DETERMINATION OF FLOW CHARACTERISTICS OF PNEUMATIC VALVES USING ISOTHERMAL CHAMBER

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ABSTRACT

In this paper, alternative methods for obtaining the sonic conductance and the critical pressure ratio are presented. The methods use the isothermal chamber that can almost realize isothermal condition due to larger heat transfer area and heat transfer coefficient by stuffing metal wire in it. Using this chamber, the sonic conductance and the critical pressure ratio are obtained by measuring only pressure in the chamber. With this method, it takes only some seconds and costs lower energy than the ISO 6358 procedure. Furthermore, the authors have investigated the effect of temperature change in the isothermal chamber. In the proposed charge method, temperature change affects pneumatic characteristics measurement not so much. On the other hand, the proposed discharge method is easy to be influenced by temperature change. However, the discharge method has the merits not to depend on the dynamic characteristics of the regulator and to simplify the measurement system.

KEY WORDS

Pneumatics, sonic conductance, critical pressure ratio, isothermal chamber, charge method, discharge method

1. Introduction

According to the ISO standard (ISO 6358, 1989)¹⁾ and JIS (JIS B 8390, 2000)²⁾, the sonic conductance and the

critical pressure ratio are used to present the flow characteristics of the pneumatic components. The sonic conductance and the critical pressure ratio is calculated from the mass flow rate through the test valve and

differential pressure across the valve, as indicated by ISO. This method takes long time to take flow characteristics of steady state flow and costs much energy to keep flowing air. On the other hand, in the case of charge or discharge a chamber with air, it costs lower energy and takes only some seconds. Therefore, if it is possible to obtain the sonic conductance and the critical pressure ratio from the pressure response of the chamber, it is simple and an energy saving measure method.

Many pressure response methods^{3) - 7)}, obtaining method of the sonic conductance and the critical pressure ratio from pressure response, were proposed. Take the case of using normal chamber, the temperature of chamber air decreases about 40[K] during discharge. Therefore, it is difficult to measure the sonic conductance and the critical pressure ratio correctly. However, when the isothermal chamber³⁾ is used, the air temperature in the chamber drops only about 1.5[K]. Because of this temperature change, it can be assumed that air state in isothermal chamber is almost isothermal condition. Consequently, the sonic conductance and the critical pressure ratio are obtained from only pressure response in the isothermal chamber^{4) 5)} accurately. In this study, charge, discharge method and the effect of temperature change is examined.

2. Nomenclature

b	:Critical pressure ratio	
C	:Sonic conductance	[m ⁴ ·s/kg]
G	:Mass flow	[kg/s]
P	:Pressure	[Pa]
R	:Gas constant	[J/(kg·K)]
t	:Time	[s]
V	:Volume of chamber	[m ³]
θ	:Temperature	[K]
ρ	:Air density	[kg/m ³]
K_p	:Ratio of initial pressure and atmosphere pressure	

Subscripts

0	:Normal condition
a	:Atmosphere
s	:Supply
b	:Critical state
c	:Choke state
i	:Initial state
f	:Finished state

3. Measurement method of flow characteristics in ISO

According to the ISO standard, the sonic conductance and the critical pressure ratio is calculated from the mass flow rate through valves and differential pressure across valves. Fig.1 shows the experimental apparatus of ISO method. It consists of an air supply, a pressure regulator, pressure sensors, a test component, a flow control valve and a flow meter. Measurement points are 5 points, 100% of mass flow rate at the time of choke, 80%, 60%, 40%, and 20%.

When the critical pressure ratio is calculated with this method, it is confirmed that it is sometimes in disagreement with measured flow characteristics. Therefore, in this study, to obtain the sonic conductance and the critical pressure ratio near actual flow characteristics, the modified ISO method is used.

In the modified ISO method the sonic conductance is calculated from mass flow rate at choked state. The critical pressure ratio is obtained, when the square error is minimum.

Fig. 1 Experimental apparatus of ISO method

4. Measurement method using isothermal chamber

In this paper, the charge method and the discharge method are defined as the dynamic measurement methods of flow characteristics using isothermal chamber. The charge method was suggested by us⁴⁾. In addition, the discharge method was suggested by Zhang et al⁵⁾. Derivation of these basic formulas and measurement methods are shown below.

4.1 Derivation of a basic formula and a measurement method during charge

The experimental apparatus of the charge method is shown in Fig. 2. It consists of an air supply, a pressure

regulator, a sub tank, a solenoid valve, an isothermal chamber and a pressure sensor.

