A DOUBLE-TANK METHOD FOR THE IDENTIFICATION OF PNEUMATIC VALVES' FLOW-RATE CHARACTERISTICS

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Abstract

In this paper, a new isothermal tank test circuit composed of two tanks and a new data-processing algorithm called Cbm method are proposed to measure the flow-rate characteristics of some pneumatic valves. The double-tank circuit is used to test some solenoid valves such as inner pilot solenoid, which the traditional isothermal discharge method can not apply to. And Cbm method changes the identification procedure of multivariable unconstrained optimal algorithm, which evidently improves the identification precision of critical pressure ratio and subsonic index.

Keywords: flow rate characteristics, identification precision, identification algorithm, double-tank test circuit

1 Introduction

Pneumatic solenoid valves are basic components of pneumatic systems, and their flow rate characteristics are crucial coefficients for the performance of the whole system. In order to construct an efficient, energy-saving and precise pneumatic system, the flow rate characteristics of those solenoid valves must be determined in advance. However, the high compressibility of air results in a nonlinear flow rate through orifice of valves, which makes the identification of these parameters not easy (Andersen, 1967). There are many efforts to study the flow rate of pneumatic components (Sanville, 1971; Salvador, 2001; Kuroshita, 2004; Kawashima, 2004; Ye, 2008). Current measurement method is defined by international standard ISO6358 (1989). However, the requirements for experimental facilities of ISO6358 method are not easy to meet, and the procedure is time-consuming and energy-wasting. So many constant volume discharge methods have been developed by Salvador de las Heras (2001), Kuroshita (2004), and Kawashima (2004).

The method proposed by Salvador de las Heras (2001) uses the characteristic unloading time defined in transitory discharge to measure the sonic conductance of some valves. Based on the isentropic hypothsis and the theory of pneumatic RC system, this method can accurately measure sonic conductance when the pressure differential is small during discharge. Adopting this method, Richard Montague (2005) successfully measured the leak of a miniature pneumatic valve for hospital patient support equipment. However this method has a disadvantage that it must compensate the measurement results according the *L*/*D* change of cylinder tank. Besides, this method can not identify the critical pressure ratio.

As alternative methods, the isothermal discharge method, in which the discharge process is considered as an isothermal process by using an isothermal tank, can also measure flow rate characteristics accurately and conveniently. But this method still has many disadvantages (Kawashima, 2004; ISO/DIS 6358-3, 2008). For example, some inner pilot solenoid valves are required to working regularly in certain pressure range, so their flow rate characteristics can not be measured properly by the set-up of discharge method defined by ISO/DIS 6358-3 (2008). The charge method proposed by Kawashima (2004) can meet the pressure range of the inner pilot valve, but its measurement precision is decreased by the pressure drop of upstream-tank at the beginning of charge. Though a larger upstream-tank is proposed by Kawashima (2004) to ensure a steady upstream pressure, it still can not accurately measure some valves with large sonic conductance. In this study, we developed a double-tank discharge method to measure the inner pilot solenoid valves and improved the current data processing algorithm of the isothermal discharge method.

The organization of this paper is as follows. Section 2 illustrates the isothermal discharge method's difficulty to identify the flow rate characteristics of inner pilot solenoid valves, and then analyzes the

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data-processing principle defined by ISO/DIS 6358-3 (2008). Section 3 develops a new algorithm and compares the results of different methods. Section 4 proposes the double-tank test circuit for those inner pilot solenoid valves. Conclusions are provided in section 5. Nomenclature used in this paper is listed in the end.

2 The Measurement of Flow Rate Characteristics by Isothermal Discharge Method

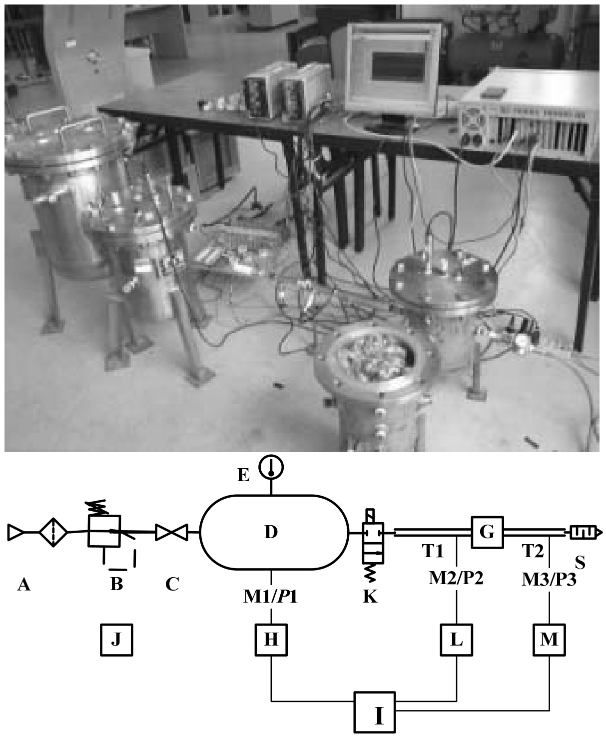
2.1 The Disadvantages of Isothermal Discharge Method

The principle of isothermal discharge method is based on the fact that tanks stuffed with proper quantity of copper wool can almost keep isothermal condition, when they are used to test pneumatic components (Kawashima, 2004). The test circuit of isothermal discharge method and its data-processing algorithm of this method are detailed by ISO/DIS 6358-3 (2008). It is called as bm method in the subsection of this paper. This method allows obtaining sonic conductance C, critical pressure ratio b and subsonic index m of the test components, based on pressure response in the tank during discharge. Compared with ISO6358 method, this method has the following advantages: no need of air source of a large flow rate, availability to test components with large bores, minimum air consumption, and short test time.

