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DEVELOPMENT OF UNSTEADY GAS FLOW GENERATOR WITH HIGHLY PRECISE INLET FLOW RATE CONTROL SYSTEM

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ABSTRACT

In industry, an unsteady flow rate measurement of gases is becoming important increasingly. Our group has been developed an unsteady flow generator with an isothermal chamber for gases and showed that the calibration of the dynamic characteristics for the tested flow meter was effective. However, not only the measurement of the instantaneous flow rate value but also the evaluation of the time mean value in the unsteady flow becomes important in industry. And it was difficult to control precisely the time mean value of the generated flow rate using the former unsteady flow generator which we developed. In this research, to improve the precision of the generated flow rate with the unsteady flow generator, we suggest the inlet flow rate control method with the sonic nozzle and the high precise pressure control system and apply this method to the developed generator. Moreover, we perform the experiments and uncertainty analysis and confirm the effective of the suggested method.

KEY WORDS

Unsteady Flow Generator, Flow rate control, Precise pressure control, Flow rate measurement

NOMENCLATURE

A:	Area of nozzle throat	[m^2]
b:	Critical pressure ratio	[-]
f:	Frequency	[Hz]
f_d:	Time constant	[s]
G:	Mass flow rate	[g/s]
G_{ref}:	Reference of Generated mass flow rate	[g/s]
K:	Coefficient of unit converter	[-]
K_G:	Gain of flow rate	[kg/(s・mm^2)]
K_p:	Proportional gain of pressure	[-]
K_{dp}:	Proportional gain of pressure differentiate	[-]
P:	Pressure	[Pa]
P_a:	Atmospheric pressure	[Pa]
$\dot{P}$:	Differentiated value of pressure	[Pa/s]
R:	Gas constant number	[J/(kg・K)]
S_e:	Effective area	[m^2]
t:	Time	[s]
T_a:	Control gain	[-]
T_b:	Control gain	[-]

T_p: Integral action time of pressure [-]
T_{dp}: Integral action time of pressure differentiate [-]
u: Input voltage to the servo valve [V]
V: Volume of the chamber [m^3]
W: Mass of air in the chamber [kg]
ΔG : Amplitude of mass flow rate [g/s]
κ : Specific heat ratio [-]
θ : Temperature of gas [K]
$\bar{\theta}$: Average temperature [K]
θ_a: Room temperature [K]
ρ : Density of air [kg/m^3]
σ^* : Critical flow coefficient [-]

Subscripts

c : chamber
f : forward
in : inlet
out : outlet
s : supply
up : upstream

INTRODUCTION

Measurement of an unsteady flow rate of compressible fluids is becoming more important with respect to energy savings, environmental protection, realizations of the technical advantages. Such a measurement provides significant information about the effective performance of engines, pumps, fuel cells and air compressors, and the ability to control the flow rates of gases and fluids in the semiconductor manufacturing process. There is substantial literature dealing with the measurement of unsteady gas flow (see [1]). Mottram et al [2] investigated the influence of pulsating flows on orifice plate flow meters. Hakanson et al [3], Berrebi et al [4] and Dane [5] studied the effects of pulsating flow on ultrasonic gas flow meters. Stone and Wright [6] investigated the dynamics of viscous flow meters both theoretically and experimentally. Uchiyama and Hakomori [7] proposed a method of measuring the instantaneous flow rate by estimating the velocity profiles in pipes. Most of these studies generated unsteady mass flows by using piston cylinders. Clearly, in these studies, substantial efforts must have been required in order to minimize the sensitivity dependence of density fluctuation on pressure and temperature variations. Durst et al [8] developed a mass flow rate controller using a valve and a laminar element that was designed to work up to unsteady oscillatory flow of 125Hz and showed experimental results up to 25Hz. Since the flow passed through a valve becomes a function of temperature, the accuracy could be improved if the temperature change is prevented. Therefore, the unsteady flow measurement of gases is still a challenging research topic and the method to calibrate the dynamic characteristic of gas flow meters has not been defined yet. To solve these problems, we developed the unsteady gas flow generator using an isothermal chamber in 1997. However, this generator has limitation in time that is only during discharge from the chamber [9,10]. By adding a charging process, Funaki et al [11] developed the newly unsteady mass flow generator for gases that provide a foundation for the effective measurement of the unsteady gaseous mass flow generator and evaluation of the dynamics of gas flow meters in 2006. But it was difficult to control and compensate precisely the time mean value of the generated mass flow rate using the unsteady mass flow generator.

