Flow Characterization of a Piezo-Electric High Speed Valve

T. Takiya*, N. Fukuda*, M. Yaga and M. Han*****
*(Hitachi Zosen Corporation, Osaka 551-0022, Japan)
** (Department of Mechanical Systems Engineering, University of the Ryukyus, Okinawa 903-0213, Japan)
*** (Department of Materials Science and Engineering, Nanjing University, Nanjing 210093, China)

ABSTRACT

Injecting a gas into fusion reactors or semiconductor manufacturing systems, one has to quickly control the flow rate by a piezoelectric valve. In order to construct a gas injection system with high speed valves in the future, performance tests have been conducted on a commercial piezoelectric valve. An orifice flowmeter for measuring time average flowrate and a hot wire anemometer for instantaneous flowrate were manufactured. The total flow coefficient of the orifice flowmeter was obtained experimentally under a low pressure of a 10^{-2} Pa and a low flowrate of a few mg/s, although they are smaller than the values specified by Japanese Industrial Standards. It is found that the hot wire anemometer installed downstream in the vicinity of the valve is suitable for detecting the change in flowrate with the response time of less than 1 ms.

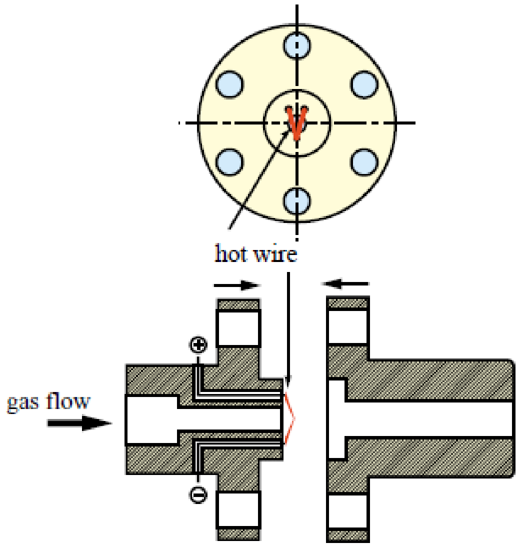
Keywords - **Compressible Flow, Flow Rate, Hot Wire Anemometer, Orifice Flowmeter, Piezoelectric Valve, Pipe Flow**

I. INTRODUCTION

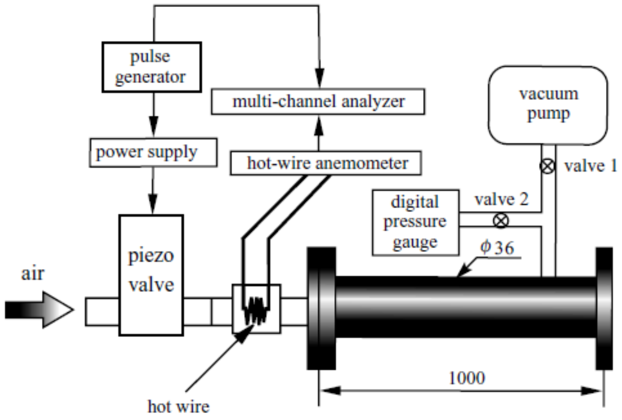
In the large helical-flow device of a fusion reactor or the gas supply device of a semiconductor manufacturing facility, it is required that various types of gases be injected into the devices under vacuum and rapidly mixed up to a specified component ratio[1][2][3]. To provide a solution for the requirement, a piezoelectric valve has been generally used to control flowrate of each component of the gas in such devices. However, because of the hysteresis inherent of piezoelectric elements, the valves are not suitable for regulating flowrate by means of ordinary feedback control; PWM (Pulse Width Modulation) control is, therefore, used often as a substitute[4][5]. Before any sort of practical application using a piezoelectric valve with the PWM control, it is necessary to investigate the basic characteristics of a single pulse flow discharged from the valve. Moreover, in order to control flowrate in real-time using a piezoelectric valve, a high speed flowmeter is needed to spontaneously monitor flowrate. Although there is a JIS(Japanese Industrial Standards)-conforming orifice flowmeter as a possibility, the discharged flow from the piezoelectric valve is so infinitely minute that the JIS flowmeter would be unsuitable for the situation. On the other hand, a hot wire anemometer might be a good choice as a flowmeter because of its higher response. But, it has yet to be ascertained whether today's commercially available hot wire anemometers are applicable to flows under vacuum condition. We made prototypes of each an orifice flowmeter and a hot wire anemometer, to measure time-averaged flowrate and instantaneous flowrate respectively, with the ultimate objective of using them as practical sensors in future control systems. We also investigated flowrate characteristics of a commercially available piezoelectric valve using the prototype flowmeters, and verified the applicability of the two prototypes as flowrate monitors.