However, the bm method has some disadvantages either. For example, not like the ISO6358 (1989) method, it can not measure flow rate characteristics of some inner pilot solenoid valves. When those components does not work in proper pressure range (e.g. 0.2 MPa ~ 1 MPa), the action of their valve core can not be accurately controlled by reset force of pilot pressure, seal rubber friction and spring elasticity.

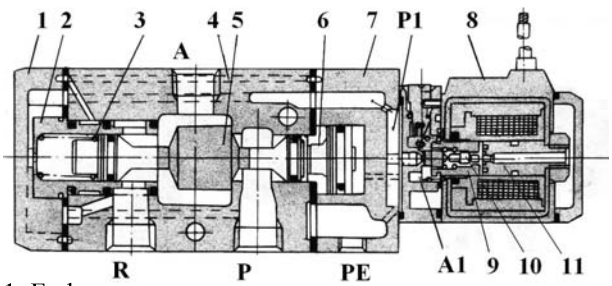
Figure 1 shows the test circuit of bm method. In Fig. 1, the volume of isothermal tank D can be chosen as 10×10^{-3} m^3, 20×10^{-3} m^3 or 50×10^{-3} m^3 according to the flow rate characteristics of test components. The pressure sensor is PMP4010 with an accuracy of 500 Pa against a full scale of 1 MPa. A 16-bits A/D NI6221 board is used to acquire data. The experimental process is controlled by a PC with software Labview installed, and the sampling frequency is 1000 Hz. The supply pressure is set to 600 kPa (gauge pressure). The requirements of size and position of rectifier tube T1 and test tube T2 are the same as that of ISO6358 method, and the control valve K may be chosen if pneumatic components other than solenoid valves are tested.

The cross section of a 2/3 inner pilot valve is shown in Fig. 2. When power is off, valve core 5 is reset. The port R and port PE respectively connect the two ends of control piston 6 through inner channels which are depicted by intermittent lines in Fig. 2. When power is on, the moving iron core 9 is attracted by the static iron core 11. Pushed by the spring, the piston 10 in moving iron core 9 blocks the inner channel in the static iron core 11. Through air chamber P1, A1 and the inner channels, the air resource connects the right chamber of control piston 6, and then control piston 6 pushes the valve core 5 to switch. Generally the inner pilot valves have the advantages of compact, energy saving, large flow rate.



A: Air source and filter
B: Pressure regulator
C: Shut-off valve
D: Isothermal tank
E: Temperature transducer
M1, M2, M3: Pressure measuring connector
H, L, M: Pressure transducer
T1, T2: Rectifier tube and test tube
G: Solenoid valve under test
I: Digital recorder and timer
S: Silencer
J: Barometer
K: Control valve

Fig. 1: *Isothermal discharge method circuit*



1: End cover
2: Sheath
3: Reset spring
4: Valve body
5: Valve core
6: Control piston
7: Joint plate
8: Pilot valve
9: Moving iron core
10: Block piston
11: Static iron core

Fig. 2: *The cross section of inner pilot valve*

Table 1: Experimental results of ISO method and bm method by single tank circuit

Solenoid Valve	Sonic conductance C 10^{-8}[m3/(sPa)] ISO Method	bm Method	Error (%)	Critical Pressure Ratio b ISO Method	bm Method	Error (%)	Subsonic index m ISO method	bm method	Error (%)
A($0.4<p_3/p_2<0.98$)	2.48	2.57	3.62	0.486	0.412	-15.2	0.496	0.543	9.48
A($0.4<p_3/p_2<0.63$)	2.48	2.57	3.62	0.486	0.35	-28.0	0.496	0.391	-21.2
B($0.4<p_3/p_2<0.98$)	0.94	0.92	-2.12	0.31	0.36	16.4	0.487	0.549	12.3
B($0.4<p_3/p_2<0.63$)	0.94	0.92	-2.12	0.31	0.52	67.7	0.487	0.458	-5.95
C($0.4<p_3/p_2<0.98$)	4.29	4.51	5.12	0.410	0.303	-26.1	0.491	0.535	8.96
C($0.4<p_3/p_2<0.63$)	4.29	4.51	5.12	0.410	0.232	-43.4	0.491	0.403	-17.9
D($0.4<p_3/p_2<0.63$)	3.42	3.29	-3.80	0.347	0.518	67.1	0.492	0.395	-19.7
E($0.4<p_3/p_2<0.63$)	7.92	8.60	8.58	0.33	0.19	-42.4	0.499	0.559	12.2

Figure 3 is the pressure curves of the 2/3 inner pilot valve measured by the set-up of Fig. 1. As shown in Fig. 3, when the upstream pressure $P1$ and $P2$ is lower than 160 KPa, the discharge flow is checked by the action of valve core for its reset force. This means pressure ratio (i.e. $P3$ / $P2$) of downstream and upstream can only be obtained higher than 0.63. This situation makes the identification of critical pressure ratio b and subsonic index m difficult, for the test pressure data under 160 kPa are always important information in the identification of critical pressure ratio b and subsonic index m by the ISO/DIS 6358-3 (2008) method.

