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Development of Continuous Unsteady Flow Generator for Gases

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ABSTRACT

Recently, unsteady flow rate measurement of gases is very important in the various industrial fields. However, there is no way to calibrate and to examine the unsteady flow rate of gases experimentally. As a result, there is no test bench for the unsteady flow rate measurement of gases.

In this paper, we developed a new type of unsteady flow generator for gases. Especially, we realized to generate the unsteady flow of gases continuously. Then, we verified experimentally the generated unsteady flow rate using a laminar flow meter that has quick response up to 50[Hz]. Moreover, we investigated the heat transfer in the generator. As a result, we confirmed that this generator could generate the oscillatory flow up to the frequency of 30[Hz], and the target flow continuously for 30 minutes. The generator is effective for the verification of the various unsteady phenomena of gases experimentally.

KEY WORDS

Flow measurement, Unsteady flow, Generator, Isothermal chamber, Heat transfer

NOMENCLATURE

a : Amplitude ratio of flow rate ($=Q_{amp}/Q_{ave}$) [-]
b: Critical pressure ratio [-]
C_P: Specific heat at constant pressure [kJ/kg・K]
C_V: Specific heat at constant volume [kJ/kg・K]
f: Frequency [Hz]
f_d: Time constant [s]
h: Heat transfer coefficient [W/(m^2・K)]
G: Mass flow rate [kg/s]
K_G: Gain of flow rate [kg/(s・mm^2)]
K_p: Proportional gain of pressure [-]
K_{dp}: Proportional gain of pressure differentiate [-]
k: Coefficient of flow rate converter [m^3/kg]
P: Pressure [Pa]
P_a: Atmospheric pressure [Pa]
P_{ref}: Target of pressure [Pa]
$\dot{P}$: Differentiated value of pressure [Pa/s]

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Q: Volumetric flow rate at standard condition [m^3/s]
Q_{amp}: Amplitude flow rate of oscillatory flow [m^3/s]
Q_{ave}: Average flow rate of oscillatory flow [m^3/s]
Q_{ref}: Reference of Generated oscillatory flow [m^3/s]
q: Heat transfer rate [W]
R: Gas constant number [J/(kg・K)]
S_e: Effective area [m^2]
t: Time [s]
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]
κ : Specific heat ratio [-]
θ : Temperature of gas [K]
θ_a: Room temperature [K]
ρ : Density of air [kg/m^3]

Subscripts
c: chamber
e: control volume
in: inlet
out: outlet
s: supply

INTRODUCTION

Recently, unsteady flow rate measurement of gases is very important in the various industrial fields. Especially, it has been increased the importance to control the gas flow rate for the fuel cell and the semiconductor fabrication equipment, to control the expired and inspired gas for the medical treatment, and to measure the pulsated flow of the pump. However, there is no way to calibrate and to examine the unsteady flow rate of gases experimentally. As a result, there is no test bench for the unsteady flow rate measurement of gases.

In this paper, we developed a new type of unsteady flow generator for gases using an isothermal chamber and two spool type servo valves. Especially, we realized to generate the unsteady flow of gases continuously for 30 minutes. Then, we verified experimentally the generated unsteady flow rate using a laminar flow meter that has quick response up to 50[Hz] [3]. Moreover, we investigated the heat transfer in the generator. As a result, it could be seen that there is no influence of the temperature change in the chamber. And it is shown that the generator is effective for the verification of the various unsteady phenomena of gases experimentally.

CONTINUOUS UNSTEADY FLOW GENERATOR

Principle

The unsteady flow generator in the former research [2] has the limitation of the generating time. In this research, we realized to generate the unsteady flow continuously. We adopted the method that the charging and the discharging in the isothermal chamber are synchronal. Here, the state equation for compressible fluids in a chamber can be written as

$$PV = WR\theta \qquad (1)$$

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

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

If the state of air in the chamber during charge or discharge remains isothermal, the volumetric flow rate can be obtained from Eq.(2).

$$Q_{out} = kG_{out} = Q_{in} - k\frac{V}{R\theta_a}\frac{dP_c}{dt} \qquad (3)$$

As the condition is isothermal, the average temperature in the chamber is equal to the room temperature. It is clear from Eq.(3) that if the volume of the chamber V and the room temperature θ_a are known, the instantaneous volumetric flow rate can be obtained from the pressure