In this study, to solve this problem, we suggest the inlet flow rate control method with a sonic Venturi nozzle [12] and a high precise pressure control system [13,14] and apply this method to the unsteady mass flow generator. Moreover, we perform the experiments and uncertainty analysis and confirm the effective of the suggested method.

UNSTEADY GAS FLOW GENERATOR

Principle

The unsteady mass flow is generated using an isothermal chamber and two spool type servo valves in former research [11]. Here, the state equation for compressible fluids in a chamber can be written as

$$PV = WR\theta \tag{1}$$

The following equation can be derived by differentiating Eq.(1), if the chamber volume is constant.

$$V\frac{dP_c}{dt} = \left(G_{in} - G_{out}\right)R\bar{\theta} + WR\frac{d\bar{\theta}}{dt} \tag{2}$$

Here, the mass flow rate G_{in} is charged through the inlet mass flow controller installed in the upstream of the isothermal chamber. The controlled mass flow rate G_{out}, which is the generated flow, is discharged through the servo valve installed in the downstream of the isothermal chamber. The generated flow G_{out} is given by the following equation by transforming equation (2).

$$G_{out} = G_{in} - \frac{V}{R\bar{\theta}}\frac{dP_c}{dt} + \frac{W}{\bar{\theta}}\frac{d\bar{\theta}}{dt} \tag{3}$$

If the state of air in the chamber during charge or discharge remains isothermal, the generated mass flow rate can be obtained from Eq.(3).

$$G_{out} = G_{in} - \frac{V}{R\bar{\theta}}\frac{dP_c}{dt} = G_{in} - \Delta G \tag{4}$$

Since the condition remains isothermal, the average temperature $\overline{\theta}$ in the chamber is equal to the room temperature θ_a. Eq.(4) indicates that if the volume of the chamber V and the room temperature are known, then the generated mass flow rate can be controlled by the pressure difference in the isothermal chamber and the inlet mass flow rate. The flow rate through a pneumatic valve is represented in the following formula for the choked condition [15],

$$G = K S_e(u) P_s \sqrt{\frac{273}{\theta_a}} \quad \left(\frac{P_c}{P_s} < b\right) \tag{5}$$

The case of non-choked flow is given by,

$$G = K S_e(u) P_c \sqrt{\frac{273}{\theta_a}} \sqrt{1-\left(\frac{P_a/P_c - b}{1-b}\right)^2} \tag{6}$$

where b is the critical pressure ratio. The critical pressure ratio is defined in ISO6358 [15]. In this paper, the inlet mass flow rate is controlled by the inlet mass flow controller with sonic Venturi nozzle, and the pressure change in the isothermal chamber is controlled by servo valve as shown in Figure 1.

Apparatus

The developed unsteady gas flow generator with highly precise inlet mass flow rate control system is shown in Figure 2. The apparatus consists of an isothermal chamber, a spool type servo valve, an inlet mass flow controller with sonic Venturi nozzle, two pressure sensors, an AD converter, a DA converter and a personal computer. The servo valve has a dynamic response of about 100Hz. The pressure sensor was a semiconductor type with a resolution of 50Pa. The inlet mass flow controller with a sonic Venturi nozzle and a precise pressure regulator controls the charged flow rate to the isothermal chamber, and the servo valve controls the generated unsteady flow from the chamber. The AD converter is used to obtain the supply pressure, the pressure in the chamber and the measured flow rate using the laminar flow meter. The internal volume of the isothermal chamber is 1.0×10^{-4} m^3.

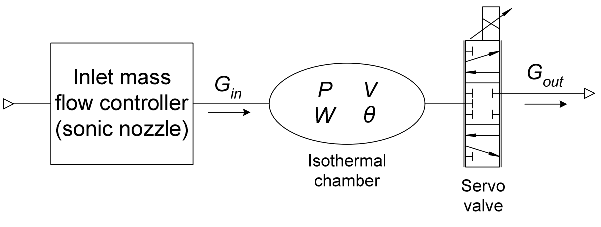

Figure 1 Schematic diagram of mass flow rate control while charging and discharging

INLET FLOW RATE CONTROL SYSTEM

The sonic Venturi nozzle can realize highly precise flow rate measurement. Therefore, if an inlet flow rate control system consists of a precise pressure regulator with very small fluctuation and a sonic Venturi nozzle, the system can realize highly precise flow rate control.

