Pressure Response of Various Gases in a Pneumatic Resistance Capacitance System and Pipe

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Abstract: City gas, such as propane and methane, is widely used as a fuel in households and factories. Recently, hydrogen as a clean and efficient fuel has been proposed for fuel cell vehicles. However, few studies have investigated pressure control and response of gases considering their properties. This study investigated the static flow rate characteristics in an orifice with four gases—air, propane, methane, and hydrogen. Then, a pressure response experiment was performed using a pneumatic resistance capacitance system comprising an isothermal chamber and a nozzle flapper, and the time constant of the pressure response with various gases was analysed with a mathematical model. The simulation results agreed with the experimental data. Finally, the differences in pressure propagation in a pipe with various gases were explicited by a pressure response experiment. The results showed that the pressure response speed of hydrogen is faster than that of the other three gases because of its small molecular weight. Therefore, the pressure control equipment of hydrogen needs a high response speed.

1. Introduction

Compressible fluid is widely used in industry as a transmission medium or an energy source. Compressed air has been applied in pneumatic products that are driven by pressure differences, such as air cylinders and rotary actuators. Pneumatic systems have numerous advantages, such as high effectiveness, high durability and reliability, and environmental friendliness. The most city energy supply systems use methane as a city gas because it is a cleaner energy source than coal. Propane, which can be liquefied, is usually employed in areas that lack the necessary infrastructure, such as gas pipelines, because of its high energy density. Recently, hydrogen has been proposed as an environmentally friendly fuel that produces only water as a combustion product [1][2]. The most compelling application is the hydrogen fuel cell vehicle [3], the pressure is needed to control within about 10 kPa in the fuel cell from the hydrogen storage which owns the ultra-high pressure about 70 MPa [4]. Pressure control technology is indispensable for utilizing different gases. Air and propane are generally controlled by a pressure regulator called the pressure reducer valve and city gas is controlled by a gas governor [5]. Recently, many manufacturers and researchers are developing a new type of pressure regulator and bombe for the application of hydrogen [6][7].

It is known that the pneumatic resistance and the capacity, are the most important constituent of pneumatic and gas pressure control systems. And the pressure response experiment is an important method to evaluate the property of the gas pressure control equipment. However, city gases or hydrogen are all flammable and dangerous. Therefore, engineers generally use air in their pressure response
research and experiments for developing new pressure control equipment for the flammable gases. Because air source can be obtained conveniently and safely, and its properties are similar to those of city gas. Kagawa performed several studies on the dynamic characteristics and transient response of air in a chamber, nozzle flapper, and pipe 30 years ago [8-10]. Many researchers investigated and resolved the pressure transient response [11] of the compressible fluid in a pipe using the characteristic method [12-14]. Recently, Takeuchi [15] developed a pressure frequency response test to evaluate the stability of gas pressure regulator. Rahman [16] presented a pressure and temperature response within control volume of a pneumatic system with thermal consideration. Li [17] investigated the pressure control performance of the solenoid valve under PWM-controlled conditions by CFD simulation. Lee [18][19] performed numerical modeling of fluid pressure transients with air entrainment and proposed an improved numerical method and computational procedure for implementing typical air vessel responses and their influence on the pressure transient of unsteady flow in a pipeline system. However, these studies are all based on the properties of air. Shin [20] investigated the characteristics of transient flow and the possibility of freezing in a pressure regulator and the rear connecting pipe of the pressure regulator during the closing process of the pressure control valve by using the properties of nature gas in the calculation. However, this study only provided a theoretical calculation without sufficient supporting experiment data. Up to now, it is difficult to find some literatures for pressure response considering the different physical properties of various gases. Therefore, this study adopted experimental method to investigate the effect of different gas properties on the pressure response in a pneumatic resistance capacitance system and pipe. Four gases—air, hydrogen, methane, and propane—were chosen to perform a static flow rate characteristic experiment and two dynamic pressure response experiments. The flow rate equation for an orifice with the four gases was confirmed based on the experimental data, and the pressure response speed with various gases in the pneumatic resistance capacitance system was discussed. Finally, changes in the propagation speed of pressure wave and pressure vibration through a pipe with the various gases were studied. The research findings can provide the reference and help in the design and manufacture of different gas pressure control systems and equipment.

2. Laminar flow rate meter

In our experiment, we used a quick flow sensor (QFS; Figure 1) based on the laminar flow theory to measure the flow rate of the various gases [21]. The flow rate calculation of the QFS uses the Hagen–Poiseuille equation:

$$Q = \frac{\pi r^4 \Delta P}{8 \mu L}$$

where $Q$ is the volumetric flow rate, $r$ is the pipe radius, $L$ is the pipe length, $\mu$ is the dynamic viscosity, and $\Delta P$ is the differential pressure.

