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Mass Flowmeter Utilizing a Pulsating Source†

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A new method is proposed for measuring mass flow rate through a pipe. A pulsating source of known strength is placed in a flow. This source produces an axial flow pulsation superimposed on the otherwise steady flow and an alternating pressure fluctuation is produced in the pipe as a direct result. The pressure difference across the source is detected by a high-sensitivity manometer. A phase sensitive detector is used and the output from the manometer converted to a DC voltage that is proportional to the mass flow rate. An experimental device that utilized condenser microphones to detect the pressure difference has been built. Several airflow measurements were performed. The mass measured flow rates were in good agreement with the flow velocity and density measurement data. Mass flowmeters based on this method are simple, compact, free from obstructions and have a minimal pressure drop.

Key Words : mass flow meter, source, pulsation, thrust force, differential pressure, phase-sensitive detector

1. Introduction

It is well known that when there is a circulation around an object in a flow, a lift proportional to the density of the fluid, the flow rate and the strength of the circulation acts on the object. The Magnus Effect Mass Flowmeter is based on this effect[1]. Whereas, if a source is placed in a flow, a pressure differential upstream and downstream of the source is produced, and a thrust force acts on the source[2]. The magnitude of this pressure differential is proportional to the fluid density, the flow rate and the strength of the source. Here we report on a mass flowmeter that utilizes this principle.

In general, a flowmeter that measures mass flow rate directly applies a perturbation to the flow from outside and the flow is measured from the physical effect that results from that perturbation[3]. For this reason, the design of flowmeters is complicated. For example, in the Magnus Effect Mass Flowmeter mentioned above, which is one type of direct mass flowmeter, it is necessary for a cylinder to be placed perpendicular to the direction of flow and rotated at a constant rate. In the Simmonds mass flowmeter[4], a branched pipe and two constant-flow pumps are used to differentially apply a fixed volume flow to two orifice meters. The flowmeter described in this paper produces flow pulsations and detects the difference in pressure upstream and downstream of the pulsation source. Consequently, it can be considered one type of differential pressure mass flowmeter, but in contrast to previous differential pressure mass flowmeters[4) 5)], the external perturbation on the mean flow is alternating. This makes it possible to simplify the mechanism that acts on the flow‡. Since the perturbation is alternating, the physical quantity that carries information on the mass flow rate becomes the fluctuating part of the pressure difference. This fluctuation can be detected without being affected by zero point drift of the pressure detector, making it possible to use a highly sensitive detector (condenser microphones normally used for acoustic measurements were used in this study). Thus, the pulsating perturbation that is applied can be of small magnitude, which further facilitates the use of a smaller and simpler perturbation mechanism. In addition, the principle of operation of the proposed flowmeter is directly based on the equations of fluid motion (the pressure equation), so it is unnecessary on principle to use a mechanism such as an orifice that causes a loss of pressure, or a bent channel. The following sections discuss the principle of this measurement method, and experiments in which air flow was measured using the proposed device are described.

2. Principle of the Proposed Method

Assume that an incompressible, inviscid fluid of density ρ flows at a constant and uniform rate U_0 in a cylindrical pipe of radius a and cross-sectional area S. Consider the case in which a source that produces a perturbation flow of volume per unit time $q(t)$ is placed at one point in this pipe (**Fig. 1**). Let the pipe axis be the x-axis, the direction of flow be positive and the position of the source be the coordinate origin. Assuming that the flow velocity at each position x is uniform across the cross section of the pipe, then $U(x, t) = U_0 + u(x, t)$. In particular, the flow rates at $x = -l$ and $+l$, in cross sections A and B, are written as $U_0 - u_A$ and $U_0 + u_B$ (in other words, $u(-l, t) = -u_A$ and $u(l, t) = u_B$). Conservation of mass then gives:

$$\rho S(U_0 + u_B) - \rho S(U_0 - u_A) = \rho q \tag{1}$$

so that

$$S(u_A + u_B) = q \tag{2}$$

‡ There are several mass flowmeters other than our flowmeter in which an alternating perturbation is applied on the flow, such as Micro motion flowmeter[6], flowmeter by Cushing[7], flowmeter by Langdon[8] and Vibrating Pitot Tube[9]; they also have a simpler construction than conventional mass flowmeters.