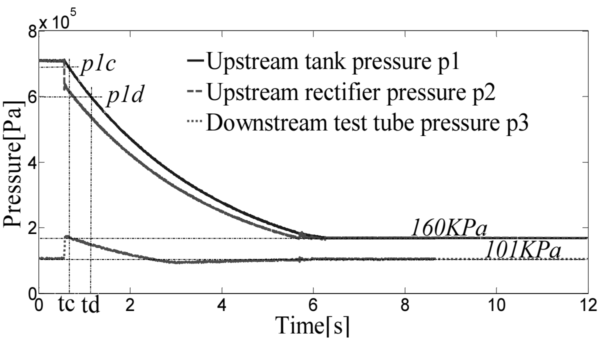


Fig. 3: *Pressure profiles of test solenoid valve*

Table 1 shows the identification results. Solenoid valve A is a direct operated valve, while valve B and C are inner pilot valves with the reset force completely composed of air pressures. During the isothermal discharge, the pressure ratio (P_3 / P_2) of test solenoid valves A, B and C can be obtained from 0.15 to 1. As the reset force is composed of pilot pressure, seal rubber friction and spring elasticity, solenoid valve D and E is different with that of solenoid valve B and C, their pressure ratio can only be acquired from 0.15 to 0.63 and from 0.15 to 0.76 respectively.

In Table 1, the pressure ratio of valve A, B and C is deliberately chosen from 0.4 to 0.98 and from 0.4 to 0.63 according to the identification algorithm of bm method. When the ISO6358 method is applied to measure the flow rate characteristics, the upstream pressure of test valve is kept at 700 kPa, and more than 10 points of data are recorded by adjusting flow rate of downstream from 90 % to 10 % (Kawashima, 2004).

As shown in Table 1, when the pressure ratio (P_3 / P_2) is chosen from 0.4 to 0.98, the error of the sonic conductance C by bm method are almost within 5 %, and the error of critical pressure b and subsonic index m within 26 % and 12 % respectively. However, when the pressure ratio (P_3 / P_2) is chosen from 0.4 to 0.63, the identification error of critical pressure b is enlarged obviously. For example, the error of critical pressure b of solenoid valve B is enlarged from16.4 % to 67.7 %, and the deviation of subsonic index m always changes from a positive error to a negative error. Since the pressure ratio of inner pilot solenoid valve D and E can only be obtained lower than 0.63 and 0.76 respectively, the errors of test results by the bm method is all large, as shown in the Table 1. So a conclusion can be made that a single isothermal tank discharge method can not measure the characteristics of some pilot valves such as D and E.

Actually, when the pressure curves in the subsonic stage are used to identify the parameters (i.e. b, m) of an elliptic curve of the subsonic flow, it is not easy from the viewpoint of nonlinear regression (Bates, 1989). As the pressure ratio P_3 / P_2 changes from 0.63 to 0.98, the nonlinearity of elliptic curve of the subsonic flow becomes stronger. On the other hand, the elliptic curve with large relative curvature offers more information for the identification of parameters. So if the pressure ratio from 0.63 to 0.98 can not be acquired during discharge, it is difficult to identify the critical pressure ratio b and the subsonic index m accurately.

In subsection, a double-tank circuit is developed to test pilot solenoid valves like the D and E. Before this, characteristics of bm algorithm are discussed and a new algorithm called "Cbm method" is proposed.

2.2 The Introduction of Current Algorithm of the Isothermal Discharge Method

The bm algorithm adopts a "two-step" strategy. It identifies the sonic conductance C with the discharge pressure curves in choked stage, and then identifies the critical pressure ratio b and subsonic index m based on the identification result of sonic conductance C (ISO/DIS 6358-3, 2008). The principle of bm algorithm is introduced as follows.

The ideal air in the isothermal tank at any time meets Eq. 1.

$$P_1V = m_t RT_t \tag{1}$$

Assume the air in the tank remain isothermal during discharge. Then the temperature derivative item $\frac{VP_1}{RT^2}\frac{dT}{dt}$ in the total differential of Eq. 1 can be omitted, and Eq. 2 can approximate the mass flow rate during discharge.

$$q = -\frac{dm_t}{dt} = -\frac{V}{RT}\frac{dP_t}{dt} \tag{2}$$

Equation 3 represents the case of choked flow and Eq. 4 represents the case of subsonic flow (Sanville, 1971).

