STUDY ON MEASUREMENT METHOD OF FLOW-RATE CHARACTERISTICS OF PNEUMATIC SOLENOID VALVE

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ABSTRACT

The test method for the flow characteristics of a pneumatic solenoid valve is specified in ISO 6358. In this standard, the flow characteristics are shown by the sonic conductance and the critical pressure ratio, and these are calculated from the flow rate, the pressure and the temperature of the air that passes the solenoid valve. When the flow characteristics of a large solenoid valve are measured by this method, a large compressor and a large flow meter are required. Therefore the power consumption and the generating noise become very large. In this study, a test method using the small and low noise test equipment is developed. In this method, at first the tank connecting to the solenoid valve is evacuated, and then the air is charged in the tank through the solenoid valve from the atmosphere. By using the pressure and temperature in this tank, the sonic conductance and the critical pressure ratio are evaluated.

KEY WORDS

Pneumatic solenoid valve, Charge method, Polytropic change, Sonic conductance, Critical pressure ratio

NOMENCLATURE

b : Critical pressure ratio [pure number]
 C : Sonic conductance [$\text{m}^4/\text{s}\cdot\text{kg}$]
 M : Mass of air [kg]
 n : Polytropic index [pure number]
 P : Absolute pressure [Pa]
 q_v : Volume flow rate at standard reference conditions(ANR) [m^3/s]
 R : Gas constant [$\text{J}/(\text{kg}\cdot\text{K})$]
 t : Time [s]
 T : Absolute temperature [K]
 V : Volume [m^3]
 ρ : Mass density [kg/m^3]

INTRODUCTION

The test method for the flow characteristics of a pneumatic solenoid valve is specified in ISO 6358 [1]. In this standard, the flow characteristics of a solenoid valve are shown by the sonic conductance and the critical pressure ratio, and these are calculated from the flow rate, the pressure and the temperature of the air that flows through the solenoid valve. This test method is normally called the flow method. When the flow characteristics of a large solenoid valve are measured by this method, a large compressor and a large flow meter are required. Therefore the power consumption and the generating

noise that arises during the test become very large. A test method that can obtain the critical pressure ratio and the sonic conductance by using the small and low noise test equipment is developed [2]. In this test method, at first the tank connecting to the solenoid valve that is to be measure for the flow characteristics is evacuated, and then the air is charged in the tank through the solenoid valve from the atmosphere. By using the pressure and the temperature in this tank, the sonic conductance and the critical pressure ratio of the solenoid valve are evaluated. In this report, this test method is named the charge method.

FUNDAMENTAL EQUATIONS

Figure 1 shows the schematic diagram of the charge method. The change of state of the air in the tank is considered when the air is charged to the tank in vacuum state through the tested solenoid valve from the atmosphere. In this figure, P is the absolute pressure of the air in the tank [Pa], V is the volume of the air [m^3], T is the absolute temperature of the air [K], M is the mass of the air [kg], q_v is the volume flow rate at standard conditions [m^3/s], C is the sonic conductance [$\text{m}^4 \cdot \text{s}/\text{kg}$], b is the critical pressure ratio [pure number].

Figure 1 Schematic diagram of charge method

Under charging, the air with the mass M in the tank is compressed by the air of mass dM that flows in the tank during the time dt , and the pressure P increases by dP , and the volume V decreases by dV . If the change of state of the air in the tank is assumed polytropic change, the next relational expression can be established between the pressure dP and the volume dV .

$$VdP = nPdV \quad (1)$$

Where, n is the polytropic index. Since the volume of the air in the tank V is equal to the internal volume of the tank V_0 , the following equation can be obtained.

$$dV = \frac{V_0}{nP} dP \quad (2)$$

Now, it is assumed that the air is the ideal gas, and that the air flows through the solenoid valve from the atmosphere in the space volume dV generated by compressing the air in the tank and rests. In such

occasions, the temperature of the air that is filled in the space volume dV equals the room temperature [4]. When the minute term of high order is neglected, the state equation of the air that is filled in the space volume dV can be expressed as

$$PdV = RT_1 dM \quad (3)$$

Where, T_1 is the room temperature, and R is the gas constant of air. From the continuity equation, the following equation can be obtained.

$$q_v = \frac{1}{\rho_0} \frac{dM}{dt} = \frac{RT_0}{P_0} \frac{dM}{dt} \quad (4)$$

Where, ρ_0 is the mass density of air at the standard reference conditions (ANR), i.e. the absolute temperature $T_0=293.15\text{K}$, the absolute pressure $P_0=100\text{kPa}$, the relative humidity 65%.