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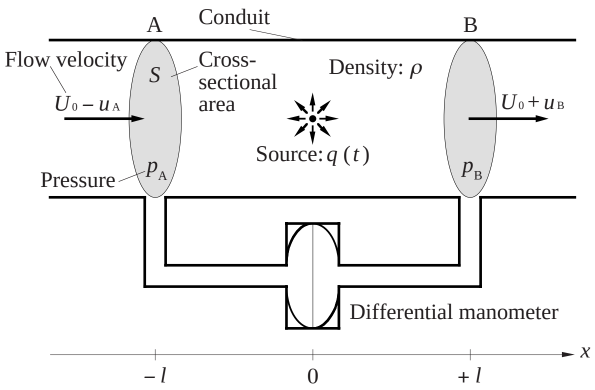

Fig.1 Principle of the proposed mass flowmeter.

Writing the velocity potential $\Phi\,(x, t)$ as

$$\Phi(x,t) = \int_{-l}^{x} U(x,t)\,dx \tag{3}$$

from the pressure equation

$$\frac{\partial \Phi}{\partial t} + \frac{1}{2}U^2 + \frac{p}{\rho} = h(t) \tag{4}$$

($h\,(t)$ is an arbitrary function of t), the following equation is obtained:

$$\frac{\partial}{\partial t}\int_{-l}^{l} u\,dx + \frac{1}{2}(U_0 + u_B)^2 + \frac{p_B}{\rho} = \frac{1}{2}(U_0 - u_A)^2 + \frac{p_A}{\rho} \tag{5}$$

Here p_A and p_B are the pressures at cross sections A and B, respectively. From (2) and (5), the pressure difference $\Delta p = p_A - p_B$ between the cross sections A and B is calculated as:

$$\Delta p = \frac{\rho U_0 q}{S} + \frac{1}{2}\left(u_B^{\,2} - u_A^{\,2}\right) + \frac{\partial}{\partial t}\int_{-l}^{l} \rho u\,dx \tag{6}$$

Since it can be considered that u, u_A and u_B have the same phase and waveform as q, the differential pressure Δp has a component proportional to the signal q (the 1st term on the right side of equation (6)), a component proportional to the square of q (the 2nd term on the right side of equation (6)) and a component proportional to the derivative of q with respect to time (the 3rd term on the right side of equation (6)). Assuming that $q\,(t)$ is a sinusoidal perturbation of known magnitude, the 2nd term on the right side of equation (6) will have a different frequency to the 1st term, while the 3rd term will have a phase shifted 90 degrees from that of the 1st term. Consequently, by detecting the pressure difference Δp and processing it using the phase sensitive detector discussed below, it is possible to isolate and measure only the 1st term. Since S and q are known, once the magnitude of the 1st term is measured, it is possible to determine the mass flow rate $\rho U_0 S$. If $q\,(t)$ is a small quantity and hence the square (the 2nd term on the right side of equation (6)) can be neglected, it is not necessary for $q\,(t)$ to be sinusoidal; it can be a random signal.

When the original flow includes a pulsation and its frequency is superimposed on that of the added perturbation, it is generally not possible to separate the contribution of the pulsation in the original flow. In such cases, it is conceivable that a random signal can be used as the pulsation $q\,(t)$.

The above is the basic principle of operation of the proposed flowmeter, but the description depends on several assumptions that are not likely to be satisfied rigorously in an actual fluid. The assumption that the fluid is incompressible applies when the conditions:

$$c >> U_0\,, \quad \frac{c}{4f} >> l \tag{7}$$

are satisfied. Here c is the speed of sound and f is the frequency of the pulsation. The 2nd inequality suggests that the size of the flowmeter is small compared with the wavelength of the pulsation. In addition, since actual fluids are always viscous, there is a pressure drop in the direction of flow. It is difficult to theoretically evaluate the effect on the flow measurement due to viscosity. Considering a range in which the flow in the pipe is turbulent, it is assumed that the flow rate U averaged over the pipe cross section and the pressure drop Δp_f between two points separated by distance Δx are related at each instant by equation (8) using Darcy's pipe friction coefficient λ, and the effect estimated[10)]

$$\Delta p_f = \lambda \cdot \frac{\Delta x}{2a} \cdot \frac{\rho U_0^{\,2}}{2} \tag{8}$$

The pressure drop Δp_f between cross sections A and B is calculated as

$$\Delta p_f = \lambda \cdot \frac{l}{2a} \cdot \rho \left\{ U_0^{\,2} - U_0(u_A - u_B) + \frac{1}{2}\left(u_A^{\,2} + u_B^{\,2}\right) \right\} \tag{9}$$

The pressure difference that is actually measured consists of components given by equation (6) and the viscous pressure drop given by equation (9).