II. EXPERIMENTAL

Figure 1 shows a schematic view of the experimental apparatus for measuring the one pulse-averaged flowrate and instantaneous flowrate of a piezoelectric valve. An enlarged drawing of the hot wire anemometer is also indicated in the same figure. The piezoelectric valve is a commercial model, which has a maximum flowrate of 20 ℓ/min in high-purity nitrogen gas equivalent. High voltage is imposed on the piezoelectric valve by a dedicated power driver whose control voltage is supplied from a pulse generator. The entrance of the piezoelectric valve is open to the atmosphere, while the exit is directly connected to a hot wire anemometer of constant temperature type we made by ourselves. The output signal from the controller of the hot wire anemometer is transmitted to a multi-channel data analyzer along with the input signal from the pulse generator. The hot wire anemometer is connected further downstream to a vacuum chamber. The vacuum chamber is a stainless steel tube of 1000 mm in length and 36 mm in inner diameter, and has a port located 200 mm upstream from its end flange. The port is connected to a vacuum pump and a vacuum gauge via valve 1 and valve 2, respectively.



(a) hot wire anemometer



(b) measuring system for the piezo-valve performance

Fig.1 Schematic of Apparatus for Measuring Flow Rates Resulted from the Pulsation of the Piezoelectric valve

Figure 2 shows a schematic view of the experimental setup used to measure the time-average flowrate of the piezoelectric valve. In this setup, the exit of the valve is connected to a vacuum chamber in which an orifice flowmeter with D•D/2 tap is installed at a distance downstream of the piezoelectric valve. The vacuum chamber is shaped like a tube 1600 mm long and 70.0 mm in diameter, while the orifice diameter of the flowmeter is 5.0 mm. In order to measure the pressure difference between the upstream and downstream sides of the orifice, a digital pressure gauge is installed. Another pressure gauge is also embedded to measure pressure upstream of the orifice.

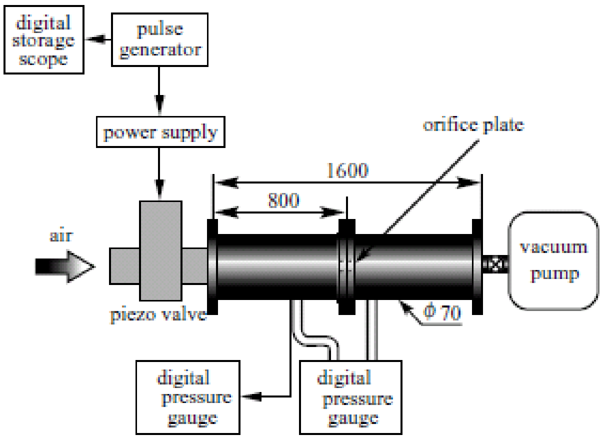


Fig.2 Schematic Apparatus for Measuring Flow Rates with the Provided Orifice Flowmeter

III. RESULTS AND DISCUSSION

Experimental results obtained by using the above mentioned setup are discussed in section Ⅲ. The threshold voltage to operate the piezoelectric valve, the critical pulse width to completely open and flow gas through the valve, the total flow coefficient to be modified for our experimental conditions and the validity of the prototype of hot-wire anemometer are explored with experimental data in the following sections.