$$q = C\rho_0 P_2\sqrt{\frac{T_0}{T}} \qquad \text{(Choked flow: } P_3/P_2 \le b\text{)} \tag{3}$$

$$q = C\rho_0 P_2\sqrt{\frac{T_0}{T}}\left[1-\left(\frac{\frac{P_3}{P_2}-b}{1-b}\right)^2\right]^m \tag{4}$$

with (Subsonic flow: P_3 / P_2 > b). Equation 5 is deduced from Eq. 2 and 3, in which N is used to calculate mean value and $P_{1(i)}$ / $P_{2(i)}$ considers the pressure loss between tank D and test component G, as shown in Fig. 1 and Fig. 3. The sonic conductance C over the pressure range of the sonic stage by the acquired discrete pressure value (i.e. $P_{1(i)}$ and $P_{2(i)}$), where P_{1c} (i.e. the initial value for calculation) is set to 690 kPa and P_{1d} (i.e. the last value for calculation) is set to 600 kPa. The pressure ratio range of P_3/P_2 at this stage is from 0.145 to 0.167, smaller than critical pressure ratio b of most valves.

$$C = 10^5 \times \frac{1}{\text{N}} \times \sum_{i=1}^{\text{N}} \frac{P_{1(i)}}{P_{2(i)}} \times \frac{V}{R\rho_0\left(t_d - t_c\right)\sqrt{T_0 T_s}} \ln\frac{P_{1c}}{P_{1d}} \tag{5}$$

Based on the calculation result of the sonic conductance C, Eq. 6 is used to calculate discrete pressure $P_{\text{cal1(1)}}$, $P_{\text{cal1(2)}}$… $P_{\text{cal1(N)}}$ successively. In the practical calculation procedure of critical pressure ratio and subsonic index, the value range of $P_{1(i)}$ is chosen from 220 kPa to 110 kPa , with pressure ratio value of P_3 / P_2 ascending from 0.46 to 0.91.

$$P_{cal1(i)} = P_{1(i-1)} - 10^5 \times \Delta t \frac{R}{V} C\rho_0 P_{2(i-1)}\sqrt{T_s T_0} \times \left\{1-\left[\frac{\left(P_{3(i-1)}/P_{2(i-1)}\right)-b}{1-b}\right]^2\right\}^m \tag{6}$$

In Eq. 7, $\delta_{(i)}$ is the differential value between the calculated pressure $P_{\text{cal1(i)}}$ and the measured pressure $P_{1(i)}$. At last Eq. 8 determines critical pressure ratio b and subsonic index m such that the total sum E of the square difference $\delta_{(i)}$ becomes the least.

$$\delta_{(i)} = P_{cal1(i)} - P_{1(i)} \tag{7}$$

$$E = \sum_{i=1}^{N} \delta_{(i)}^2 \tag{8}$$

This "two-step" identification algorithm is the current algorithm of bm method.

2.3 The Error Analysis of BM Method and Some Improvements

The "two-step" identification algorithm is simple and easy to operate. However, the identification precision of sonic conductance is reduced by the isothermal hypothesis through Eq. 5. And the error of sonic conductance is inevitably transferred to the critical pressure ratio and subsonic index through Eq. 6. There are two main reasons that lead to the error of the sonic conductance C, critical pressure ratio b and subsonic index m, which are analyzed as follows.

The Error of Pressure Derivative

The aqcuired pressure is descending from 700 kPa to 110 kPa, and the measurement noise of pressure sensors are smaller than 2 kPa, so the Signal-to-noise Ratio is always larger than 45 dB. As a recurrence formula, Eq. 6 is deduced from pressure derivative of Eq. 2, which is calculated by first-order upwind difference scheme. The theoretical precision of difference equation by first-order upwind difference scheme only reachs first-order precision. The noise error of the pressure derivative is always larger than noise of pressure.

Now that the instantaneous pressure and time are acquired after the measurement experiments, the pressure derivative can be calculated more accurately by the first-order central difference, which has a second-order precision. There are a lot of algorithms and convergence analysis for this problem. Among those algorithms, the often used one is finite difference method with appropriate step. In fact, if the discrete function value contains too many errors, then the corresponding step can not be too small, which is a typically ill-posed problem of numerical solution. The optimum step of central difference algorithm and its highest precision is deduced in Appendix. And the first-order central difference and its optimum step are used in the Eq. 9 in Cbm algorithm in subsection 3.1.

The Effect of Disregarded Temperature Change

It is well known that the temperature of isothermal tank still drops a little during discharge (Kawashima, 2004), and those rectifier tube and test tube are not adiabatic. In fact, if a set of data is processed by the "two-step" algorithm, it can be proven that an error of 2 % of the sonic conductance can lead to more than 10 % error of critical pressure ratio (Lihong, 2008). Table 1 also shows a trend that the larger error of sonic conductance is, the larger the errors of b, m are. As Eq. 5 disregards the change of temperature, it will inevitably result in identification error of sonic conductance C. And Eq. 6 is an approximate formula including many errors, such as ignoring the temperature gradient, disregarding the error of test pressure, and containing the calculation error of sonic conductance C. So the errors of bm algorithm are inevitably enlarged by the intrinsic defects of "two-step" algorithm.