From Eq.(2), Eq.(3) and Eq.(4), the following equation is given,

$$q_v = \frac{V_0}{nP_0} \frac{T_0}{T_1} \frac{dP}{dt} \quad (5)$$

For choked flow, i.e. when $P/P_1 \leq b$

For this case, the volume flow rate q_v that flows through the solenoid valve is shown by the following equation according to ISO 6358.

$$q_v = CP_1 \sqrt{\frac{T_0}{T_1}} \quad (6)$$

Where, P_1 is the upstream absolute pressure of the solenoid valve, T_1 is the upstream absolute temperature. From Eq.(5) and Eq.(6), the following equation is given,

$$\frac{dP}{dt} = \frac{nCP_0P_1}{V_0} \sqrt{\frac{T_1}{T_0}} \quad (7)$$

When Eq.(7) is integrated from the start time of charge ($t=0$) to the any time ($t=t$), the following equation can be obtained.

$$P = \frac{nCP_0P_1}{V_0} \sqrt{\frac{T_1}{T_0}} t + P_i \quad (8)$$

Where, P_i is the initial pressure in the tank and P is the pressure at the time t . Eq.(8) shows that the time variation of pressure P is the straight line for the choked flow. And, the sonic conductance C is shown by the following equation, when Eq.(7) is rearranged.

$$C = \frac{V_0}{nP_0P_1} \sqrt{\frac{T_0}{T_1}} \frac{dP}{dt} \quad (9)$$

Then, the sonic conductance C can be calculated using the value of gradient dP/dt in the straight section for the choked flow of the measured pressure change.

For subsonic flow, i.e. when $P/P_1 > b$

For this case, the volume flow rate q_v that flows through the solenoid valve is shown by the following equation according to ISO 6358.

$$q_v = CP_1 \sqrt{\frac{T_0}{T_1}} \sqrt{1 - \left(\frac{\frac{P}{P_1} - b}{1 - b} \right)^2} \quad (10)$$

Where, P is the downstream absolute pressure of the solenoid valve, b is the critical pressure ratio. From Eq.(5) and Eq.(10), the following equation is given,

$$\frac{dP}{dt} = \frac{nCP_0P_1}{V_0} \sqrt{\frac{T_1}{T_0}} \sqrt{1 - \left(\frac{\frac{P}{P_1} - b}{1 - b} \right)^2} \quad (11)$$

When Eq.(11) is integrated from the time ($t=t_c$) to the any time ($t=t$) and the relation of $P_c/P_1=b$ is substituted, the following equation can be obtained.

$$P = (1-b)P_1 \sin \left\{ \frac{nCP_0}{V_0(1-b)} \sqrt{\frac{T_1}{T_0}} (t-t_c) \right\} + bP_1 \quad (12)$$

Where, t_c is the time when the pressure in the tank reached the critical pressure P_c . Then the time variation of pressure P is the sine curve for the subsonic flow.

When the values (t_n, P_n) and (t_{n+1}, P_{n+1}) are substituted in Eq.(12) and t_c is eliminated, the following equation can be obtained.

$$(1-b) \left\{ \sin^{-1} \left(\frac{\frac{P_{n+1}}{P_1} - b}{1-b} \right) - \sin^{-1} \left(\frac{\frac{P_n}{P_1} - b}{1-b} \right) \right\} = \frac{nCP_0}{V_0} \sqrt{\frac{T_1}{T_0}} (t_{n+1} - t_n) \quad (13)$$

