

A concise method for determining a valve flow coefficient of a valve under compressible gas flow

Wu-Shung Fu *, Jia-Shyan Ger

Department of Mechanical Engineering, National Chiao Tung University, 1001 Ta Hsueh Road, Hsinchu 30050, Taiwan, ROC

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Abstract

This work presents a novel method of determining a valve flow coefficient for a valve and transient mass flow rate of compressible gas discharged from a reservoir. The proposed method consists of a set of equations to express the physical phenomena and measurement equipment to measure the indispensable data used in the above equations. Regardless of the kind of valve, the valve flow coefficient can be obtained efficiently and feasibly. The results of this study indicate not only that the valve flow characteristics of the diaphragm valve significantly differ from those of the ball valve, but also that the C_v flow equation conventionally used is no longer valid for the diaphragm valve. The valve flow coefficient of the ball valve determined by the proposed method is about 48 and the representative one proposed by the ANSI/ISA is about 56. In addition, the mass flow rate of gas flow through a valve under transient process can be estimated without using a flow meter. Moreover, the cumulated masses discharged predicted by the method proposed herein are consistent well with those of the experimental results. The deviations are smaller than 6%. © 1999 Elsevier Science Inc. All rights reserved.

Keywords: Valve flow coefficient; Compressible flow; Numerical; Experimental

1. Introduction

Pulse-jet bag filters have found extensive industrial applications particularly in separating fine dust from dust laden gas stream. The mechanisms of the pulse-jet cleaning system have been experimentally studied as well [1–5]. According to those results, some important parameters heavily influence the cleaning performance, which include the volume of the reservoir, the pressure of air in the reservoir, the valve flow coefficient of the diaphragm valve, the size of the blow tube and the size and number of the jet nozzles on the blow tube.

Upon initiating the cleaning processes, the compressed air is immediately discharged from the reservoir via the diaphragm valve which is controlled by a solenoid valve into the blow tube. The pressurized blow tube then discharges the high pressure air through the numerous nozzles drilled on the blow tube into the corresponding bag filters which are generally made of flexible fiber. The discharged high pressure air not only inflates the bag filter abruptly, but also penetrates from the inner to

outer surfaces of the bag filter. In doing so, the dust deposited on the outer surface of the bag filter is removed effectively. Closely examining the above processes reveals that the diaphragm valve plays an important role as a switch to discharge the air in the reservoir. However, owing to the complicated geometry of the diaphragm valve, the air flow through the valve is extremely difficult to calculate. Furthermore, the discharge process is a transient process and the displacement of the diaphragm valve heavily relies on the upstream and downstream pressures, causing the valve flow coefficient of the diaphragm valve to no longer be a constant and subsequently difficult to measure directly. Consequently, under the above circumstances, the flow equation proposed by ANSI/ISA [6] could not adequately predict the flow rate through the diaphragm valves. Therefore, developing a model capable of predicting the mass flow rate of the air discharged from a reservoir through a diaphragm valve is rather difficult, accounting for why the quantitative analysis of the pulse-jet cleaning system is rare.

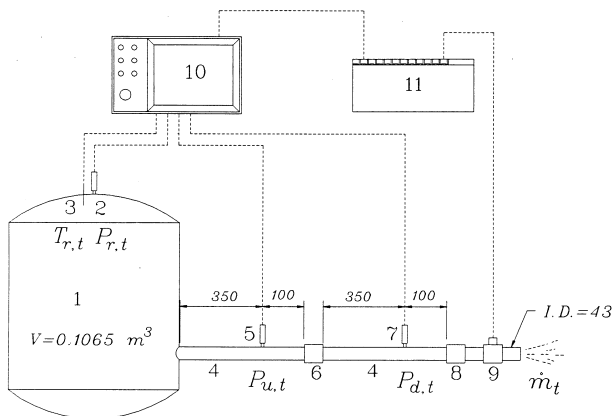
Sequential studies largely focus on analyzing the pulse-jet cleaning system. In light of the complications associated with the system mentioned above, the study presents a preliminary method which includes theoretic-

* Corresponding author. Tel.: 00886-3-5712121; fax: 00886-3-5720634.