Ⅲ-1 Basic Characteristics of the Piezoelectric Valve

Figure 3 shows the typical static flow characteristics of a piezoelectric element. Because of the hysteresis inherent to the elements, the relationship of the valve aperture to the applied voltage is generally not unique.

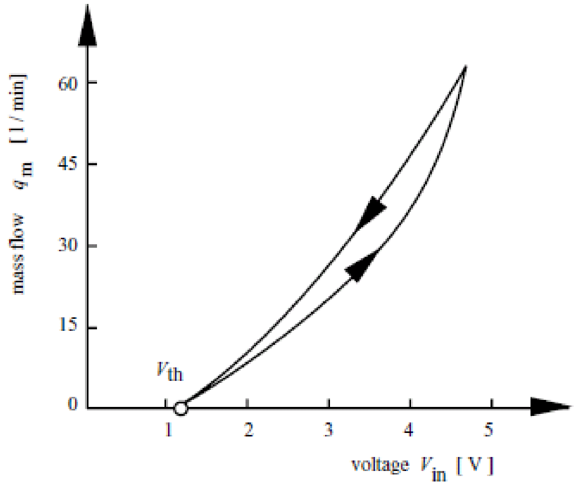
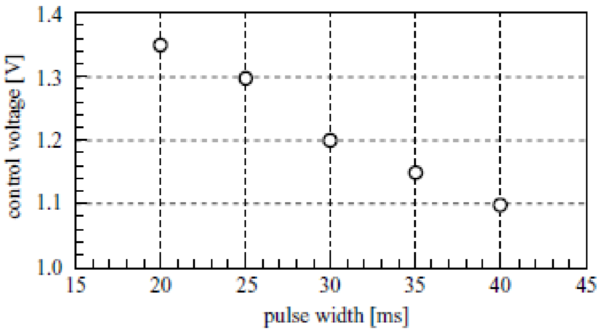
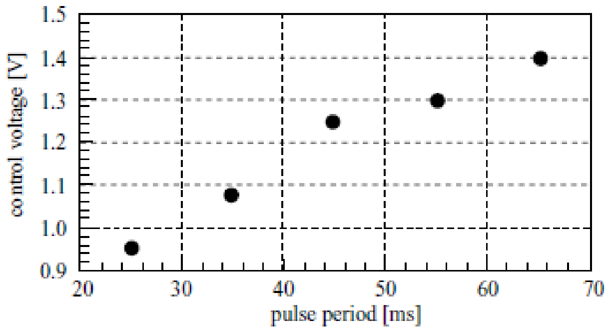


Fig.3 Variation in Mass Flow Rate against Control Voltage



(a) dependence of pulse width (pulse period: 55ms)



(b) dependence of pulse period (pulse width: 25ms)

Fig.4 Pulse width and period dependence on the threshold voltage of the piezoelectric valve

For a piezoelectric valve, there is a minimal voltage required to actually operate the valve, that is, a threshold voltage. Measuring the dependence of the pulse width and the pulse period on the threshold voltage E_{th} (control voltage) by using the hot wire anemometer, as shown in Fig.4, we found that E_{th} decreased as pulse width increased in the case of a constant period, as was the case with the control voltage in Fig. 4(a). On the other hand, with a constant pulse width, threshold voltage E_{th} increased as the period became longer in Fig. 4(b). In order to come up with a piezoelectric valve for PWM control, the next step is to learn the flowrate feature for a single pulse operation. The vacuum chamber was initially depressurized to an order of 10^{-2} Pa and then pressure in the chamber was gradually raised as the piezoelectric valve was operated by single pulse-driving. The relationship between pressurization rate $\Delta p/\Delta t$ and mass flowrate Q is expressed with the following equation,

