the clean room and draft chamber. Assuming the time is approximately 0.5s, the flow meter having the response time of 9 Hz is considered to be useful.

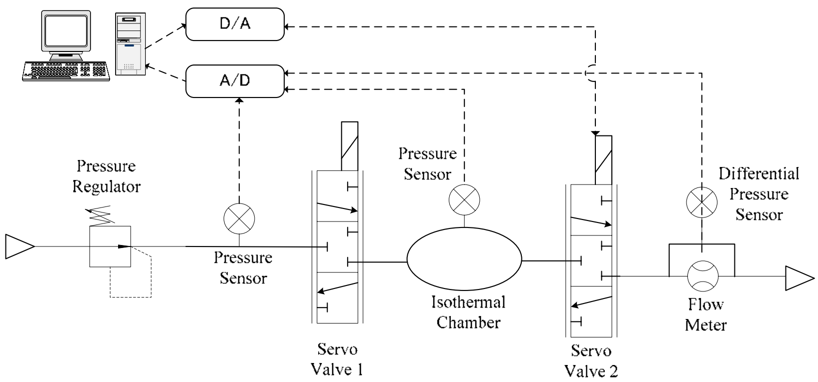


Fig. 10. Experimental apparatus for unsteady flow characteristic measurement

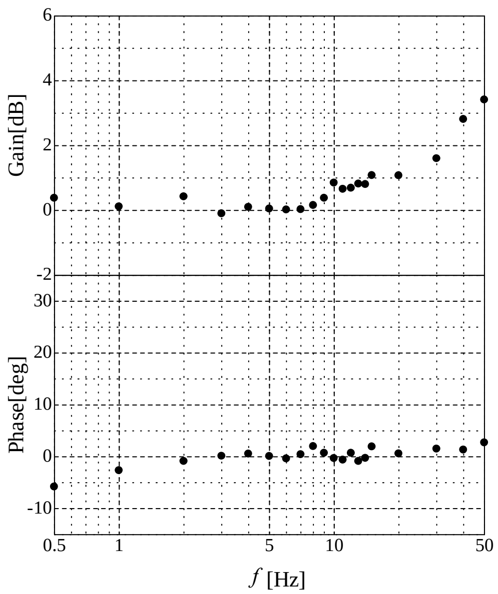


Fig. 11. Bode diagram of new FQFS

COLCLUSIONS

In this paper, a flute type element, which is light, cheap and has high efficient contact area, was used in a laminar flow meter to expand the application fields of the flow meter including critical environment.

At first, the theoretical characteristics of the flute type element are verified in terms of CFD.

Next, the steady characteristics of the flow meter were measured and the representative diameter of flute type cross section was derived by the compensation of hydraulic diameter. In spite of the length of laminar element, the value is approximated as a constant value.

Then, the unsteady flow characteristics of the flow meter were measured using the unsteady flow generator we have developed. We confirmed experimentally that the hydraulic diameter which was derived from the steady characteristics of the flow meter is useful to estimate the unsteady flow characteristics of the flow meter.

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