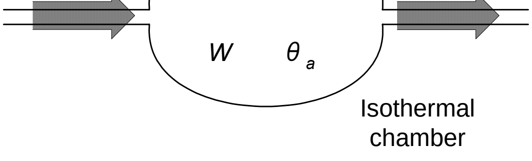

Fig.1 Schematic diagram of mass flow rate while charging and discharging from an isothermal chamber

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response and the inlet volumetric flow rate. The flow rate through a pneumatic valve is represented in the following two formulas [4]. The case of choked flow is given by,

$$Q = 11.1 S_e P_s \sqrt{\frac{273}{\theta_a}} \qquad (4)$$

The case of non-choked flow is given by,

$$Q = 11.1 \quad S_e \quad P_c \sqrt{\frac{273}{\theta_a}} \sqrt{1 - \left(\frac{P_a / P_c - b}{1 - b} \right)^2} \qquad (5)$$

where b is the critical pressure ratio. In the choked flow, the pressure response equations in the chamber, which can be derived from Eqs.(2), (3) and (4), are provided below when we assume the supply pressure is P_s and downstream pressure is the pressure in the chamber.

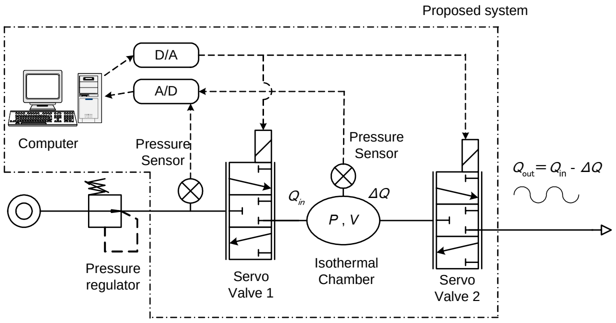

Fig.2 Apparatus of a continuous flow generator

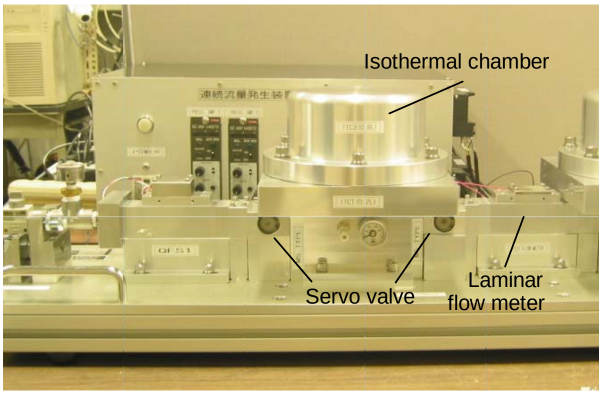

Fig.3 Photograph of a continuous flow generator

In the case of non-choked flow, the critical pressure ratio b and the uncertainly of the pressure and the temperature in the chamber are important factors in this generator.

Generally, the unsteady flow can be generated using the servo valve with choked flow. However, there is a problem of changing the temperature in the chamber. Therefore, the former research [2] has been reported that the measured sinusoidal flow rate has error on the gain and the phase. In this paper, we controlled the inlet mass flow rate using a servo valve. And the generated unsteady flow rate using this system is controlled using a servo valve at the downstream side.

Apparatus

The developed continuous flow generator is shown in Fig.2 and the photograph of it is shown in Fig.3. The apparatus consists of an isothermal chamber, two spool type servo valves, two pressure sensors, an AD converter, a DA converter and a personal computer. The servo valve has a dynamic response of about 100[Hz]. The pressure sensor was a semiconductor type with a resolution of 50[Pa]. The servo valve 1 controls the charged flow rate to the isothermal chamber, and the servo valve 2 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 2.0×10^{-4} [m^3].