| Gas       | Density [kg/m$^3$] | Relative density | Viscosity [10$^{-7}$ Pa·s] | Relative viscosity | Gas constant [J/(kg·K)] | Specific heat ratio |
|-----------|-------------------|------------------|-----------------------------|--------------------|--------------------------|---------------------|
| Air       | 1.205             | 1.000            | 181                         | 1.000              | 287                      | 1.40                |
| Methane   | 0.668             | 0.554            | 108                         | 0.597              | 518.3                    | 1.32                |
| Hydrogen  | 0.083             | 0.068            | 88                          | 0.486              | 4128.5                   | 1.41                |
| Propane   | 1.882             | 1.562            | 80                          | 0.442              | 189                      | 1.13                |

*Temperature = 20 °C at atmospheric pressure
Figure 1. Laminar flow rate meter (QFS)

A flow rate meter is usually designed for air because of its universality. Therefore, the parameters of the QFS can only be used for air measurements; that is, the dynamic viscosity $\mu$ is of air. The parameters of the QFS must be modified to enable measurements for other gases. Table 1 presents the properties of the four gases. Based on the experimental data $Q_m$ obtained with the QFS, the real flow rate $Q_{\text{real}}$ of various gases can be obtained with equation (2), which uses the relative viscosity $\mu^*$.

$$Q_{\text{real}} = \frac{Q_m}{\mu^*}$$

(2)

3. $P-Q$ characteristics of an orifice with various gases

An orifice as a restriction is the most widely used pneumatic resistance. The relationship between the pressure and the flow rate $G$ is summarized by the well-known flow rate equation [22]:

when $\frac{P_D}{P_U} \leq \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa - 1}}$,

$$G(P_U, P_D, S_e) = S_e P_U \left[ \frac{\kappa}{R \theta_l} \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa + 1}{\kappa - 1}} \right]$$

(3.1)

and $\frac{P_D}{P_U} > \left(\frac{2}{\kappa + 1}\right)^{\frac{\kappa}{\kappa - 1}}$,

$$G(P_U, P_D, S_e) = S_e P_U \left[ \frac{2\kappa}{\kappa - 1} \frac{1}{R \theta_l} \left(\frac{P_D}{P_U}\right)^{\frac{2}{\kappa}} \left(\frac{P_D}{P_U}\right)^{\frac{\kappa + 1}{\kappa}} \right]$$

(3.2)
where \( S_e \) is the effective area, \( d \) is the orifice diameter, \( C_D \) is the discharge coefficient, \( R \) is the gas constant, \( P_U \) is the upstream pressure, \( P_D \) is the downstream pressure, \( \theta_1 \) is the flow temperature, and \( \kappa \) is the specific heat ratio.

Generally, the discharge coefficient \( C_D \) is mostly dependent on the structure and dimensions of the orifice, while at times, it is affected by the Reynolds number. In this experiment, the orifice was not changed and the Reynolds number was large most of the time. At large Reynolds numbers, changes in \( C_D \) are very small. Therefore, to compare the primary factor of influence, \( C_D \) was set to a constant equal to the \( C_D \) of air. Curve fitting of the experiment data revealed that the discharge coefficient is 0.89. On the other hand, the specific heat ratio \( \kappa \) of the different gases is close to each other; therefore, it is not a primary influencing factor compared with the gas constant. If the specific heat ratios of all gases are assumed to be the same as that of air, that is 1.4, it is not difficult to determine that the mass flow rate of the various gases is only dependent on the gas constant under a certain pressure difference. Therefore, the calculation results indicate that the volume flow rate of hydrogen, propane, and methane were 3.80, 0.79, and 1.34 those of air, respectively, under the same pressure difference. Note that we are talking about the volume flow rate, and not the mass flow rate.

A static experiment using a \( \phi 1 \) mm orifice was conducted to confirm the \( P-Q \) characteristic curve with various gases. The experimental location and sources of the various gases were provided by KATSURA Co., Ltd (Figure 2). Figure 3 shows the pneumatic circuit of the static experiment. Here, the upstream pressure was set constant at 0.1 MPaG and the downstream pressure was changed from 0.1 MPaG to atmospheric pressure through the flow rate control valve.

Figure 4 shows the static flow rate characteristic curve, that is, the \( P-Q \) characteristic curve with the various gases. The dashed curve represents the calculation results without considering the influence of \( \kappa \), that is, \( \kappa \) of all gases set to 1.4. The solid curve represents the calculation results considering the different values of \( \kappa \) of the various gases. The two curves of the same gas were generally coinciding, and the experimental data were consistent with these calculations. Therefore, it is believed that the flow rate equation for the orifice with various gases can neglect the effect of the specific heat ratio when its value is from 1.13 to 1.4.
4. Pressure response in a pneumatic resistance capacitance system

The gas flow through a valve or a pressure regulator can sometimes be seen as though a nozzle flapper. Next, the pressure response with the various properties of gases in an isothermal chamber (ITC) [23], which is a tank filled with copper wire, with an orifice and the step action of a nozzle flapper was investigated.