The 1st and 3rd terms on the right side of equation (9) are removed by the phase sensitive detector to be described below. The 2nd term is a signal having the same phase as the 1st term on the right side of equation (6). Its magnitude tends to zero when the impedance upstream and downstream from the source point are equal and $u_A = u_B$. If the impedance differs by a significant amount, then it approaches

$$\lambda \cdot \frac{l}{2a} \cdot \frac{\rho U_0 q}{S}$$

The effect of the viscous pressure drop decreases with l. However, when l becomes extremely small, it is possible that the effect caused by two dimensionality of the flow near the source will not be negligible. How much of this effect appears for a given value of l depends on case specific conditions such as the shape of the source and the properties of the fluid. In the conditions of the experiment to be described in Section 3, if l is of the same order of magnitude as a or larger, then it can be considered that the effect of 2-dimensionality can be neglected. Therefore we take

$$l \approx a \tag{10}$$

as a rough estimate of the magnitude of l. λ has been measured to be in the range 0.04 to 0.01 for Reynolds numbers 3×10^3 to 3×10^6, hence the term expressing pressure drop due to viscosity is, at a maximum, of the order of 2% of the original signal (the 1st term on the right side of equation (6)).

It is also conceivable that there will be an effect on the distribution of flow velocity within the pipe cross section. In order to evaluate this effect rigorously, the actual flow must be known in detail. However, in the proposed flowmeter, the momentum passing through a cross section upstream and downstream from the source is different, and it can be assumed that the pressure difference Δp is just sufficient to compensate for that difference. Consequently, the error due to the flow velocity distribution within a cross section can be assumed to be of similar order to the difference between the actual momentum (the component in the axial direction) passing through the cross section in a unit time and the value calculated using the average flow rate. This has been calculated for the case of the flow velocity profile in well developed turbulent flow through a cylindrical pipe, and it was found to be of the order of 2%[11].

3. The Experiment

The experimental apparatus was as shown in **Fig. 2**. An air flow was produced inside a cylindrical brass pipe of inner diameter 32 mm, using a compressor or blower. A vibration exciter and bellows were used to blow small amounts of air into the pipe sinusoidally. The volumetric flow rate $q(t)$ of air blown into the pipe was maintained at a constant value by the action of a velocity sensor attached to the exciter and a servo system; it had the same phase and waveform as the reference signal $A\sin\omega t$ of a two-phase oscillator. The differential pressure fluctuations were detected from the difference between the outputs of two condenser microphones for ultra low frequency use (a condenser microphone cannot sense static pressure, so the steady component of the differential pressure was removed at this stage). The actual shapes of the air injection port and pressure detection port are shown in **Fig. 3**. A ring-shaped chamber was attached and air blown in from all around the circumference of the pipe. The output $s(t)$ detected by the two microphones was multiplied by the outputs $\sin\omega t$, $\cos\omega t$ of the two-phase oscillator and the results smoothed (the smoothing time constant was approximately 0.5 second) to give the output voltages E_x and E_y.

Photo 1 shows an example of an actual differential pressure fluctuation waveform $s(t)$ when an air flow is produced by a blower. It is seen that high frequency noise produced by the air flow is superimposed on the sinusoidal pulsations. In Photo 1, the ordinate is 1.9 Pa / div, calculated from the microphone sensitivity. It is seen that the amplitude of the sinusoidal pressure fluctuations agree approximately with the theoretically predicted value (2.3 Pa p-p).

The servo analyzer section in Fig. 2 forms a phase sensitive detector. It decomposes the signal $s(t)$ from the microphone into a component having the same phase as the pulsation $q(t)$ and a component having

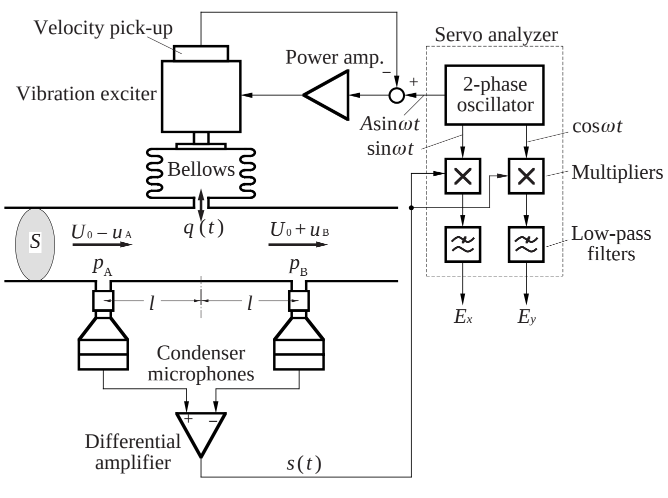

Fig.2 Experimental setup.