Arrangement of a precise pressure regulator

The arrangement and the picture of the precise pressure regulator are shown in Figure 3 and Figure 4. The components are a spool type servo valve (FESTO MYPE-5-1/8-HF- 010-B), a laminar flow meter, an isothermal chamber, a pressure differentiator (PD sensor), and a pressure sensor (KEYENCE AP-13S). Though the spool valve has 5 ports, the valve is used as a 3 port type spool type servo valve, having ports of supply, control and exhaust. The unused 2ports are plugged. An 'isothermal chamber' was developed in a previous work. This chamber is filled with copper wool, which allows the state change in the chamber to become nearly isothermal. The isothermal chamber used in this research has a volume of 1.57×10^{-3} m^3. The laminar flow meter [16,17] and the PD sensor [13,14] were also developed in previous research. The laminar flow meter is a differential pressure type flow meter, whose dynamic characteristics are calibrated. The 'PD sensor' is a unique sensor which can directly measure the differentiated value of gas pressure at a high resolution and high response.

Sonic Venturi nozzle

Sonic Venture nozzle is a famous instrument of the precise flow rate measurement. The sonic nozzle is an ISO type toroidal throat Venturi nozzle in which the radius of curvature of the throat is twice the throat diameter and the length of the diffuser with a half angle of 3 degrees is three times of the throat diameter [12,18]. The schematic diagram of the sonic Venturi nozzle used is shown in Figure 5. The throat diameter which we used is 0.594mm. This sonic Venturi nozzle was set up at the nozzle holder as shown in Figure 6.

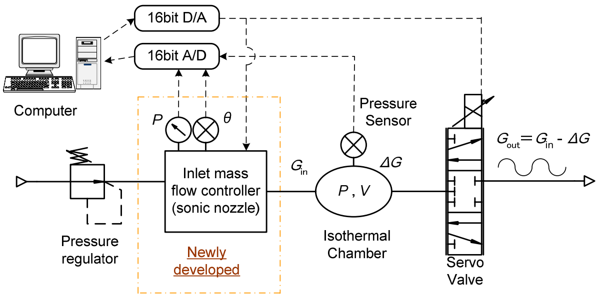

Figure 2 Apparatus of oscillatory gas flow generator

Design of the controller

The purpose of the new pressure regulator is to keep the pressure in the isothermal chamber at a set value, as shown in Figure 3. The objective component, that is the unsteady gas flow generator, is to be connected to the downstream of the isothermal chamber. The very important factor is that, when disturbance of pressure of the flow rate occurs either on the supply or downstream of the pressure regulator, the pressure in the isothermal chamber should be kept stable or immediately recovered. A pressure feed-back loop is the main loop, mean while there are 2 minor loops. One is a flow rate control loop, the other one is to estimate and compensate the output flow rate G_{out}. As a result, we confirmed that the new pressure regulator regulate the fluctuation of the upstream pressure of the sonic nozzle less than 0.9%. Therefore, the inlet mass flow rate G_{in} is controlled precisely and constantly using this inlet mass flow controller, and can be written as Eq.(7).

$$G_{in} = \frac{P_{up} A}{\sqrt{R\theta_{up}}} \sigma^* = \frac{P_{up} A}{\sqrt{R\theta_{up}}} \sqrt{\kappa \left(\frac{2}{\kappa + 1} \right)^{\frac{\kappa+1}{\kappa-1}}} \qquad (7)$$

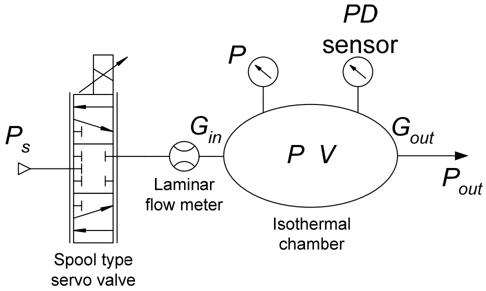

Figure 3 Diagram of precise pressure regulator

Figure 4 Photograph of precise pressure regulator

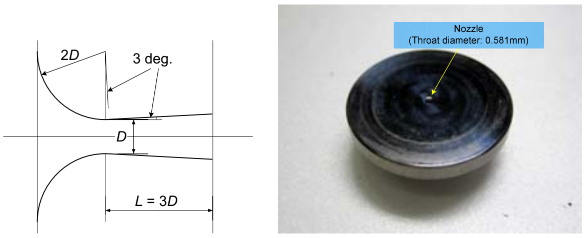

Figure 5 Schematic diagram and photograph of the ISO type toroidal throat sonic Venturi nozzle