Control method

We controlled the absolute pressure in the isothermal chamber to be the choked flow at the servo valve 1 and the non-choked flow at the servo valve 2. The supply pressure was set up at 600[kPa] and the pressure in the isothermal chamber was about 180[kPa]. Therefore, the pressure ratio is about 0.3. We confirmed that the choked condition is realized at the servo valve 1, because the critical pressure ratio of this valve was about 0.35. The manipulated value by the servo valve 1 is the average value of the generated flow rate. Fig.4 shows the block diagram of the continuous flow generator. At first, we calculated the reference flow rate using Eq.(3). 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 two PI controllers were adopted for the

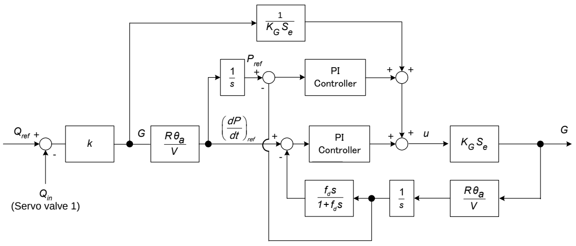

Fig.4 Block diagram of a continuous flow generator

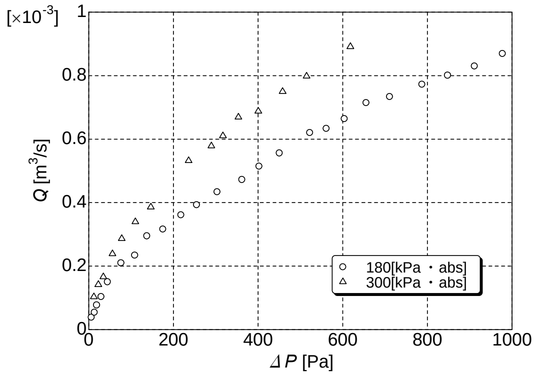

Fig.5 Pressure loss through the isothermal chamber

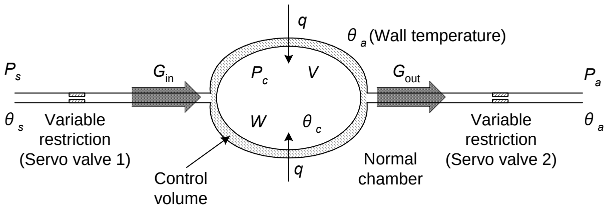

Fig.6 Control volume in the chamber

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 servo valve 1. And the input voltage of servo valve 2 can be written as follows.

$$u = K_p\left(1+\frac{1}{T_p s}\right)\left(P_{ref}-P_c\right) + K_{dp}\left(1+\frac{1}{T_{dp} s}\right)\left(\dot{P}_{ref}-\dot{P}_c\right)+\frac{G}{K_G S_e} \qquad (6)$$

SPECIFICATION

Pressure distribution

In this system, the isothermal chamber that was set up in the line was a resistant component. We measured the pressure loss of the chamber, when the flow rate is constant. Fig.5 shows the experimental results of the pressure loss through the isothermal chamber. The symbol "○" is the results when the pressure in the chamber was 180[kPa] and the symbol "△" is that of 300[kPa]. From this figure, if the generated volumetric flow rate is about 8.0×10^{-4} [m^3/s], the pressure loss through the isothermal chamber is about 800[Pa]. As a result, the measured error of the pressure in the chamber has a maximum of 0.44[%]. Therefore, the pressure loss through the chamber was very small, and there was no influence in pressure measurement of the chamber. In addition, the pressure in the isothermal chamber was measured at the both side of cylindrical chamber and confirmed that the pressure distribution in the chamber was negligible small, when the unsteady flow was generated.

Temperature change

In this generator, it is very important to know the influence of changes in air temperature on the accuracy of it. However, it is very difficult to measure temperature change of air in the chamber rapidly. Therefore, we confirmed the temperature change in the normal chamber and the isothermal chamber theoretically while generating the sinusoidal flow, considering the energy change of air in the chamber.