$$Q = \frac{V}{RT}\frac{\Delta p}{\Delta t} \tag{1}$$

Here, V is the volume of the vacuum chamber, R the gas constant of air and T the air temperature. Figure 5 shows the flowrate, which is converted from the pressure increase detected by a Pirani gauge when pressure equilibrium was reached, against the pulse width of the pulse generator. The flowrate is actually calculated from the average pressure increase which is obtained from a 10 times pulse discharge. The variable Δt means the pulse width, so the flowrate shown here is given as the time averaged flowrate for one pulse discharging. From the Fig.5, it can be understood that the mass flowrate increases as the voltage applied to the piezoelectric valve increases under a constant pulse width. When the pulse width was varied under the condition of a constant control voltage, the mass flowrate increased as pulse width became longer in the range of more than 20 ms. It is also found that the mass flowrate becomes nearly constant above the pulse width of 70ms in case of the control voltage of 2.5 V.

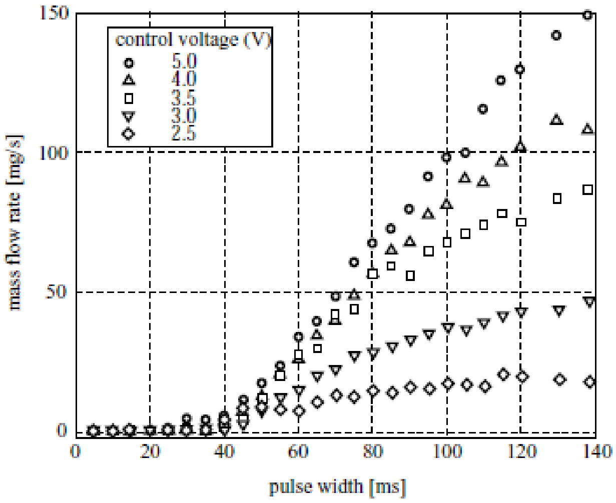


Fig.5 Mass flow rates of air versus pulse width of control voltage

This fact would suggest that it takes some little time occupied to obtain the expected valve aperture corresponding to a given applied voltage. And also, when even the control voltage is more than 3.0 V, the graph shows a tendency that flowrate reaches at a constant value for a certain pulse width. From these facts, it can be proved that the critical pulse width which makes flowrate constant depends on the control voltage and that the higher the control voltage is, the longer the critical pulse width is. We further learned that the flowrate is almost zero, regardless of the control voltage, when the pulse width of the control voltage is shorter than 20 ms. This is attributed to the fact that the variations in flowrate of the gas discharged from the valve are too small to detect the pressure by the Pirani gauge.

Ⅲ-2 Orifice Flowmeter

The relationship between the mass flowrate *Q* and differential pressure *Δp* can be expressed as the following equation

$$Q = \eta A\sqrt{2\rho_1 \Delta p} \qquad (2)$$

Here, ρ_1 is the gas density upstream of the orifice, *A* the area of orifice aperture and η the total flowrate coefficient of the orifice. The coefficient η is designated by the flowrate coefficient for incompressible flow, *C*, and the compensation coefficient of the gas, ε, as follows:

$$\eta = \frac{C}{\sqrt{1-\beta^4}}\varepsilon \qquad (3)$$

Where β is the ratio *d*/*D*, in which *d* is the orifice diameter and *D* is the tube inner diameter. In the standard, JIS Z9762, both the coefficients *C* and ε are defined in detail as the function of β, and an application range of the orifice diameter and Reynolds number are also specified. From the viewpoint of the application ranges, the manufactured flowmeter is no adopted for the standard. Also, if we compute the compensation coefficient by the equation provided by JIS using the experimental data obtained here, we find it would be between 0.98122 and 0.99855. However, being calculated by substituting the experimental data into Eq. (2), the actual total flow coefficient is considerably lower than these values. So it is plausible that the actual phenomena are greatly affected by gas compressibility because of reduced orifice diameter.

Figure 6 shows the relationship between the actual total flow coefficient and the pulse width using pulse voltage as a parameter. Though the coefficient of flowrate is dependent on both the pulse width and pulse voltage, the total flowrate coefficient changes monotonically for the most part when pulse voltage is constant. Accordingly, by experimentally investigating the relationship between pulse width and this total flowrate coefficient in advance, it is possible to measure minute and low pressure flowrates using our test apparatus.