cal and experimental work to analyze the flow mechanism of the diaphragm valve. The proposed method consists of several equations expressing compressed air discharged from a reservoir through a diaphragm valve controlled by a solenoid valve to atmospheric environment. Results obtained from the experimental work are used to solve the above equations. In addition, combining the data obtained from the theoretical and experimental work, the valve flow coefficient is determined. Herein, an 1.5 in. ball valve is tested as well. The valve flow coefficient of the ball valve obtained by the proposed method is about 48, and the representative value proposed by the ANSI/ISA [6] is about 56. To express the flow characteristics of the air flow through the diaphragm valve, this work also derives an empirical equation of dimensionless mass flow rate G_f as a function of the pressure ratio x_f . Moreover, data obtained from measured time-dependent pressures can be used to reasonably calculate the mass flow rates of air during the transient period. Furthermore, the experimental work confirms the validity of the theoretical results of the cumulated mass discharged. The deviations are smaller than 6% and the accuracy of the transient mass flow rate is indirectly validated.

2. Modeling

Fig. 1 shows the experimental apparatus used herein to depict a physical model. The volume of the air reservoir is V , and the temperature, pressure and mass of the air in the air reservoir are $T_{r,t}$, $P_{r,t}$ and $m_{r,t}$, respectively. The air discharged from the air reservoir is \dot{m}_t .



- Descriptions:
- 1 : Air reservoir
 - 2 : Pressure transmitter
 - 3 : Thermocouple
 - 4 : Connecting pipe
 - 5 : Upstream pressure transmitter
 - 6 : Test valve
 - 7 : Downstream pressure transmitter
 - 8 : Throttling valve
 - 9 : Quick-opening valve (diaphragm valve)
 - 10 : Data acquisition unit
 - 11 : Programmable logic controller
- (Unit : mm)

Fig. 1. Experimental apparatus.

The upstream and downstream pressures at both sides of the test valve are $P_{u,t}$ and $P_{d,t}$, respectively.

The air discharging from the air reservoir to the atmosphere take a relatively short time. Herein the processes are regarded as adiabatic to facilitate the analysis. In addition, the volume of the connecting pipe between the exit of the air reservoir and the downstream pressure transmitter is about 1.2% of the air reservoir. While assuming that the process is adiabatic, the stagnation temperature and mass flow rate at downstream of the test valve are estimated to be 0.5% and 1.5%, respectively, i.e. higher than those at exit of the reservoir at the same time. For simplifying the calculation procedure, the stagnation temperature and mass flow rate of the flow along the connecting pipe are assumed to be the same as those at the exit of the air reservoir, i.e. the process is assumed to be quasi-steady. Since the instrument used to measure the variation of the pressure is more sensitive and quicker than that to measure the variation of the temperature during a transient process. To obtain more accurate results, this work adopts the experimental data of the pressure variation in the derived governing equations.

Based on the above assumptions and the ideal-gas equation of state, the temperature $T_{r,t}$ and mass $m_{r,t}$ of the air in the reservoir during the discharge process are then expressed as the following equations:

$$T_{r,t} = T_{r,t=i} \left(\frac{P_{r,t}}{P_{r,t=i}} \right)^{\gamma-1/\gamma}, \quad (1)$$

$$m_{r,t} = m_{r,t=i} \left(\frac{P_{r,t}}{P_{r,t=i}} \right)^{1/\gamma}, \quad (2)$$

where $t=i$ denotes the initial condition. By differentiating Eq. (2) with respect to time t , the transient mass flow rate \dot{m}_t discharged from the air reservoir is then expressed in terms of $P_{r,t}$ and $dP_{r,t}/dt$.

$$\dot{m}_t = -\frac{dm_{r,t}}{dt} = -\frac{1}{\gamma} \frac{m_{r,t=i}}{P_{r,t}} \left(\frac{P_{r,t}}{P_{r,t=i}} \right)^{1/\gamma} \frac{dP_{r,t}}{dt}. \quad (3)$$

According to Saad [7], the mass flow rate \dot{m}_t may be expressed as a function of the upstream static pressure $P_{u,t}$, the stagnation temperature $T_{r,t}$, the Mach number $M_{u,t}$ and the pipe cross-sectional area A as the air flows through the connecting pipe.