Fig.6 shows the RC circuit of the continuous unsteady flow generator. The state equation for compressible fluids in the chamber is given by as follows using the spatial average density of air.

$$P_c = \rho_c R\,\theta_c \qquad (7)$$

Pressure change ratio in the chamber is,

$$\frac{dP_c}{dt} = \rho_c R\frac{d\theta_a}{dt} + \frac{R\theta_a}{V}G \qquad (8)$$

As Eq.(8), the pressure change in the chamber is obtained from the mass flow rate and the average air temperature change in the chamber. Considering the energy change of air in the chamber, energy equation is expressed as follows.

$$\frac{d}{dt}\int_V C_V\,\rho_c\theta_a\,dV = G\,C_V\,\theta_e + \frac{P_c}{\rho_e}G + q \qquad (9)$$

where θ_e and ρ_e are temperature and density of air across the control volume respectively.

In the case of $G < 0$, discharging air temperature across the control volume is equal to spatial average temperature in the chamber. And based on the Newton's law of cooling the heat transfer rate q is written as,

$$q = h\,S_h\left(\theta_a - \theta_c\right) \qquad (10)$$

Finally, while discharging from the chamber, the spatial average temperature change can be obtained as follows.

$$C_V W\frac{d\theta_c}{dt} = G_{out}R\,\theta_c + h\,S_h\left(\theta_a - \theta_c\right) \qquad (11)$$

In the case of $G > 0$, the air temperature across the control volume θ_e is thought to be different from former case. Through the restriction, the air temperature approaches to the atmospheric temperature, the energy equation (9) can be transformed as,

$$\frac{d}{dt}\int_V C_V\,\rho_c\theta_a\,dV = G_{in}\,C_V\,\theta_a + \frac{P_c}{\rho_{ca}}G_{in} + q \qquad (12)$$

Using the Eq.(7) and Eq.(10), the spatial average temperature change in the chamber can be written as,

$$\begin{aligned} C_V W\frac{d\theta_c}{dt} &= G_{in}C_V\left(\theta_a - \theta_c\right) \\ &\quad + R\,\theta_a G_{in} + h\,S_h\left(\theta_a - \theta_c\right) \end{aligned} \qquad (13)$$

Comparing the Eq.(13) with Eq.(11) which is discharged case, Eq.(13) has additional term.

Based on the above mentioned, the pressure changes in the chamber while charging and discharging can be obtained as follows.

$$\begin{aligned} \frac{dP_c}{dt} &= \frac{\kappa - 1}{V}h\,S_h\left(\theta_a - \theta_c\right) \\ &\quad + \frac{1}{V}\left\{G_{in}\left(\kappa - 1\right)C_p\,\theta_a - \kappa\,G_{out}\,R\,\theta_c\right\} \end{aligned} \qquad (14)$$

And the spatial temperature change in the chamber can be written as follows from Eq.(11) and Eq.(13).

$$C_V W\frac{d\theta_c}{dt} = G_{in}\left(C_P\theta_a - C_V\theta_c\right) - G_{out}\,R\,\theta_c + q \qquad (15)$$

Here, we considered the case that the oscillatory flow is set at $5.0\times10^{-4} + 2.5\times10^{-4}\sin\left(2\pi\,f\,t\right)$ [m^3/s] and h is 20[W/(m^2・k)], S_h of the normal chamber is 199.25[cm^2], S_h of the isothermal chamber is 7155[cm^2]. Fig.7 shows the simulation results of the pressure and the temperature changes in the normal chamber and the isothermal chamber. As a result, the magnitude of the temperature changes is about 8[K] using the normal chamber. On the other hand, the magnitude of it is about 1.5[K] using the isothermal chamber. Therefore, it could be confirmed that there is no influence of the temperature changes in the chamber.

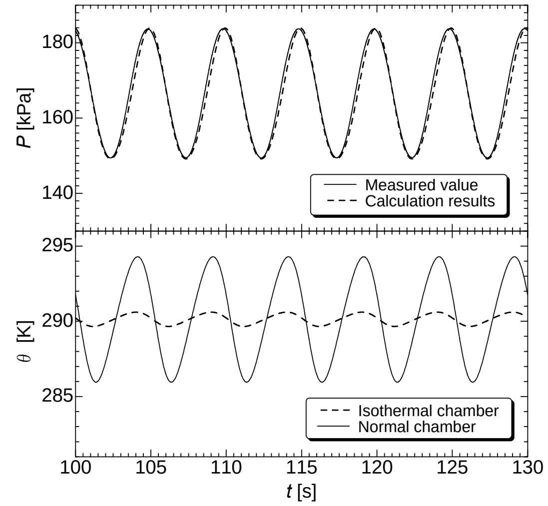

Fig.7 Pressure and temperature change in the isothermal chamber when the oscillatory flow was generated