When an isothermal chamber is used, the pressure response equations can be derived. It is reasonable to suppose that the air condition in the chamber is isothermal condition. Accordingly, Eq. (1) is obtained from the state equation of ideal gases.

$$V \frac{dP}{dt} = GR\theta \quad (1)$$

The flow rate equation through a pneumatic valve is written as the following two formulas.

1) The case of choke flow

$$G = C\rho_0 P_s \sqrt{\frac{\theta_0}{\theta}} \quad (2)$$

2) The case of subsonic flow

$$G = C\rho_0 P_s \sqrt{\frac{\theta_0}{\theta}} \sqrt{1 - \left(\frac{\frac{P}{P_s} - b}{1 - b} \right)^2} \quad (3)$$

Pressure response equations are deduced from Eq. (1), (2) and (3).

1) The case of choke flow

$$P = P_a + \frac{C\rho_0 P_s}{V} R\sqrt{\theta_0 \theta_a} t \quad (4)$$

2) The case of subsonic flow

$$P = P_s (1 - b) \cdot \sin \left(\frac{C\rho_0}{(1 - b)V} R\sqrt{\theta_0 \theta_a} (t - t_b) \right) + bP_s \quad (5)$$

The sonic conductance and the critical pressure ratio are obtained by fitting of experimental pressure response with theoretical equations (4) and (5). The procedure is explained as follows. Comparing measured flow characteristics with theoretical formula, the square error of these values is calculated. When the error gets the minimum value, the sonic conductance and the critical pressure ratio will be identified values.

Fig.2 Experimental apparatus of charge method

4.2 Derivation of a basic formula and a measurement method during discharge

Fig.3 shows the experimental apparatus of discharge method. It consists of an air supply, a pressure regulator, a solenoid valve, an isothermal chamber and a pressure sensor.

In discharge processes, it is possible to obtain the sonic conductance and the critical pressure ratio under the isothermal condition. The procedure to measure these parameter is explained as follows. The critical pressure ratio is calculated from the ratio of the critical point time and the finish time of discharge. Initial pressure ratio is defined as $K_p = \frac{P_a}{P_i}$. Then the ratio of critical point time t_b to discharge finish time t_f is written as Eq. (6).

$$\frac{t_b}{t_f} = \begin{cases} \frac{\ln \frac{b}{K_p}}{\ln \frac{b}{K_p} + \frac{1-b}{\sqrt{1-2b}} \ln \frac{b}{1-b-\sqrt{1-2b}}} & 0 \leq b < \frac{1}{2} \\ \frac{\ln \frac{1}{2K_p}}{\ln \frac{1}{2K_p} + 1} & b = \frac{1}{2} \\ \frac{\ln \frac{b}{K_p}}{\ln \frac{b}{K_p} + \frac{1-b}{\sqrt{2b-1}} \left(\frac{\pi}{2} - \sin^{-1} \frac{1-b}{b} \right)} & \frac{1}{2} < b \leq 1 \end{cases} \quad (6)$$

Eq. (6) is only correct in critical point. In addition, it is not correct even if it substitutes a pressure ratio and a time of sampling points expect a critical point. Therefore, the pressure ratio and time are applied to b and t_b of Eq.(6) one by one, and then it turns out that the pressure ratio is identification value of critical pressure ratio when Eq. (6) is correct. The sonic conductance is obtained from Eq. (7) with critical point time t_b and critical pressure ratio b .

$$C = \frac{V}{Rt_b \rho_0 \sqrt{\theta_0 \theta}} \ln \frac{b}{K_p} \quad (7)$$

Fig.3 Experimental apparatus of discharge method

5. Temperature change

The temperature change of an isothermal chamber depends on the stuffing metal wire diameter. In this experiment, the steel wool that diameter is about $25\ \mu\text{m}$ and the copper wire that diameter is about $100\ \mu\text{m}$ were used. In order to investigate the degree of the temperature change by the difference in these metal wires, the temperature is calculated by the stop method⁸⁾, and Fig. 4 shows these temperature changes.

When the steel wool is used, the temperature drops about 1.5 [K] in the worst state, and temperature recovers to room temperature quickly. On the other hand, when the copper wire is used, temperature change is about 3 [K]. Compared with the steel wool, the temperature is changing gently.

Fig. 4 Temperature change of isothermal tank

6. Experimental results of measurement method

The sonic conductance and the critical pressure ratio of valves were obtained with the measuring methods

described previously. These results are shown in Table 1 and 2. Table 1 is the case of the chamber stuffed with the steel wool, and Table 2 is the case of the chamber stuffed with the copper wire.