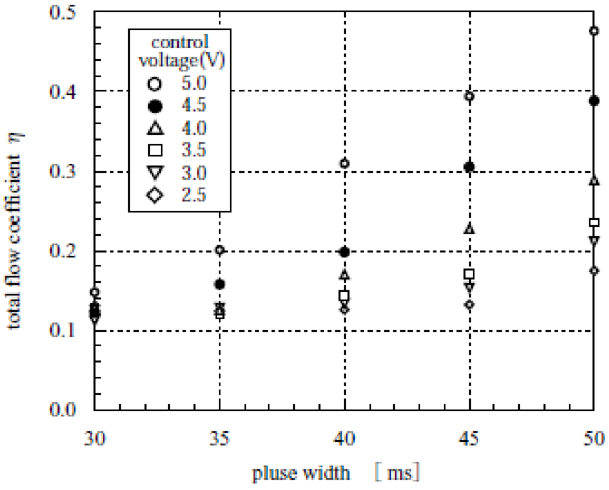


Fig.6 Total flow coefficients versus pulse width of control signal

Ⅲ-3 Flowrate Measurement Using a Hot Wire-Anemometer

Flowrate can be controlled to some extent using an orifice flowmeter, but it is necessary to monitor instantaneous flowrate for high speed response control. A hot wire anemometer is a suitable sensor for this purpose. In this research, the hot wires were connected downstream near to the piezoelectric valve and tests were made to see if we could measure instantaneous flowrate. The hot wires were made of platinum and mounted in the V-shape inside an electrically insulated tube of a 5 mm inner diameter as shown in Fig.1. The heat *H* radiated from the hot wires to the surrounding medium can be expressed using King's equation [6] as follows.

$$H = \left(a + b\sqrt{U}\right)\left(T_W - T_f\right) \tag{4}$$

Here, *a* and *b* are constants, while *U* is the averaged flowrate in cross-section, T_w the temperature of the hot wires and T_f the temperature of the medium. In general, the sensitivity to changes in resistance in the hot wires is affected by the averaged flowrate, but it has been electrically linearized by using Eq. (4).

The flowrate is obtained by multiplying the cross-sectional volume by the average flowrate. The time constant of the flowmeter *M* can be estimated from the following equation [7]:

$$M = \frac{mc_v \Delta R}{\alpha I^2 R_f^2} \tag{5}$$

Here, *m* is the mass of the hot wires, c_v the specific heat of the hot wires, R_f the resistance of the hot wires at the medium's temperature, *ΔR* the deviation in resistance from R_f caused by the flow, *α* the temperature coefficient of resistance, and *I* the electric current flowing through the hot wires. Substituting representative values for a platinum wire of 30 µm in diameter, the time constant results in approximately 0.25 ms.

Figure 7 shows an example readout of instantaneous flowrate measured at a pulse period of 25 ms and pulse width of 15 ms. No delay time of sensor response can be recognized at this time scale, therefore the chart would appear to exactly reflect the change in flowrate based on the piezoelectric valve operation. As control voltage becomes higher, that is, as flowrate becomes higher, short-period tiny variations are seen in the detected signal, which are probably due to turbulence in the flow. The graph certainly indicates that the response time of the hot wire is within the 1 ms. Although the changes in the graph shows a 25 ms period flow repeatedly discharged by the valve, an offset signal remains in the graph, never returning to zero. This indicates that the piezoelectric valve cannot operate follow the fast movement of the input signal.