Uncertainty

The error for the pressure sensor is 0.5[%]. The error due to the change in the pressure of the chamber is a maximum of 2[%]. The temperature measurement error is a maximum of 2[K]. The error of the chamber volume measurement error is 1[%]. The error of the inlet volumetric flow rate is a maximum of 3[%]. As a result, the generated flow rate has a maximum of 5.1[%]. Therefore, this generator has sufficient accuracy for the practical use.

EXPERIMENTAL RESULTS

Fig.8 shows the experimental results when the generated flow rate was set at $5.0\times10^{-4} + 2.5\times10^{-4}\sin\left(2\pi\,f\,t\right)$ [m^3/s] and the frequency 0.1[Hz]. From the figure, the target flow rate and the generated flow rate show good agreement. Also, the measured flow rate using the laminar flow meter and the generated flow rate show good agreement. And we generated the flow for 30 minutes continuously and confirmed its effectiveness. Fig.9 shows the experimental results at the frequency of 1[Hz]. Fig.10 shows the experimental results at the frequency of 30[Hz]. From these results, it could be confirmed that the target flow rate and the generated flow rate show good agreement. On the other hand, it can be seen that there is a difference between the generated flow rate and the measured flow rate using the laminar flow meter, when the frequency is 30[Hz]. This is because of the characteristics of the laminar flow meter [3].

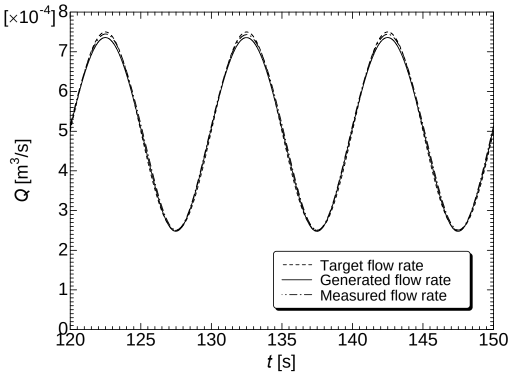

Fig.8 Generated oscillatory flow at 0.1[Hz]

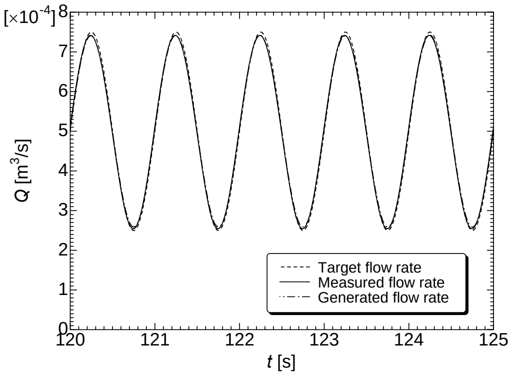

Fig.9 Generated oscillatory flow at 1[Hz]

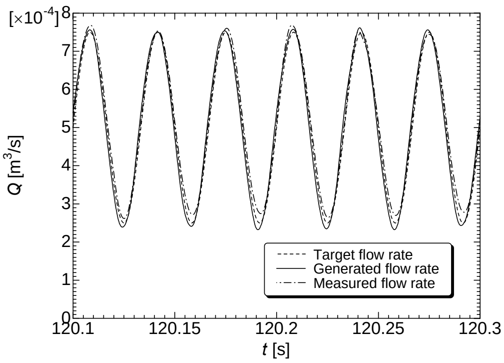

Fig.10 Generated oscillatory flow at 30[Hz]

CONCLUSIONS

In this research, a continuous flow generator for gases was developed. Then, the performance of the generator was evaluated experimentally using a laminar flow. As a result, we confirmed that this generator could generate the oscillatory flow up to the frequency of 30[Hz]. Moreover, the uncertainty due to temperature change in the chamber was investigated theoretically. Finally, we confirmed that the generator could generate the target flow continuously for 30 minutes.

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