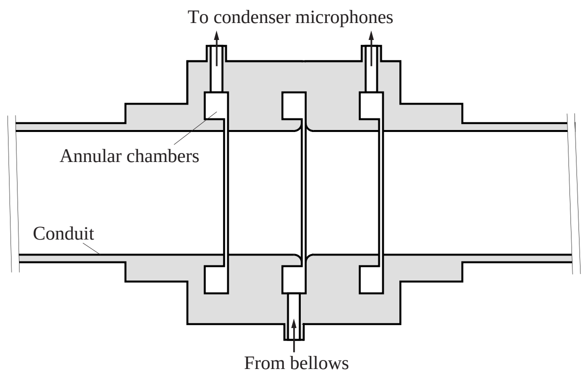

Fig.3 Schematic diagram of the nozzle and the pressure taps.

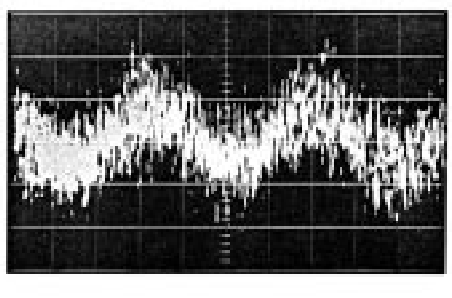

Photo 1 Waveform of $s(t)$: horizontal – 50 ms/div, vertical – 1.9 Pa/div ($\rho U_0 = 11$ kg s^{-1} m^{-2}, $f = 5$ Hz, $q = 6 \times 10^{-5}$ m^3 s^{-1} rms)

the same phase as the derivative of $q(t)$ with respect to time, which is shifted 90 degrees from the phase of $q(t)$. This reveals the magnitude of each of these components, and in addition removes components having frequencies different from that of $q(t)$ (the 2nd term on the right side of equation (6), the 1st and 3rd terms on the right side of equation (9) and high frequency noise produced by the air flow). Among the terms in equation (6), the component with the same phase as $q(t)$ is denoted by $p_v(t)$ and the component with the same phase as the derivative of $q(t)$ is denoted by $p_a(t)$, giving the following:

$$p_v(t) = \frac{\rho U_0 q}{S} \equiv 2P_v \sin\omega t$$
$$p_a(t) = \frac{\partial}{\partial t}\int_{-l}^{l} \rho u\, dx \equiv 2P_a \cos\omega t \tag{11}$$

The signal components of $s(t)$ corresponding to the pressure fluctuations $p_v(t)$ and $p_a(t)$ are denoted as $s_v(t)$ and $s_a(t)$, respectively. If there is no phase rotation in the measurement system, selecting the appropriate voltage units, we have

$$s_v(t) = p_v(t) = 2P_v \sin\omega t$$
$$s_a(t) = p_a(t) = 2P_a \cos\omega t$$

so that the output voltages E_x and E_y become P_v and P_a, respectively. However, phase rotation exists in an actual measurement system. If θ is the angle of lead, then $s_v(t)$ and $s_a(t)$ become

$$s_v(t) = 2P_v \sin(\omega t + \theta)$$
$$s_a(t) = 2P_a \cos(\omega t + \theta) \tag{12}$$

The output voltage at this time is calculated as:

$$E_x = P_v \cos\theta - P_a \sin\theta$$
$$E_y = P_a \cos\theta + P_v \sin\theta \tag{13}$$

Considering the vector diagram on the E_x–E_y plane, when the phase lead in the measurement system is θ, the output voltage vector is the vector when there is no phase rotation rotated by the angle θ around the origin (**Fig. 4**). Consequently, when the output voltage vector is decomposed into the vector component QP in the direction of the E_x axis rotated by the angle θ and the vector component OQ in the direction of the E_y axis rotated by the angle θ, the magnitude of the component QP is proportional to the magnitude of $p_v(t)$ (the mass flow rate) and the magnitude of the component OQ is proportional to the magnitude of $p_a(t)$ (the magnitude of the fluid acceleration). If the mass flow rate is increased gradually from 0, the locus described by the tip of the output voltage vector is a straight half line passing through the point P with the origin at point Q. The actual locus described when the flow rate was varied and the output voltage was input to an *X-Y* recorder is shown in **Fig. 5**. In this example, the pulsation frequency was 5 Hz, the pulsation volume flow rate was 8 $\times 10^{-5}$ $m^3 s^{-1}$ rms and l = 20 mm.