Substituting the values (t_n, P_n) and (t_{n+1}, P_{n+1}) of two points of the measured pressure in Eq.(13) and solving this equation, the critical pressure ratio b can be obtained. Although it is difficult to obtain the analytic solution of Eq.(13), the critical pressure ratio can be easily obtained by the numerical analysis by using the off-the-shelf software. The method for obtaining polytropic index n

under charging is shown as follows. The absolute temperature at the end of charge T_f is given by the following equation [4].

$$T_f = \frac{n}{1 + \frac{P_i}{P_f}(n-1)} T_i \quad (14)$$

Where, T_i and P_i are the temperature and the pressure at the start of charge respectively, and P_f is the pressure at the end of charge. Since the value of P_i/P_f is about 0.02 for the charge method, the next approximate expression has the sufficient accuracy.

$$n = \frac{T_f}{T_i} \quad (15)$$

EXPERIMENTAL APPARATUS

Figure 2 shows the schematic diagrams of the experimental apparatus and Figure 3 is a photograph of the tested valve (50mm nominal bore) and the tank ($V_0=2209\text{dm}^3$). By connecting the tubes specified in JIS B 8390 to the inlet and outlet ports of the tested valve, the consistency with the flow method in ISO 6358 was attempted.

Figure 2 Experimental apparatus

The experimental method is shown as follows. By the vacuum pump, the gauge pressure in the tank is reduced to about -98kPa. Then, the shut-off valve connected to the vacuum pump is closed, and it is left until the pressure and the temperature in the tank become a steady state. Next, by opening the tested valve, the atmospheric air is charged in the tank, and the pressure under charging is detected by the pressure transducer and the temperature is detected by the copper-constantan thermocouple of the 0.2mm diameter. They are recorded

in the digital recorder. The mercury manometer was used for the calibration of the pressure transducer, and the atmospheric pressure was measured by the aneroid barometer.

Figure 3 Tested valve (50mm Nominal bore) and tank ($V_0=2209\text{dm}^3$)

EXPERIMENTAL RESULTS

First, the flow characteristic of the restriction (the cylindrical restriction of $D=5.18\text{mm}$ diameter and $L=5.0\text{mm}$ length) measured by the charge method is shown. The restriction does not have the control function of the flow. Then, the flow of the restriction was controlled by the tested valve H in Table 3 that has about 5 times of the sonic conductance of the restriction.

Figure 4 Pressure and temperature change in tank
Diameter of restrictor $D = 5.18\text{mm}$
 $C = 3.71\text{dm}^3/(\text{s}\cdot\text{bar})$, $b = 0.514$
 $P_1 = 101.0\text{ kPa(abs)}$, $T_1 = 292.15\text{K}$, $V_0 = 47.78\text{dm}^3$

Figure 4 shows the pressure and the temperature in the tank. Just after the start of charge, the pressure change is the straight line, and then the flow in the restriction is the

choked flow. On the way, the pressure change becomes the sine curve, and the flow in the restriction becomes the subsonic flow.

Figure 5 Straight section of pressure change

The straight section of pressure change under charging was extracted in Figure 5. From the regression formula of this straight line, the time derivative of the pressure dP/dt was obtained, and its value was 8.21kPa/s . Furthermore, the polytropic index n was obtained by Eq. (15) using the temperature at the start of charge (17.0°C) and the temperature at the end of charge (31.2°C) of the temperature change in Figure 4, and then $n=1.048$. Substituting these values in Eq.(9), the sonic conductance C was obtained, and consequently $C=3.71\text{dm}^3/(\text{s}\cdot\text{bar})$. Here, the unit of sonic conductance C is the practical unit allowed in ISO 6358. Moreover, the combination error of sonic conductance was determined by the root mean square method [1] using the actual systematic errors of the pressure, the temperature, the time, etc. and its value was 0.97% . The temperature change was measured at the position of 75mm distance from the inside wall of the tank.