Assume that air in a tank is ideal gas and discharge process is a polytropic process. A study shows that if the discharge time is 12 seconds, then its polytropic exponent changes from 1.4 to 1.15 in about 4 seconds, and it changes slowly from 1.15 to 1.05 in surplus time (Ye, 2008). That is to say, the temperature drops mostly in the choked stage, while almost keeping a constant in the subsonic stage. This means that the isothermal hypothesis in choked stage is not properly, while the subsonic stage can be treated as an isothermal process more reasonably.

It can be concluded from the above analysis that the error of sonic conductance C from Eq. 5 is caused mainly by the isothermal hypothesis in choked stage, and then the error of sonic conductance C reduces the measurement precision of critical pressure b and subsonic index m through Eq. 6.

3 The Data Processing Principle of Cbm Algorithm

A new algorithm to identify b, m is proposed according to the above analysis. That is, using Eq. 5 to identify the sonic conductance C by the pressure data in the choked flow, and identifying C_e, b, m, at the same computation of multivariate unconstrained optimization, but discarding the C_e when the computation procedure is terminated. The C_e is considered a calculated sonic conductance value, the subscript e of which means error. We call this algorithm as Cbm method.

3.1 The Steps of Cbm Method

Step 1. Use Eq. 5 to calculate the sonic conductance C over the pressure range of the choked flow.

Step 2. Use Eq. 9 to obtain the discrete mass flow rate calculated on the isothermal hypothesis, in which the pressure derivative is calculated by the first-order central difference and its optimum step deduced in Appendix.

$$q_{m(i)} = -\frac{V}{RT_s}\frac{dP_{1(i)}}{dt} \tag{9}$$

Step 3. The mass flow rate in subsonic stage is calculated by Eq. 10, with subscript mcp(i) meaning discrete calculated valve of mass flow rate.

$$q_{\mathrm{mcp(i)}} = C_e \rho_0 P_{2(i)} \sqrt{\frac{T_0}{T_s}} \times \left[1 - \left(\frac{P_{3(i)}/P_{2(i)} - b}{1-b}\right)^2\right]^m \tag{10}$$

Step 4. Use Eq. 11 to calculate the differential value between the calculated valve of mass flow rate and the one calculated based on isothermal hypothesis.

$$\delta_{(i)} = q^i_{mcp(i)} - q^i_{m(i)} \tag{11}$$

Step 5. With C_e, b, m as optimization variable, the sum square error is defined as optimization object function, which is described by Eq. 12

$$E = \sum_{i=1}^{N} \delta^2_{(i)} \tag{12}$$

The critical pressure ratio b and subsonic index m can be figured out from Eq. 12, and the sonic conductance C_e calculated by the pressure curve of subsonic flow should be abandoned.

3.2 The Comparison of Different Methods

To testify Cbm algorithm, we identified the flow rate characteristics of these pneumatic solenoid valves in Table 1. The same test pressure curves are used in different algorithms. Table 2 shows the identification results of these pneumatic solenoid valves. It also shows that the errors of Cbm method are generally smaller than that of bm method when their results are compared with the results of ISO6358 method.

The identification results of solenoid valves A and B, which have small C value, are more accurate than that of valve C. This is the result of isothermal hypothesis, for under the same condition, the discharge time of a solenoid valve with a small C is always longer than the one with big C, and longer discharge time will allow the heat exchange adequately, which reduces the error caused by the temperature drop.

In the calculation procedure, we found that Cbm method is sensitive to the value range of P_3 / P_2, as showed in Table 3. The sensitivity of algorithms is testified by valve A and B in different pressure range of the subsonic stage. When the valve range of P_3 / P_2 changes from (0.4, 0.98) to (0.6, 0.98), the critical pressure ratio b of Cbm method of valve A changes continually from 0.442 to 0.415, with its error ascending from -9.05 % to -14.6 %. However its measurement error of valve A by the bm method almost keeps a constant at 15.4 %. The same trend appears in the calculation results of valve B and C. The sensitivity of Cbm algorithm may be caused by the fact that Cbm method identifies three parameters in an optimal calculation procedure, while the bm method identifies two parameters in a calculation process. Though the Cbm method has the advantage over bm method, it can not accurately identify the inner pilot solenoid valve D and E either, as shown in Table 2.

Table 2: comparison of ISO6358 method, bm method and Cbm method by single tank circuit