$$\dot{m}_t = \frac{P_{u,t}}{\sqrt{T_{r,t}}} \sqrt{\frac{\gamma}{R}} AM_{u,t} \sqrt{\left(1 + \frac{\gamma-1}{2} M_{u,t}^2 \right)}, \quad (4)$$

where the static pressure $P_{u,t}$ is obtained from experimental work and the stagnation temperature $T_{r,t}$ is calculated from Eq. (1). Then, the Mach number $M_{u,t}$ is determined from Eq. (4). Consequently, the static temperature $T_{u,t}$ of the air flow at the upstream of the test valve is obtained from Eq. (5).

$$T_{u,t} = \frac{T_{r,t}}{1 + ((\gamma-1)/2)M_{u,t}^2}. \quad (5)$$

Applying the same method allows us to calculate the properties of $M_{d,t}$ and $T_{d,t}$ of the air flow at the downstream of the test valve.

In industrial applications, as air flows through a valve, the relationship between the volumetric flow rate q and the pressure ratio x_t is expressed concisely as the C_v flow equation shown in Eq. (6) [6].

$$q = 4.17 Y C_v P_{u,t} \sqrt{\frac{x_t}{T_{u,t}}}, \quad (6)$$

Where q denotes the volumetric flow rate at 101.3 kPa and 15.6 °C and C_v is the valve flow coefficient. The pressure ratio x_t is defined as

$$x_t = \frac{P_{u,t} - P_{d,t}}{P_{u,t}}. \quad (7)$$

According to Driskell [8], the expansion factor Y can be expressed as a linear function of x_t as

$$Y = 1 - \frac{x_t}{3Fx_T} \quad (8)$$

where x_T represents the pressure drop factor and a kind of limiting value of x_t . For $x_t \geq x_T$, the value of q no longer increases. Where F equals the unit when air is the working fluid. Based on Eq. (8), as x_t is extremely close to zero, the value of Y is approximately equal to unit. Substitute the value of Y into Eq. (6), the valve flow coefficient C_v is obtained.

In addition to the volumetric flow rate q shown in Eq. (6), the dimensionless mass flow rate G_t which is defined in Eq. (9) is used to express the flow characteristics of the valve.

$$G_t = \frac{\dot{m}_t \sqrt{RT_{u,t}}}{AP_{u,t}}. \quad (9)$$

The calculation procedures for solving the above equations are summarized as follows:

1. Calculate the initial mass $m_{r,t=i}$ in the reservoir by applying the ideal-gas equation of state;
2. Use the time-dependent pressures $P_{r,t}$ obtained from the experimental work to calculate the pressure change rates $dP_{r,t}/dt$ of the air in the reservoir during the discharge process;
3. Calculate the temperature $T_{r,t}$ of the air in the reservoir from Eq. (1);
4. Calculate the mass flow rate of air \dot{m}_t from Eq. (3);
5. Obtain the upstream and downstream Mach numbers of $M_{u,t}$ and $M_{d,t}$ from Eq. (4);
6. Calculate the upstream and downstream static temperatures of $T_{u,t}$ and $T_{d,t}$ from Eq. (5);
7. Calculate the values of x_t , YC_v and G_t from Eqs. (6), (7) and (9), respectively; and
8. Plot the figures of YC_v and G_t versus x_t .

2.1. Experimental apparatus and procedure

Experiments are performed not only to provide data for the method proposed in the previous section, but also to validate the results calculated by the above method. Fig. 1 shows the experimental apparatus. An air reservoir

with a volume of 0.1065 m³ is used. The pressure and temperature of the air in the reservoir are measured by the pressure transmitter and thermocouple, respectively. The diameter of the thermocouple used is 0.003 in. A connecting pipe with the diameter 43.0 mm is connected to the air reservoir. Next, the ball valve with a nominal diameter of 1.5 in. is set at the middle section of the connecting pipe. The valve flow coefficient C_v obtained by this method is compared with that proposed by the ANSI/ISA [6] by initially performing a study to determine the valve flow coefficient C_v of a ball valve. Two pressure transmitters are separately installed on both sides of the test valve. The sampling rate of the data acquisition unit is set at 500 Hz. A throttling valve is installed at the position downstream of the test valve to vary the mass flow rate of the air discharged from the air reservoir. Finally, a diaphragm valve used as a quick-opening valve is installed at the exit of the connecting pipe and controlled by a programmable logic controller (PLC).