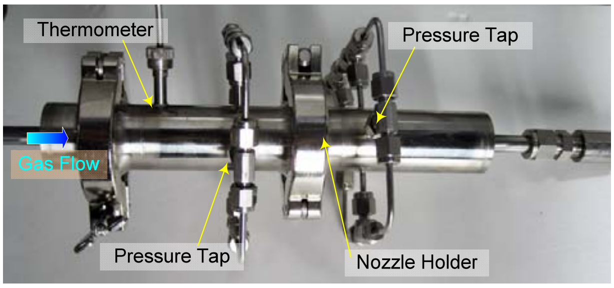

Figure 6 Nozzle Holder

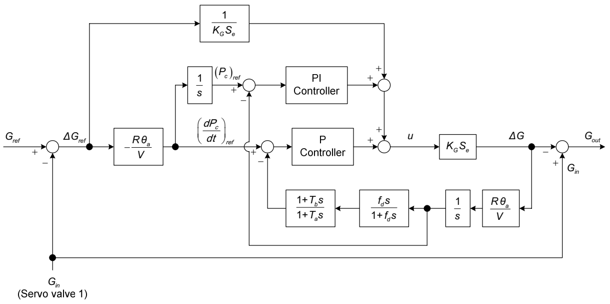

Figure 7 Block diagram of an unsteady gas flow generator

CONTROL METHOD

We controlled the absolute pressure in the isothermal chamber to be the choked flow at the sonic Venturi nozzle of the inlet mass flow rate controller and the non-choked flow at the servo valve. The supply pressure was set up at 600kPa. The precise pressure regulator was set up about 350kPa and the pressure in the isothermal chamber was about 150kPa. Therefore, the pressure ratio is about 0.43. We confirmed that the choked condition is realized at the sonic Venturi nozzle, because the critical pressure ratio of this nozzle was up to 0.6. The manipulated value by the inlet mass flow rate controller is the average value of the generated flow rate. That is, the pressure at the upstream side of the sonic nozzle was constant value. Figure 7 shows the block diagram of the unsteady gas flow generator which we developed in this study. At first, we calculated the reference flow rate using Eq.(4). The control signal to the servo valve is estimated as $G/(K_G S_e)$. This value is given as a feed-forward element to the system. And a PI controller and a P controller were adopted for the pressure control in the isothermal chamber. Therefore, this flow generator can generate the unsteady flow rate continuously, calculating the pressure change in the isothermal chamber and the charged flow rate through the inlet mass flow controller. And the input voltage of servo valve can be written as follows.

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$$u = K_p\left(1+\frac{1}{T_p s}\right)\left\{\left(P_c\right)_{ref} - P_c\right\} + K_{dp}\left\{\left(\dot{P}_c\right)_{ref} - \dot{P}_c\right\} + \frac{G_{ref}}{K_G S_e} \tag{8}$$

EXPERIMENTAL RESULTS AND DISCUSSIONS

Evaluation of inlet flow rate control system

The sonic Venturi nozzle which we used has the uncertainty within ±0.1% [18]. We confirmed that the inlet mass flow rate can be realized the uncertainty within ±0.4% using the inlet mass flow rate control system.

Generation of oscillatory gas flows

At first, the target oscillatory mass flow rate is given as 0.216 + 0.107 sin($2\pi f t$) g/s. The experiment was performed at several frequencies. The low-pass filter was used for the processing of the measured data. The cut-off frequency of the filter was set at five times the frequency of the phenomenon. Figure 8 shows the experimental results at a frequency of 1Hz. In this figure, the black line show the target mass flow rate, the blue line shows the generated mass flow rate using the unsteady gas flow generator and the red line indicates the measured mass flow rate using the laminar flow meter. From this figure, the target flow rate and the generated flow rate is consistent with the measured flow rate using the laminar flow meter to finish the calibration with the former generator. Figure 9 shows the experimental results at a frequency of 10Hz. From this result, it could be confirmed that the target flow rate and the generated flow rate show good agreement.
Moreover, the flow is generated continuously for 60minutes. These results show that the maximum error between the target mass flow rate and the generated mass flow rate is less than approximately 5%.