6.1 Experimental result of stuffing steel wool

The temperature of stuffing steel wool changes less than the case of copper wire. For this reason, it becomes closer to isothermal condition than the copper wire, and it is likely that the error of temperature change decreases. As shown in Table 1, in charge method, the sonic conductance is less than 2% of accuracy, and critical pressure ratio is about 0.08 errors at worst. And in discharge method, the sonic conductance is less than 2% of accuracy, and critical pressure ratio is about 0.09 error at worst.

It may be appeared that the measurement error percentage of the critical pressure ratio is higher. However, the influence of the error of the critical pressure ratio on the flow characteristic is small. For example, the difference of the error of the flow rate between $b=0.3$ and $b=0.4$ is about 4.6%. Therefore, if the error percentage of the critical pressure ratio will be high, from viewpoint of flow characteristics, the error of flow rate is not so much. Moreover, it is difficult to determine a critical pressure ratio as a value, because of the error for the ellipse approximation of flow characteristics. For this reason, these experimental results can be said to be quite appropriate like Fig.5. Comparing the result of the charge method with the discharge method, the result of the charge method is better than the discharge method. The reason is that the temperature change during discharge is more than during charge. Therefore, if same isothermal chamber is used, the measurement accuracy of the discharge method is inferior to that of the charge method.

6.2 Experimental result of stuffing copper wire

When the copper wire is used, sonic conductance is less than 2% of accuracy, and critical pressure ratio is less than 10% of accuracy except for valve A. The error of critical pressure ratio of valve A is as large as about 14%, because its critical pressure ratio is smaller than the others. Compared to the steel wool, the copper wire is not so good isothermal condition. Nevertheless, the accuracy of sonic conductance and critical pressure ratio using the

Table 1. Experimental result with chamber filled steel wool

Valve	Sonic conductance 10^{-9} [$\text{m}^4/(\text{sPa})$]			Critical Pressure Ratio		
	Modified ISO method	Charge method	Discharge method	Modified ISO method	Charge method	Discharge method
A	4.84	4.81	4.85	0.15	0.23	0.18
B	8.42	8.24	8.59	0.33	0.37	0.21
C	2.76	2.76	2.80	0.35	0.41	0.22
D	5.61	5.58	5.72	0.39	0.45	0.33

Table 2. Experimental result with chamber filled copper wire

Valve	Sonic conductance 10^{-9} [$\text{m}^4/(\text{sPa})$]			Critical Pressure Ratio		
	Modified ISO method	Charge method	Discharge method	Modified ISO method	Charge method	Discharge method
A	4.84	4.87	5.55	0.15	0.18	0.18
B	8.42	8.32	–	0.33	0.34	–
C	2.76	2.78	–	0.35	0.38	–
D	5.61	5.54	5.73	0.39	0.40	0.32

copper wire is better than the steel wool. This reason is that the influence of temperature change compensate a measurement tendency of the critical pressure ratio. In the case of using the steel wool, there is a tendency to obtain critical pressure ratio highly and to obtain sonic conductance lowly. However, in the case of using the copper wire, the temperature change counteracts these tendency. Accordingly, the measurement result of using the copper wire case is better than case of using the steel wool.

In the discharge method, the sonic conductance and the critical pressure ratio of Valves A and D can be obtained, but the error of them is not so a little. Moreover, they could not be calculated in Valves B and C. This reason is that the change of the critical pressure ratio to the pressure response during discharge is small. Accordingly, the change of the pressure response affects the critical pressure ratio greatly. In order to show it, the calculated result of the pressure response during charge and discharge is shown in Fig. 6 and 7. Fig. 6 shows the pressure response during charge. Fig. 7 shows pressure response during discharge. Comparing these graphs, it turns out that change of the pressure response during discharge is smaller than during charge. The temperature change does influence equally to both pressure response of charge and discharge. Therefore, the discharge method is easy to be influenced by temprerature changes.

The other reason is that the temperature change during discharge is more than during charge. Therefore, In the case of using same isothermal chamber, the measurement accuracy of charge method is better than that of discharge method.

In charge method, it is possible to obtain the sonic conductance and the critical pressure ratio when copper wire is used. But In discharge method, high isothermality is requested.

Fig. 5 Flow rate of valve D (ANR)

Fig. 6 Pressure response of charge process

Fig. 7 Pressure response of discharge process

7. Conclusions

- 1) Using isothermal chamber, the sonic conductance and the critical pressure ratio can be obtained. Moreover, from the viewpoint of time or consumption energy and measurement time, the method is suitable for practical use.
- 2) Charge method has robustness to temperature change of isothermal chamber. On the other hand, discharge method is easy to be affected by temperature change.
- 3) The temperature change affects the measurement accuracy of discharge method. Therefore, the performance of isothermal chamber is important.

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