The procedures of the experimental work are as follows:

1. Set a certain displacement of the throttling valve;
2. Measure and record the initial pressure $P_{r,t=i}$ and temperature $T_{r,t=i}$ of the air in the reservoir under stable situation;
3. Execute the PLC program to open the diaphragm valve (quick-opening valve) under a designed duration Δt ;
4. Measure and record the pressure variations of $P_{r,t}$, $P_{u,t}$ and $P_{d,t}$ of the air in the reservoir, upstream and downstream of the test valve;
5. Measure and record the final state pressure $P_{r,t=f}$ and temperature $T_{r,t=f}$ of the air in the reservoir under a stable situation. The final state implies that the experimental work is completed and the values of the pressure and temperature of the air in the reservoir are invariant; and
6. Change the displacement of the throttling valve and iterate the above procedures until enough data are obtained.

The experimental apparatus to determine the valve flow coefficient of the diaphragm valve resembles that of the ball valve. The ball valve shown in Fig. 1 is displaced by the diaphragm valve. Under such a circumstance, the diaphragm valve simultaneously functions as the test valve and the quick-opening valve. The procedures are the same as those mentioned above.

Prior to conducting the experimental work, the pressure transmitters used are calibrated by a standard pressure gauge. These pressure transmitters are made of the TRANSBAR[®] ceramic sensing element. The measuring range is 0–10 bar. The error is within $\pm 0.2\%$ F.S. The typical response time is less than 3 ms. These pressure transmitters are calibrated by a WIKA standard pressure gauge which has the measuring range of 0–10 kg/cm², the scale division of 0.05 kg/cm² and accuracy within $\pm 0.5\%$ F.S.D. Calibration results indicate that the discrepancies between the readings of the standard pressure gauge and those of the pressure transmitters are within $\pm 0.5\%$.

3. Results and discussion

Fig. 2 shows the experimental results of pressures of $P_{r,t}$, $P_{u,t}$ and $P_{d,t}$ and a curve of the empirical equation of $P_{r,t}^*$. In this case, the test valve is a ball valve. The duration of the electric pulse for opening the diaphragm valve is 0.5 s. The initial pressure $P_{r,t=i}$ and temperature $T_{r,t=i}$ of the air in the reservoir are 620 kPa and 301 K, respectively. Due to the mechanical delay of the opening and closing of the diaphragm valve, the beginning and end of the pressure variation are slower than those of the electric pulse. After the diaphragm valve is opened, the discharged air decreases the pressure of the air in the reservoir and the value of $P_{r,t}$ decreases monotonously with time.

The ripples are hardly excluded in the pressure variation of $P_{r,t}$, which markedly affect the differential values of $dP_{r,t}/dt$. Then, an equation in Ref. [7] is modified to express the variations of pressure $P_{r,t}$ in the following Eq. (10). Where C_d denotes the discharge coefficient and equal to 0.388 and t_i represents the initial time and equal to 0.413 in this situation. Both values are obtained by the least squares method.

$$P_{r,t}^* = P_{r,t=i} \left[1 + \frac{(\gamma - 1) C_d A \sqrt{\gamma R T_{r,t=i} (2/(\gamma + 1))^{(\gamma+1)/(\gamma-1)}}}{2V} \right]^{2\gamma/(1-\gamma)} \times (t - t_i) \quad (10)$$

Notably, the deviations between the experimental results of $P_{r,t}$ and the numerical results of $P_{r,t}^*$ are smaller than 0.6%. Since the precision of the pressure transmitter used is 0.5%, the uncertainty of $P_{r,t}^*$ is about

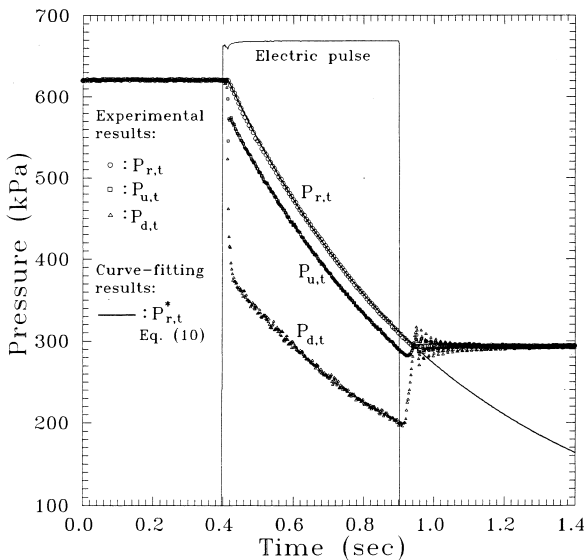


Fig. 2. The pressure variations of $P_{r,t}$, $P_{u,t}$ and $P_{d,t}$ with time.