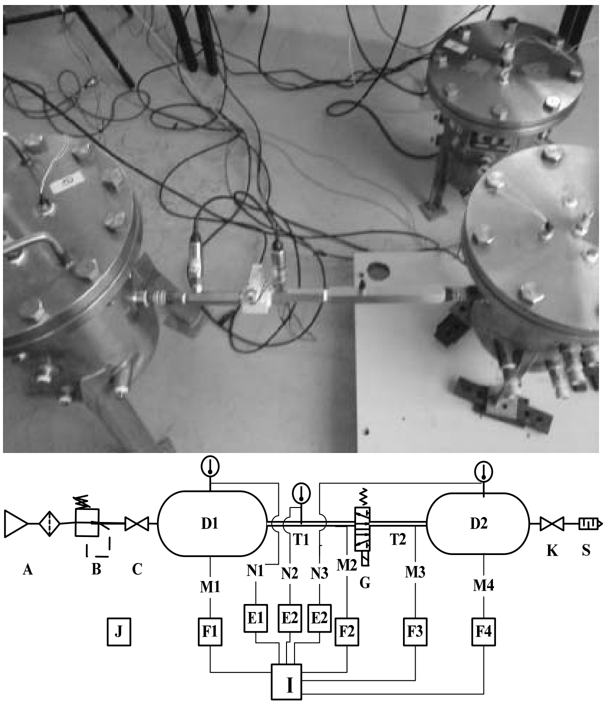
Solenoid Valve	Critical Pressure Ratio *b*					Subsonic index *m*				
	ISO Method	bm method	Error (%)	Cbm method	Error (%)	ISO method	bm method	Error (%)	Cbm method	Error (%)
A($0.4<p_3/p_2<0.98$)	0.486	0.412	-15.2	0.442	-9.05	0.496	0.543	9.48	0.546	10.1
B($0.4<p_3/p_2<0.98$)	0.310	0.360	16.4	0.35	12.9	0.487	0.549	12.73	0.545	11.9
C($0.4<p_3/p_2<0.98$)	0.410	0.303	-26.1	0.349	-14.9	0.491	0.535	8.96	0.525	6.92
D($0.4<p_3/p_2<0.76$)	0.347	0.518	67.1	0.498	43.5	0.492	0.395	-19.7	0.389	-20.9
E($0.4<p_3/p_2<0.64$)	0.331	0.191	-42.4	0.20	-33.3	0.499	0.559	12.02	0.535	7.21

Table 3: Sensitivity comparison of Cbm and bm method

Solenoid Valve	Critical Pressure Ratio b					Subsonic index *m*				
	ISO method	bm method	Error (%)	Cbm method	Error (%)	ISO method	bm method	Error (%)	Cbm method	Error (%)
A($0.4<p_3/p_2<0.98$)	0.486	0.412	-15.2	0.442	-9.05	0.496	0.543	9.48	0.546	10.1
A($0.5<p_3/p_2<0.98$)	0.486	0.411	-15.4	0.432	-11.1	0.496	0.541	9.06	0.533	7.46
A($0.6<p_3/p_2<0.98$)	0.486	0.409	-15.8	0.415	-14.6	0.496	0.538	8.47	0.521	5.04
B($0.4<p_3/p_2<0.98$)	0.310	0.361	16.4	0.351	13.2	0.487	0.549	12.7	0.545	11.9
B($0.5<p_3/p_2<0.98$)	0.310	0.363	17.1	0.354	14.2	0.487	0.546	12.1	0.535	9.82
B($0.6<p_3/p_2<0.98$)	0.310	0.364	17.4	0.359	15.8	0.487	0.544	11.7	0.526	8.01
C($0.4<p_3/p_2<0.98$)	0.410	0.303	-26.1	0.349	-14.9	0.491	0.535	8.96	0.525	6.92
C($0.5<p_3/p_2<0.98$)	0.410	0.295	-28.0	0.335	-18.2	0.491	0.532	8.35	0.515	4.89
C($0.6<p_3/p_2<0.98$)	0.410	0.289	-29.5	0.317	-22.6	0.491	0.529	7.76	0.503	2.44

4 Double Isothermal Tank Method

Figure 4 is the test circuit of double-tank discharge method, in which the downstream tube T2 of Fig. 1 is supplemented with a Tank D2. Tank D2 is attached by pressure transducer F4 and temperature transducer N3.



A: Air source and filter
B: Pressure regulator
C, K: Shut-off valve
D1: Upstream isothermal tank
D2: Downstream tank
E1, E2, E3: Temperature transducer
J: Barometer
F1, F2, F3, F4: Pressure transducer
T1, T2: Rectifier tube and test tube
M1, M2, M3, M4: Pressure-measuring Connector
N1, N2, N3: Temperature-measuring Connector
G: Solenoid valve under test
I: Digital recorder and timer
S: Silencer

Fig. 4: *Double-Tank Test circuit*

In Fig. 4, D1 is an isothermal tank, while D2 can be chosen as an isothermal tank or an empty tank according to the requirement of measurement precision. The volumes of D1 and D2 can be chosen to match pressure range of the test valve G, and the parameter of initial pressure in D1 is set to 700 kPa. The sampling frequency is 1000 Hz. The requirements of other units in Fig. 4 are the same as that of Fig. 1.

4.1 Experimental Results and Discussions

Table 4 shows the flow rate characteristics of the above solenoid valves which are tested again by the double-tank circuit. Isothermal tank D1 and D2 are respectively chosen as 10 x 10^{-3} m^3 and 50 x 10^{-3} m^3. The upstream pressures (i.e. P_1, P_2) of the test valves decrease from 700 kPa to about 200 kPa, while downstream pressures increasing from P_a (i.e. standard atmosphere pressure) to about 200 kPa. All these test valves work in required pressure range, and the pressure ratio P_3 / P_2 of all these valves can be acquired from about 0.15 to 1. The Cbm method and bm method are used to identify the critical pressure ratio *b* and subsonic index *m*, in which all the range of pressure ratio are from 0.4 to 0.98.