Table 1 Critical pressure ratio

P/P_1 [%]	t [s]	P [bar(abs.)]	Range [%]	b [—]
90	10.24	0.9100	80~90	0.536
80	8.52	0.8075	70~80	0.513
70	7.12	0.7075	60~70	0.556
60	5.84	0.6050	50~60	0.450
50	4.60	0.5050	Mean value $b = 0.514$	

From the pressure change in Figure 4, the times and the pressures at the point of 50% and 60%, 60% and 70%, 70% and 80%, 80% and 90% of the pressure at the end of charge (the atmospheric pressure P_1) were obtained as shown in Table 1. The critical pressure ratio b was calculated by substituting these values in Eq.(13), and then the mean value of these critical pressure ratios was 0.514 .

Figure 6 Pressure - flow characteristics by flow method
Diameter of restrictor $D = 5.18\text{mm}$
 $C = 3.70\text{dm}^3/(\text{s}\cdot\text{bar})$, $b = 0.610$
 $P_1 = 500\text{kPa(absolute)}$, $T_1 = 292.25\text{K}$, $q_v^* = 18.41\text{dm}^3/(\text{s(ANR)})$

Figure 6 shows the pressure-flow characteristic of the restriction measured by the flow method specified in ISO 6358. Substituting the flow rate, the pressure and the temperature of the choked flow for the equation regulated in ISO 6358, the sonic conductance C was calculated, and then $C = 3.70\text{dm}^3/(\text{s}\cdot\text{bar})$. Moreover, substituting the flow rate and the pressure of the subsonic flow for the equation regulated in ISO 6358, the critical pressure ratio b was calculated, and then $b = 0.610$. The symbol (•) in the figure shows the experimental values, and the broken line shows the calculated value of flow rate that was obtained by substituting the measured values of C and b for the equation regulated in ISO 6358. The symbol q_v^* is the volume flow rate of the choked flow. Supposing that the coefficient of viscosity of air is

$18.21 \times 10^{-6}\text{Pa}\cdot\text{s}$ and calculating the Reynolds number Re in the restriction, $Re = 5.94 \times 10^4$ in the charge method and $Re = 2.97 \times 10^5$ in the flow method. When the discharge coefficient C_d is calculated in regarding the restriction as a critical nozzle [5], $C_d = 0.984$ in the charge method and $C_d = 0.992$ in the flow method. Since the sonic conductance is dependent only on the discharge coefficient, the sonic conductance given by the charge method is about 0.8% smaller than that by the flow method. Next, assuming a 50mm nominal bore solenoid valve as a critical nozzle of the 33mm diameter and calculating the Reynolds number under the same condition, $Re = 3.82 \times 10^5$ in the charge method and $Re = 1.91 \times 10^6$ in the flow method. When the discharge coefficient C_d is calculated, $C_d = 0.993$ in the charge method and $C_d = 0.996$ in the flow and so the sonic conductance given by the charge method is about 0.3% smaller than the value by the flow method. Therefore, the value of the sonic conductance measured by the charge method agrees well with that by the flow method for the large solenoid valve.

Next, the flow characteristic of the solenoid valve and the restriction obtained by the charge method, the flow method and the discharge method specified in Annex E of JIS B 8390 [3] are shown in Table 2. In the case of the small solenoid valve, the values of sonic conductance C measured by the charge method agree well with the values obtained by the flow method and the discharge method.

Table 2 Experimental results

Tested Valve and Restrictor	Sonic conductance C [$\text{dm}^3/(\text{s}\cdot\text{bar})$]			Critical Pressure Ratio b [—]			Diameter of Connecting Tube [mm]	Nominal Bore [mm]	Note
	Flow Method	Charge Method	Discharge Method	Flow Method	Charge Method	Discharge Method			
Valve A	0.630	0.618	0.612	0.519	0.503	***	6	6	2 Port Valve
Valve B	1.26	1.30	1.27	0.517	0.542	***	9	8	2 Port Valve
Valve C	2.33	2.39	2.33	0.233	0.252	***	9	8	3 Port Valve
Valve D	3.59	3.60	3.67	0.308	0.239	***	9	8	3 Port Valve
Valve E	***	9.23	9.32	***	0.250	***	13	10	3 Port Valve
Valve F	***	7.20	7.21	***	0.211	***	13	10	5 Port Valve
Valve G	***	7.75	7.66	***	0.176	***	13	10	2 Port Valve
Valve H	***	17.7	17.6	***	0.187	***	16	15	2 Port Valve
Valve I	***	25.3	25.0	***	0.221	***	22	20	3 Port Valve
Valve J	***	50.6	51.1	***	0.184	***	28	25	2 Port Valve
Valve K	***	54.8	55.3	***	0.151	***	36	32	2 Port Valve
Valve L	***	123.5	***	***	0.216	***	43	40	2 Port Valve
Valve M	***	132.5	***	***	0.228	***	53	50	3 Port Valve
Valve N	***	185.9	***	***	0.186	***	53	50	2 Port Valve
Restrictor $D = 3.96\text{mm}$	2.10	2.12	2.12	0.585	0.564	***	9	—	Controlled by Valve H
Restrictor $D = 5.18\text{mm}$	3.70	3.71	3.75	0.610	0.514	***	9	—	Controlled by Valve H