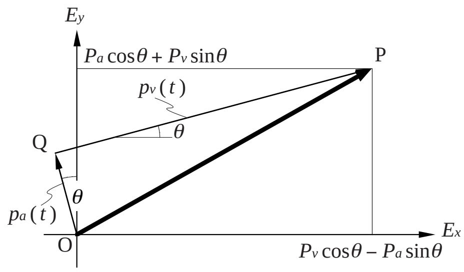

Fig.4 Vector diagram.

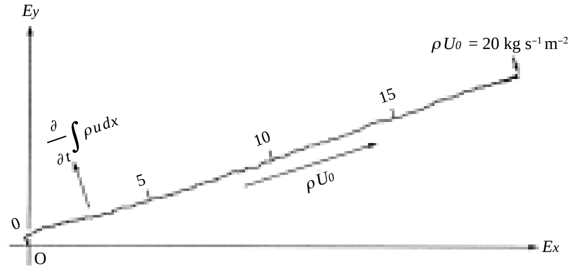

Fig.5 Vector locus for a change of mass flow rate (f = 5 Hz, $q = 8 \times 10^{-5}$ $m^3 s^{-1}$ rms, l = 20 mm).

Additional loci like the one shown in Fig. 5 were described by varying f from 2 to 20 Hz and l from 10 to 90 mm. As l increased, fluid acceleration could be detected over a broader range. As can be expected to follow from this observation, the acceleration component, that is, the vector OQ component, increased approximately in proportion to l. In principle the acceleration component can be separated, but to increase the signal to noise ratio it is desirable for the acceleration component to be minimized. To decrease the effect of viscosity and acceleration, l should be minimized. However, as explained in Section 2, if l is too small, it is possible that the effect of 2-dimensionality of the flow will become important. Comparing outputs for the same magnitude of ρU_0, for any value of f, as long as $l \geq$ 20mm, the magnitude of QP was independent of l. It follows that provided that $l \geq$ 20mm, the effect of 2-dimensionality can be neglected. With respect to the variation of f, the anticipated result was obtained. That is to say, the magnitude of the acceleration component was approximately proportional to f. The smaller f becomes, the smaller the acceleration component becomes, but at the same time the displacement of the exciter needed to apply the same volume pulsation increases. From these considerations, in the following experiment we took f to be 5 Hz and l to be 20 mm.

The mass flow can be found by measuring the distance from the point where ρU_0= 0 to the tip of the output voltage vector on the E_x–E_y plane, but in an actual measurement device, either a reference signal or the detected signal $s(t)$ is passed through a suitable phase shift circuit and the voltage E_x (or E_y) itself is taken to be proportional to the mass flow rate and output. **Fig.6** shows the results of measurements of mass flow rate with $q = 8 \times 10^{-5}$ m^{3}s^{-1} rms, $f = 5$ Hz and $l = 20$ mm. The output voltage from this flowmeter was added to the ordinate of an X-Y recorder; the voltage which was obtained by taking the square root of the output of a reference pitot tube (under the condition that ρ is fixed at the position of the pitot tube) has been added to the abscissa. The flow rate was varied and the results recorded. The abscissa scale was determined by calculation from the pitot tube pressure and density. From Fig. 6, it can be confirmed that the output of this flowmeter agrees well with the mass flow rate.

These results show that the proposed flowmeter operates in accordance with the principle on which it was based. However, in the experiment of which the results are shown in Fig. 6, the density ρ was fixed and U_0 varied. To confirm that the mass flow rate can be measured accurately when both ρ and U_0 are varied, the following experiment was performed. The device shown in **Fig. 7** was built to add pulsations to the flow. Air was blown out of a small hole in the side of a brass pipe having an outer diameter of 7 mm and inner diameter of 5 mm. The piston was vibrated by an exciter, similar to the one used in the experiment described above. Here a general purpose exciter was used, but it is possible to reduce the size of the system by using, for example, a moving coil type acoustic speaker instead of a piston and exciter. The main pipe, pressure detection port, condenser microphones and signal processing circuit were as used in the experiment described above, and the configuration was the same as that shown in Fig. 2. The airflow was produced by connecting a hair dryer to one end of the main pipe. The flow rate and density were varied by changing the rotation rate of the hair dryer and by turning the heater ON or OFF. A graph showing flowmeter output voltage as a function of time is given in **Fig. 8**. Here the pulsation frequency was taken to be 5 Hz, the volume flow rate was 6×10^{-5}m^{3}s^{-1} rms and l was 20 mm. The ordinate scale was determined from the known mass flow rate. The numbers that appear above the graph give the mass flow rates calculated from the separately measured flow rate and density. It is seen that the mass flow rate was measured accurately even when the density was varied.