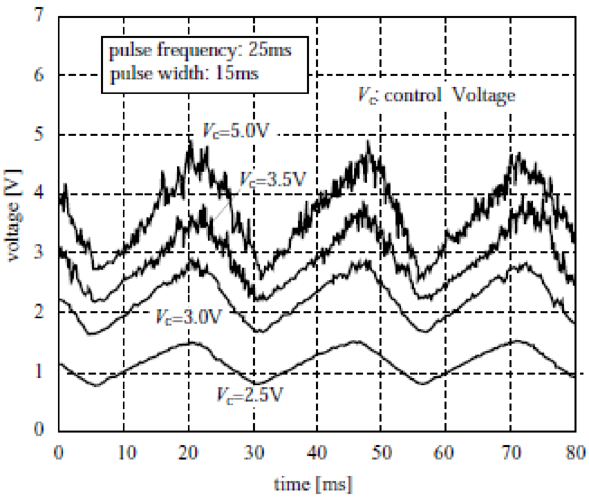


Fig.7 Flow rate variances measured by the hot-wire anemometer

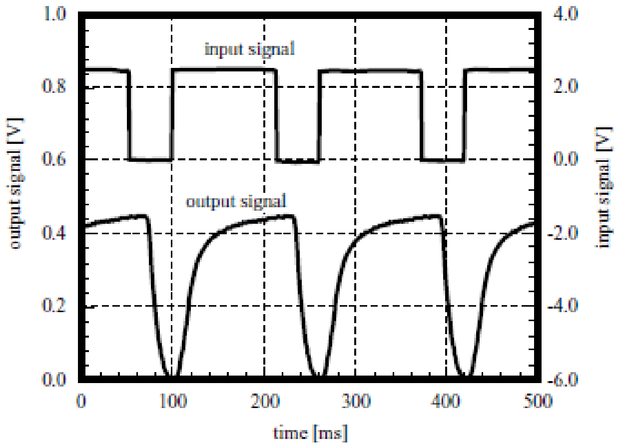


Fig.8 Response of the piezo-electric valve estimated by the relation between an input signal of the pulse generator and an output signal of the hot-wire anemometer

Figure 8 shows the input control voltage and output signal from the hot wire anemometer for a control voltage of 2.5 V, pulse period of 160 ms and pulse width of 110 ms. The output signal exhibits a delay time of approximate 70 ms with respect to the input voltage during the valve opening. As already described in section Ⅲ-1, a constant flowrate in measuring the flowrate of a single pulse could not be obtained with a shorter pulse width, because of valve operation delay. According to Fig.5, the pulse width for obtaining the constant flowrate at a control voltage of 2.5 V was 70 ms at minimum. The minimum pulse width in the previous case, 70 ms, is nearly consistent with the value as detected by the hot wire anemometer, telling us that flowrate can be correctly measured using a hot wire anemometer. As a result, it was found that the prototype hot wire anemometer of ours could sufficiently monitor flowrates of a piezoelectric valve in the circumstances of the minute and low pressure.

IV. CONCLUSION

In this work, we investigated the characteristics of a piezoelectric valve at low flowrate and low pressure, with the ultimate goal of designing a high speed gas supply control system for use in fusion reactors and semiconductor manufacturing systems. As a part of the work, we built prototypes of an orifice flowmeter and a hot wire anemometer to use as the sensors in the eventual control system.

The threshold voltage of the piezoelectric valve was firstly investigated by changing the pulse width and the pulse period. As a result, it was found that the threshold voltage decreases with increasing of pulse width and increases with increasing of pulse period.

Secondly, the averaged flowrate of single pulse was investigated by changing the pulse width and the control voltage. As a result, it was found that there is a critical pulse width which makes the flowrate constant and then keeps the constant level, and that the critical pulse width becomes larger with increasing of the control voltage. That is to say, the time needed to completely open the piezoelectric valve depends on the control voltage, with the higher the voltage, the longer the time needed. When control voltage is 2.5 V, it takes approximately 70 ms.

Thirdly, it is possible to measure time-average flowrate using the prototype orifice flowmeter under the conditions of a low pressure of an order of 10^{-2} Pa and a low flow rate of a few tens mg/s. However, because this type of flowmeter did not conform to JIS, the total flowrate coefficients were modified and actually identified through the present experiments.

The prototype of hot wire anemometer were finally built, capturing suitably the changes in flowrate under our experimental conditions and proving effective toward real-time measurement in the response time of less than 1 ms.

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