For the capacity shortage of the compressor, the test by the flow method was not possible on the medium and the large solenoid valves, and the critical pressure ratio cannot be obtained by the discharge method in principle. Therefore, it is difficult to evaluate the measurement accuracy of the critical pressure ratio obtained by the charge method for the large solenoid valve. However, by estimating from the measurement results of the small solenoid valve, it is guessed that the measurement accuracy of the critical pressure ratio obtained by the flow method is at the same level as that obtained by the charge method. Also in the case of the medium solenoid valve, the values of sonic conductance C measured by the charge method agree well with the values obtained by the discharge method. On the large solenoid valve, the test by the discharge method was not carried out, because it was dangerous for the human body. In addition, the symbol (***) shows the item that could not be measured. The charge method is the only method for measuring the critical pressure ratio and the sonic conductance of the large solenoid valve at this time.

In the test of the valve C by the charge method, the equivalent sound level measured at the position of 1m from the tested valve was 74.0dB(A), and the equivalent sound level under the test of the same valve by the flow method was 92.0dB(A). Moreover, the equivalent sound level at the test of the characteristic of the solenoid valve N (50mm nominal bore) by the charge method was about 100dB(A). Then, the charge method is extremely low noise in comparison with the conventional test method.

Table 3 Polytrropic index

Distance from wall surface [mm]	Temperature at start [°C]	Temperature at end [°C]	Polytropic index
0	18.2	27.0	1.030
30		29.9	1.040
60		31.4	1.045
90		31.7	1.046
120		32.9	1.050
150		33.7	1.053
Internal diameter of tank $d = 304\text{mm}$			Mean value $n = 1.044$

In this study, the change of state of the air in the tank is assumed as the polytrropic change. It is necessary to examine the optimum position of the thermometry in the tank in order to obtain the accurate polytrropic index n from the temperature change in the tank. Then, the thermocouple was installed in the tank, and the thermocouple moved radially, and the temperature change in the tank was measured. Under the test of the valve C, the values of the polytrropic index obtained by substituting the measurement values of the temperature at the start of charge and that at the end of charge in Eq.

(15) are shown in Table 3. The mean value of polytrropic index n was 1.044, and the mean value of polytrropic index can be obtained at the position of 60mm~90mm from the wall surface. This position is correspondent to the position of $0.2d \sim 0.3d$ from the wall surface, where d is the inside diameter of the tank. In this study, the temperature was measured at the position of $0.25d$ from the inner wall surface of the tank.

When the flow characteristic of large solenoid valve is measured by the flow method, the large test equipment is necessary and the power consumption increases. As a example, if the flow characteristic of the tested valve N (50mm nominal bore) is measured by the flow method at the upstream absolute pressure of 500kPa, then the air consumption required is about $55\text{m}^3/\text{min}$ (ANR), and the power of the compressor required is about 350kW. However, the power of the vacuum pump used for the charge method in this study was 1.5kW. Therefore, the charge method is the energy saving method in comparison with the flow method.

CONCLUSIONS

The measurement of the critical pressure ratio and the sonic conductance of the large pneumatic solenoid valve became possible by the charge method. Furthermore, the charge method is the energy saving test method and the low noise test method in comparison with the conventional test method.

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