$\pm 1.6\%$ under a confidence level of 95%. Therefore, the values of $P_{r,t}$ and $dP_{r,t}/dt$ in Eqs. (2) and (3) are displaced by the values of $P_{r,t}^*$ and $dP_{r,t}^*/dt$, respectively, to calculate the values of $T_{r,t}$ and \dot{m}_t .

Fig. 3 shows the variations of the values of x_t , YC_v and G_t with time. From $t = 0.5$ to $t = 0.9$ s, the values of x_t , YC_v and G_t are nearly constant, attributed to that the flow is choked in this duration. The time average values of x_t , YC_v and G_t in the duration are 0.328, 29.9 and 0.283, respectively. The maximum difference between the values of x_t , YC_v and G_t to their the average values are about 5%, 4% and 1%, respectively. These time average values are a set of useful data to obtain the flow characteristic curve of the valve as shown in the following figures.

Fig. 4 shows the linear relationship between the value of YC_v and the pressure ratio x_t . The maximum devia-

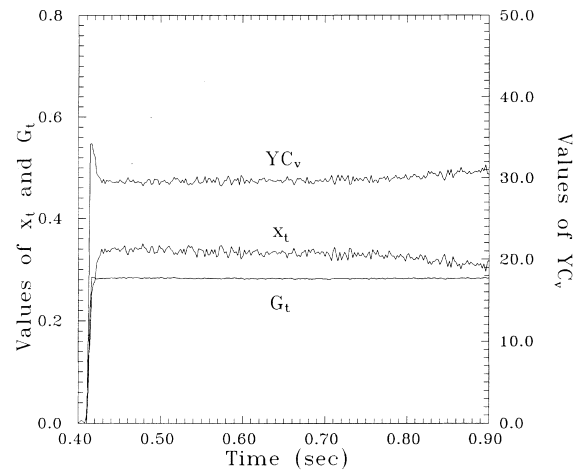


Fig. 3. The variations in the pressure ratio x_t , the value of YC_v and dimensionless mass flow rate G_t with time.

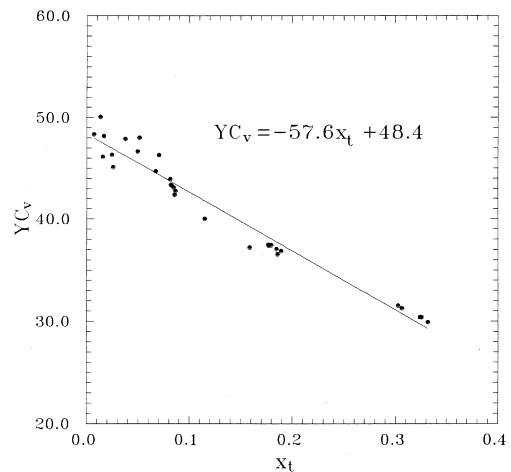


Fig. 4. The relationship between the value of YC_v and the pressure ratio x_t for the ball valve.

tion between the results of the empirical equation and the experimental work is about 10%. In addition, the value of C_v is calculated by an extrapolation method as $x_t=0$ and $Y=1$. In this case, the valve flow coefficient C_v of the ball valve is equal to 48.4, i.e. about 14% smaller than the representative value which is equal to 56.3 suggested by ANSI/ISA [6].

Fig. 5 shows the relationship between the dimensionless mass flow rate G_t and the pressure ratio x_t for the ball valve. A concise empirical equation which differs from the conventional form shown in Eq. (6) is proposed in a logarithmic form as

$$G_t = C_1 \ln(x_t) + C_2. \tag{11}$$

In this case, the constants of C_1 and C_2 are equal to 0.0625 and 0.361, respectively. The maximum deviation between the results of Eq. (11) and the experimental work is about 3%.