As showed in Table 4, all the sonic conductance values of Cbm method are smaller than that of ISO6358 method, which is determined by the new double-tank dynamic system. The measurement errors of sonic conductance by the double-tank circuit are almost the same as the traditional single isothermal tank circuit. The measurement precision of critical pressure *b* of the Cbm method is better than that of bm method in the same double-tank circuit, Especially, when it is applied to the valves with big sonic conductance such as valve C and E.

The test errors of critical pressure ratio *b* of valve D and E are improved evidently, which decrease respectively from 67.1 % and -42.4 % in Table 1 to 17.3 % and 24.5 %, as shown in Table 4. Though the dynamic system of the double-tank is different from that of ISO method and bm method, the identification results of Cbm method based on double-tank dynamic system are accurate enough for practical use. Figure 5 also shows mass flow rate of valve E calculated by the parameters of the Cbm method fits the values of ISO method very well, and it is better than the result of bm method. Table 5 illustrates some match patterns for double-tank method which is chosen according to the flow-rate characteristics of test valves.

As shown in Table 5, the flow-rate characteristics of valve A is tested most accurately by the pattern of 10×10^{-3} m^3 to 50×10^{-3} m^3 (Isoth to Isoth), which means upstream tank is 10×10^{-3} m^3 isothermal tank and downstream tank is 50×10^{-3} m^3 isothermal tank. When downstream tank is empty, the test value of sonic conductance is often bigger than test value of that pattern with downstream isothermal tank. However the deviations of the two patterns are ignorable in practical use. When the pattern is from empty tank to isothermal tank, its test results are not as good as the pattern of isothermal tank to empty tank. And if both upstream and downstream tank are empty tank, the test result are totally unacceptable. From the viewpoint of energy-saving, the pattern of 10×10^{-3} m^3 to 10×10^{-3} m^3 is the best choice. Taking the test procedure of valve A for example, the surplus gas pressure is almost 400 kPa in tank D1, in which 3 kJ is saved for another identification process.

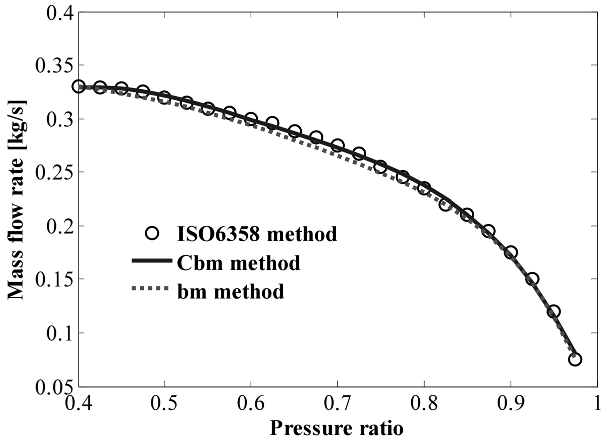


Fig. 5: *Flow-rate comparison of different methods by double-tank circuit*

Table 4: Comparison of ISO method, bm method and Cbm method by double tank circuit

Valve	C 10^{-8}[m^3/(sPa)]			b					*m*				
	ISO	Cbm	Error (%)	ISO	Cbm	Error (%)	bm	Error (%)	ISO	Cbm	Error (%)	bm	Error (%)
A	2.48	2.39	-3.63	0.49	0.52	6.38	0.54	11.1	0.496	0.463	-6.65	0.455	-8.27
B	0.94	0.92	-1.81	0.31	0.34	9.03	0.35	13.5	0.487	0.505	3.69	0.542	11.29
C	4.29	4.02	-6.29	0.41	0.44	8.08	0.52	26.8	0.491	0.449	-8.54	0.432	-12.0
D	3.42	3.22	-5.85	0.35	0.41	17.3	0.43	23.6	0.492	0.451	-8.33	0.425	-13.6
E	7.92	7.43	-6.18	0.33	0.41	24.5	0.49	50.0	0.499	0454	-9.01	0.559	12.02

Table 5: Results of different match patterns by double-tank circuit

Value A	10×10^{-3} m^3 to 10×10^{-3} m^3		10×10^{-3} m^3 to 20×10^{-3} m^3		10×10^{-3} m^3 to 50×10^{-3} m^3		10×10^{-3} m^3 to 50×10^{-3} m^3		20×10^{-3} m^3 to 50×10^{-3} m^3	
	Isoth to isoth	Isoth to empty	Isoth to isoth	Isoth to Empty	Isoth to isoth	Isoth to empty	Empty to isoth	Empty to empty	Isoth to Isoth	Isoth to empty
C	2.192	2.201	2.290	2.311	2.391	2.412	2.210	1.690	2.35	2.38
b	0.525	0.523	0.520	0.524	0.517	0.521	0.537	0.661	0.520	0.519
m	0.473	0.474	0.471	0.454	0.463	0.459	0.440	0.293	0.458	0.456

5 Conclusions

A new data-processing algorithm called Cbm method is proposed to identify the solenoid valves, especially those with large sonic conductance value. The Cbm method has the advantage of identifying the critical pressure ratio and subsonic index more accurately. But it has a disadvantage of being sensitive to choice range of pressure ratio of the upstream and downstream.