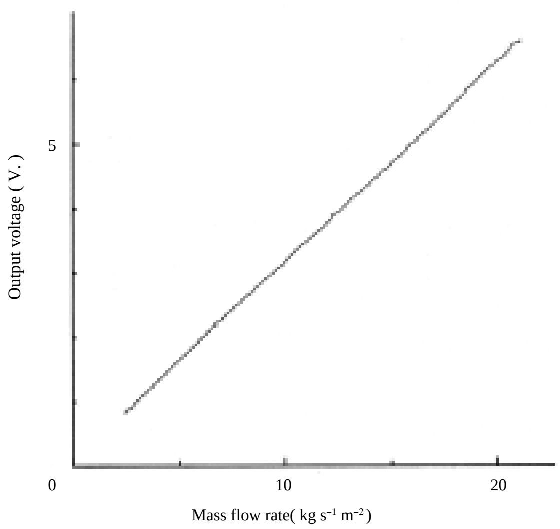

Fig.6 A plot of the output voltage versus the mass flow rate (f = 5Hz, q = 8×10^{-5} m^{3}s^{-1} rms, l = 20 mm).

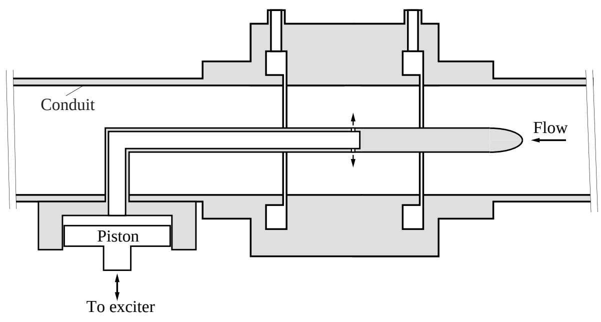

Fig.7 Pulsation generator in the experiment of Fig.8.

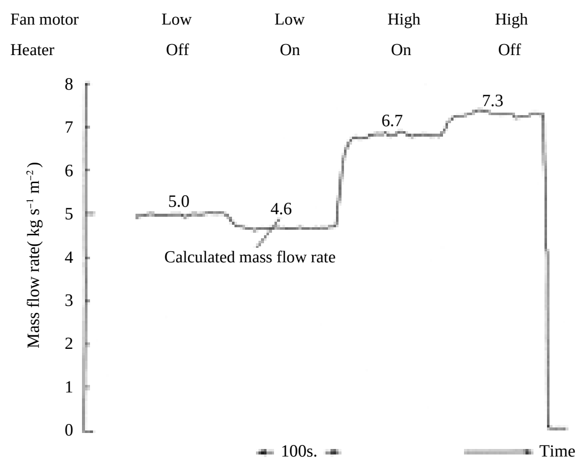

Fig.8 Measured mass flow rate of an air flow by a hairyer.

4. Summary

A mass flowmeter that uses a pulsating source placed in a flow was constructed and several experiments performed. It was confirmed that the flowmeter operates according to the principle on which it was designed. There is a strong possibility that this measurement method can be employed in the design of a simple and highly applicable flowmeter.

A variety of mechanisms can be conceived to apply pulsations and a variety of designs developed for the source and pressure detection ports. It would be necessary to investigate the optimum configuration for the conditions under which the flowmeter is to be used. The effects that various factors have on the performance of the proposed flowmeter were estimated in this paper. However, to evaluate these effects rigorously and to evaluate the overall characteristics of the flowmeter, detailed knowledge of the actual flow is necessary. The actual flow must be related to the configuration of the flowmeter. Consequently, an investigation of the optimum configuration mentioned above should be conducted together with flow analysis. In recent years, it has become easy to perform flow analyses by numerical fluid dynamics. These problems will be analyzed in future work.

Finally, I wish to express thanks to Prof. Yasushi Ishii of Institute of Interdisciplinary Research, Faculty of Engineering, The University of Tokyo, who provided daily guidance in this work.

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