Until now, the flow characteristics of the diaphragm valves used in the pulse-jet cleaning system have rarely been investigated; it is unfeasible for industrial applications as well. Two different diaphragm valves, which are separately designated as "Valve A" and "Valve B", are examined by the method mentioned above. Both valves have the same nominal diameter of 1.5 in., where valve A is a double diaphragm valve and valve B is a single diaphragm valve.

Fig. 6 shows the relationships between the value of YC_v and the pressure ratio x_t for both the valve A and valve B. For $x_t < 0.15$, the trend markedly differs from that of the ball valve shown in Fig. 4. This large discrepancy is attributed to that the difference between the upstream and downstream pressures influences the displacement of the diaphragm. Under such a circumstance, the conventional C_v flow equation (Eq. (6)) is no longer adequate.

Fig. 7 shows the relationships between the dimensionless mass flow rate G_t and the pressure ratio x_t for both the valve A and valve B. This figure also contains

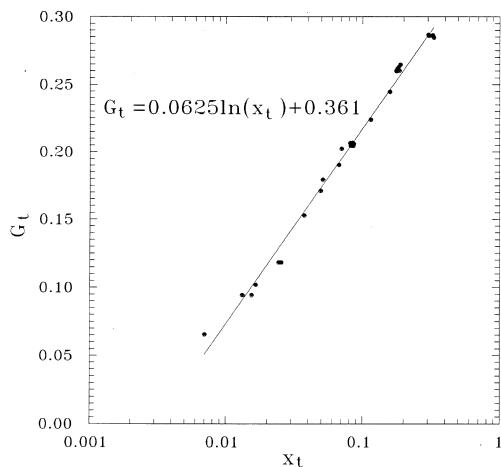


Fig. 5. The relationship between the dimensionless mass flow rate G_t and the pressure ratio for the ball valve.

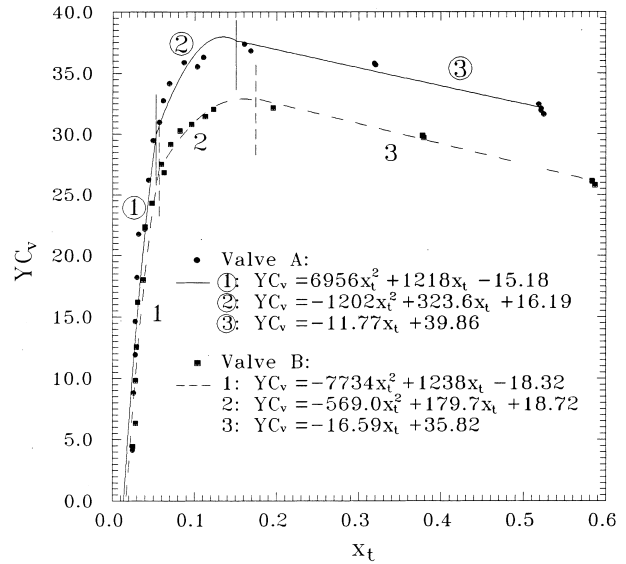


Fig. 6. The relationships between the value of YC_v and the pressure ratio x_t for the diaphragm valves.

empirical equations in the form of Eq. (11). The 95% confidence limits for the empirical equations of valve A and valve B are ± 0.0047 and ± 0.0064 , respectively.

Moreover, the proposed method's accuracy is evaluated by performing several experiments of different initial pressure $P_{r,t=i}$ (from 400 to 800 kPa) of the air in the reservoir. For each value of $P_{r,t=i}$, experiments of different electric pulse duration Δt (from 0.1 to 1.2 s) are conducted. The cumulated mass discharged obtained from experimental work and Eq. (2) are designated as $\Delta m_{i,f}$ and Δm_{cal} , respectively. Fig. 8 shows the results of the deviation between $\Delta m_{i,f}$ and Δm_{cal} versus the ratio of $\Delta m_{i,f}/m_{r,t=i}$. All the deviations are positive and smaller than 6% owing to that the assumption of adiabatic