A double-tank test circuit with different dynamic system is proposed to measure some inner pilot valves which can not be tested by the traditional single-tank method. Compared with other test methods, the Cbm method plus double-tank circuit has the best test accuracy when applied to some inner pilot valves. The test accuracy of this new circuit is affected by the match patterns, in which the pattern of isothermal upstream tank discharging to empty downstream tank is the best choice according to the experimental results. From the practical viewpoint, the double-tank circuit is useful supplement to isothermal tank test method.

This double-tank test circuit may measure flow rate characteristics of other pnuematic components which are requiured to work in a certain pressure extent just like inner pilot valves.

Nomenclature

b	Critical pressure ratio	[-]
C	Sonic conductance	[$m^3s^{-1}Pa^{-1}$]
m	Subsonic index	[-]
P_a	Standard atmosphere pressure	[Pa]
P_1	Gas pressure in upstream tank	[Pa]
P_2	Gas pressure in rectifer tube	[Pa]
P_3	Gas pressure in test tube	[Pa]
P_4	Gas pressure in downstream tank	[Pa]
R	Ideal gas constant	[$Nmkg^{-1}K^{-1}$]
T	Gas temperature	[K]
T_0	Temperature of environment	[K]
T_s	Initial temperature of gas	[K]
ρ_0	Gasdensityconstant	[g/dm^3]
q_m	The calculated mass flow rate	[$kg\ s^{-1}$]
G	Mass flow rate of gas	[$kg\ s^{-1}$]
t	Time	[s]
t_c	Time when P_1 is 690 MPa	[s]
t_d	Time when P_2 is 600 MPa	[s]
V	Volume of the chamber	[m^3]
h	Calculation step	[-]
	Subscripts	
i	Time series	
cal	calculated value	
e	error	

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Appendix

The optimum step of first-order central difference algorithm and its highest calculation step for Cbm method is deduced as follows:

Suppose the known function $f(x) \in C^3[a,b]$, the test data of $f(x)$ is $y^e(x)$, and the error of $y^e(x)$ meets Eq. A1 as follows,

$$\left\| y(x) - y^{\varepsilon}(x) \right\| \le \varepsilon \left| y(x) \right| \tag{A1}$$

when one-order central difference is used to approximate the value of one-order derivative of $f(x)$, we have Eq. A2,

$$\begin{aligned} D_h(x) &= \frac{y(x+h) - y(x-h)}{2h} \\ &= y'(x) + \frac{1}{3} y'''(x) h^2 + O(h^3) \end{aligned} \tag{A2}$$

The first-order central difference Eq. (A3) calculated by test data with errors can be described as follows:

$$D_h^{\varepsilon}(x) = \frac{y_{\varepsilon}(x+h) - y_{\varepsilon}(x-h)}{2h} \tag{A3}$$

The error between the real derivative $y'(x)$ and the central difference $D_h^{\varepsilon}(x)$ meets Eq. (A4),

$$\begin{aligned} &\left\| D_h^{\varepsilon}(x) - y'(x) \right\| \le \left\| D_h(x) - y'(x) \right\| + \\ &\left\| D_h(x) - D_h^{\varepsilon}(x) \right\| \le \frac{1}{3} \left| y'''(x) \right| h^2 + \frac{\varepsilon}{h} \left| y(x) \right| \\ &\approx \left(\frac{1}{3} h^2 + \frac{\varepsilon}{h} \right) \left| y(x) \right| \end{aligned} \tag{A4}$$

$y(x)$ and $y^{m}(x)$ in the Eq. A4 are supposed to be the same order of magnitude, and nearly equal. From Eq. A4, we can infer that if the step h is too small, then the corresponding differential algorithm will result in a drastically deteriorated error. To obtain a stable algorithm of minimum error, we derive Eq. A5 with the partial differential as as follows:

$$\partial \frac{\left\| D_h^{\varepsilon}(x) - y'(x) \right\|}{\partial h} = \left(\frac{2}{3} h - \frac{\varepsilon}{h^2} \right) \left| y(x) \right| = 0 \tag{A5}$$

So the optimum step is derived as the following Eq. (A6):

$$h = \left(\frac{3}{2} \varepsilon \right)^{1/3} \tag{A6}$$

Substitute the optimum step to Eq. (A4), we get the highest precision as following Eq. (A7):

$$\begin{aligned} &\left\| D_h^{\varepsilon}(x) - y'(x) \right\| \le \left(\frac{1}{3} \left(\frac{3}{2} \varepsilon \right)^{2/3} + 3 \frac{\varepsilon}{\left(\frac{3}{2} \varepsilon \right)^{1/3}} \right) \left| y(x) \right| \\ &\propto \left(\varepsilon^{2/3} \right) \left| y(x) \right| \end{aligned} \tag{A7}$$

With the optimum step showed in Eq. A6, the computation program of optimization can be adjusted according to the acquired pressure and its error bound. And the highest precision indicated by Eq. A7 can be used to analyze the measurement errors.

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