Evaluation of time mean flow rate

When we examine the dynamic characteristics of the tested flow meter, there are two important factors. One is the responsibility of measured value of tested flow meter in comparison with a standard flow rate wave pattern. Second is the fluctuation of the time mean measured value. In this time, when the generator occurred by various oscillatory flows, we confirmed the fluctuation of the time mean generated value by experiments. As a result, it became clear that the uncertainty is less than ±0.4%.

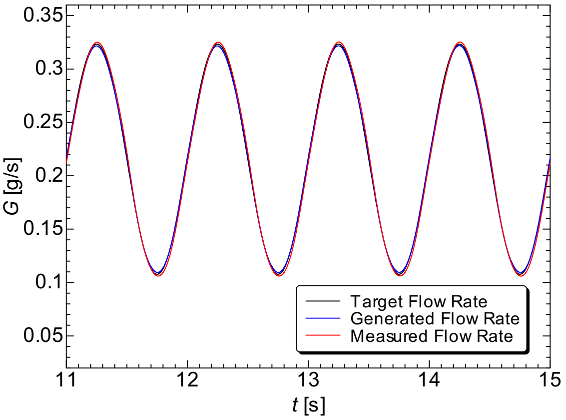

Figure 8 Generation of oscillatory gas flow at the frequency of 1Hz

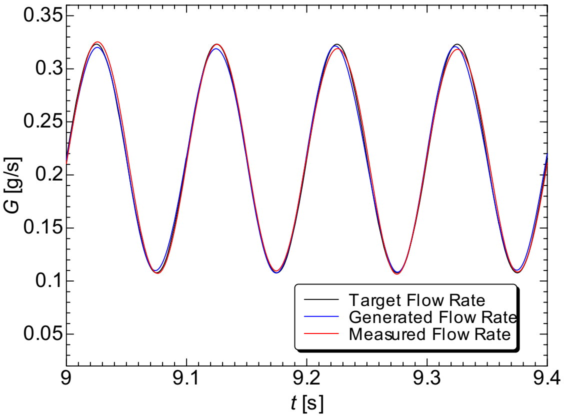

Figure 9 Generation of oscillatory gas flow at the frequency of 10Hz

Analysis of uncertainty

The total uncertainty of the oscillatory gas flow generator is given by the following formula from the propagation of uncertainty as shown in guide by ISO (1993 and 2002) [19,20].

$$\frac{\delta G_f}{G_f} = \sqrt{\left\{\left(\frac{\delta P_{up}}{P_{up}}\right)^2 + \left(\frac{\delta A}{A}\right)^2 + 0.25\left(\frac{\delta \theta_{up}}{\theta_{up}}\right)^2\right\}} + \sqrt{\left\{\left(\frac{\delta \theta}{\theta}\right)^2 + \left(\frac{\delta V}{V}\right)^2 + \left\{\frac{\delta\left(dP/dt\right)}{\left(dP/dt\right)}\right\}^2\right\}} + \sqrt{\left\{\left(\frac{\delta \theta}{\theta}\right)^2 + \left\{\frac{\delta\left(d\theta/dt\right)}{\left(d\theta/dt\right)}\right\}^2\right\}} \tag{9}$$

Where the first term is the uncertainty of the inlet mass flow rate, the second term is the uncertainty of the pressure change of the isothermal chamber, and the third term is the uncertainty of the temperature change. The uncertainty of the chamber volume measurement is considered to be 0.5[%]. The uncertainty of the effective area is considered to be 0.5[%]. The uncertainty due to the pressure change speed is considered to be 1[%]. The uncertainty of the temperature change is estimated as 3[%] at maximum. The other factors affecting the uncertainty are as mentioned above. From Eq.(15), the generated mass flow rate with only forward direction has a maximum uncertainty of 4.9[%]. Moreover, inlet mass flow rate, that is, the average mass flow rate is within an uncertainty of ± 0.4%. Therefore, the unsteady mass flow generator for gases has sufficient accuracy for practical use.

CONCLUSIONS

In this paper, the performance of the unsteady gas flow generator with highly precise inlet mass flow rate control system which we developed is investigated experimentally. At first, we developed and manufactured a highly precise inlet mass flow rate control system with the precise pressure regulator and the sonic Venturi nozzle. Secondly, the mean value of the generated oscillatory flow is investigated. It became clear that the uncertainty is within ± 0.4%. The effectiveness of the generator for calibrating the dynamic characteristics of gaseous flow meters is confirmed.

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