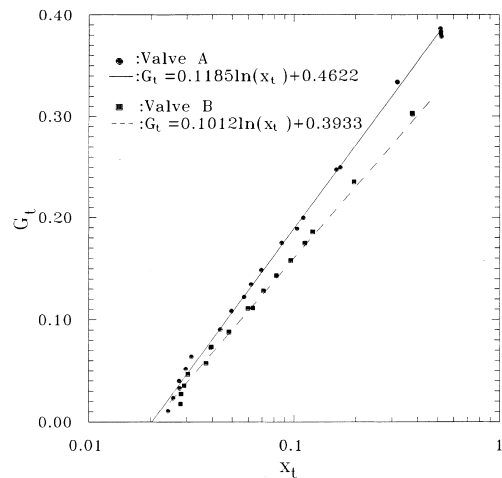


Fig. 7. The relationships between the dimensionless mass flow rate G_t and the pressure ratio x_t for the diaphragm valves.

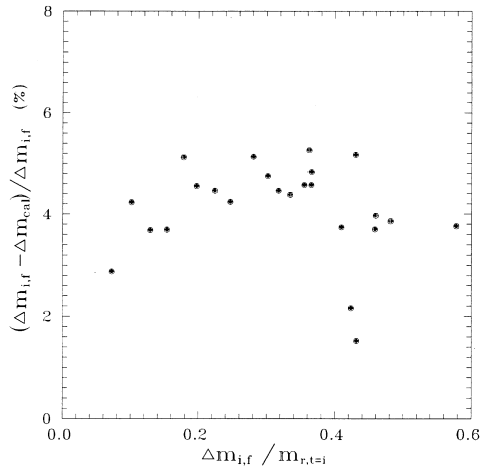


Fig. 8. The deviations of the cumulated mass discharged between the experimental and theoretical results.

process does not completely hold and the measurement error of $P_{r,t}$ is difficult to avoid. In experimental work, heat transfers to the air in the reservoir which subsequently increases the pressure of $P_{r,t}$ and increases the mass flow rate \dot{m}_t as well. Therefore, the values of $\Delta m_{i,f}$ are greater than the values of Δm_{cal} .

3.1. Practical significance and usefulness

A diaphragm valve is a very important device used to control the gas discharged from a reservoir. As the gas is discharged from the reservoir, the gas flow is a transient process and the mass flow rate of gas is difficult to measure. To our knowledge, no device is available to measure the mass flow rate of gas under the transient process. The method proposed in this study can accurately predict the mass flow rate of gas under the transient process. Besides, the method proposed herein can determine the valve flow coefficient used in the flow equation as well.

4. Conclusions

This work presents a novel method which combines the theoretical and experimental work to accurately determine the characteristics of a compressible gas flow through valves. One ball valve and two diaphragm valves are examined as well. Based on the results presented herein, the following conclusions are drawn:

1. Without any flow meter, the mass flow rate discharged from a reservoir can be obtained easily under a transient process and the accuracy is fairly good;
2. The valve flow coefficient can be determined conveniently under a transient condition; and
3. The conventionally used C_v flow equation is inadequate for the diaphragm valve.

Nomenclature

A	pipe cross-sectional area, m^2
C_1, C_2	constant
C_d	valve discharge coefficient, dimensionless
C_v	valve flow coefficient, dimensionless
F	ratio of specific heats factor, ($=\gamma/1.4$), dimensionless
G_t	dimensionless mass flow rate, dimensionless
$m_{r,t}$	mass of air in a reservoir ($= P_{r,t}V/RT_{r,t}$), kg
Δm	cumulated mass discharged, kg
\dot{m}_t	mass flow rate discharged from the air reservoir, kg/s
M	Mach number, dimensionless
P	pressure, kPa
q	volumetric flow rate at 101.3 kPa and 15.6 C, m^3/h
R	gas constant of air, ($= 287.04$), $m^2/(s^2 K)$
T	temperature, K
V	volume of the air reservoir, m^3
x_t	ratio of pressure drop to absolute upstream pressure, dimensionless
x_T	pressure drop ratio factor, dimensionless
Y	expansion factor, ratio of flow coefficient of a gas to that of a liquid at the same Reynolds numbers, dimensionless
γ	ratio of specific heats, ($= c_p/c_v$), dimensionless

Subscripts

r	reservoir
u	upstream conditions
d	downstream conditions
i	initial state fluid properties
f	final state fluid properties
t	time, second

Superscripts

*	curve fitting results
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