4.1. Calculation

The mathematical model of the ITC with an orifice and nozzle flapper is shown in Figure 5. The ideal gas equation for the ITC was differentiated with respect to time:

\[ P_2 V = mR \theta \]  
\[ VdP_2 \frac{dt}{dt} = R\theta \frac{dm}{dt} + mR \frac{d\theta}{dt} \]  

where \( P_2 \) is the pressure in the chamber, \( V \) is the volume, \( m \) is the mass of air in the chamber, \( \theta \) is the temperature, and \( R \) is the gas constant. Because the chamber is isothermal, \( d\theta / dt = 0 \) and \( \theta = \theta_a \). Furthermore, \( dm / dt = G \), where \( G \) is the mass flow rate. Therefore, equation (6) was changed to

\[ \frac{dP_2}{dt} = R\theta_a \frac{(G_1 - G_2)}{V} \]  
\[ P_2 = \int \frac{R\theta_a (G_1 - G_2)}{V} \, dt \]  

Figure 6. Block diagram
The flow rate through the upstream orifice $G_1$ and the downstream nozzle flapper $G_2$ are also determined by equations (3) and (4). The specific heat ratios of all gases are set to 1.4 according to the conclusion of Section 3. So, we propose the gas constant and simply note:

$$G_1 = \frac{1}{\sqrt{R}} \phi_1 (P_1, P_2, S_{a_1}), \quad G_2 = \frac{1}{\sqrt{R}} \phi_2 (P_2, P_a, S_{ex})$$

(9)

The flow rate $G_1$ and $G_2$ are linearized at the pressure balance point $P_{2ref}$ and the flow rate gain $a$ is defined as follows:

$$a = \frac{\Delta G_1 - \Delta G_2}{\Delta P_2}$$

(10)

The block diagram is shown in Figure 6. From this block diagram, the transfer function is obtained:

$$F(s) = \frac{1}{1 + T_p s}$$

(11)

Here, $T_p$ is the time constant [9] of the system:

$$T_p = \frac{V}{aR\theta_a}$$

(12)

Using equations (9) and (10), we have

$$a = \frac{1}{\sqrt{R}} \left( \frac{\Delta \phi_1 (P_1, P_2, S_{a_1}) - \Delta \phi_2 (P_2, P_a, S_{ex})}{\Delta P_2} \right)$$

(13)

Figure 7. Pressure response of $P_2$
Defining
\[ \alpha^* = \frac{\Delta \varphi_1(P_1, P_a, S_{ex}) - \Delta \varphi_2(P_2, P_a, S_{ex})}{\Delta P_2} \]
we get
\[ \alpha = \frac{1}{\sqrt{R}} \alpha^*, \text{ and } T_p = \frac{1}{\sqrt{R}} \frac{V}{\vartheta_a} \] (15)

From equation (15), it can be seen that the time constant is inversely proportional to the square root of the gas constant of the various gases when the other experimental conditions are fixed.

4.2. Pressure response experiment
The pneumatic circuit of the pressure response experiment is also shown in Figure 3, but the flow control valve is changed to a nozzle flapper. In the discharge process, the effective area of the downstream restriction was changed from 0.15 mm² to 0.85 mm² by controlling the displacement between the nozzle and flapper with propane, while the effective area of the downstream restriction was changed from 0.1 mm² to 0.9 mm² with the other gases. Of course, the action is opposite in the charge process. The upstream pressure was set to 0.1 MPa.

The pressure response of \( P_2 \) in the ITC is shown in Figure 7. The black dashed curve represents the simulation results obtained with MATLAB, and the orange curve is the experimental sampling data. The results obviously show that the pressure response speed of hydrogen is the fastest, while that of propane is the slowest. The time taken to reach an 63.2% drop in the response pressure is defined as the time constant of the various gases. Note that \( T_{pA}, T_{pH}, T_{pM}, \) and \( T_{pP} \) represent the time constant of air, hydrogen, methane, and propane, respectively. The calculation results show that \( T_{pA} = 1.91 \text{ s}, T_{pH} = 0.50 \text{ s}, T_{pM} = 1.42 \text{ s}, \) and \( T_{pP} = 2.31 \text{ s}. \) Therefore, the time constant of air is 3.82 times that of hydrogen, which is precisely equal to the reciprocal of the square root of the gas constant times. The experiment data also show agreement with the calculations, that \( T_{pA}^* = 2.12 \text{ s}, T_{pH}^* = 0.55 \text{ s}, T_{pM}^* = 1.48 \text{ s}, \) and \( T_{pP}^* = 2.61 \text{ s}. \) Therefore, the results verify the conclusion of equation (15). As we know, the gas constant refers to the molecular weight of the gas. Thus, it is certainly believed that the high response speed of hydrogen is owing to its small molecular weight. Finally, it must be noted that the pressure control system needs a high response speed when hydrogen is used. These results can help engineers in designing gas pressure control equipment with various gases, particularly, hydrogen pressure control systems.

5. Pressure propagation through a pipe with various gases
Pipe is another important constituent of pneumatic and gas pressure control systems. We performed a pressure response experiment using an 20 m pipe, and the dynamic characteristics of the pressure propagation with various gases were explicated; the pipe’s inner diameter was 6.5 mm.
5.1. Experiment

Figure 8 shows the pneumatic circuit of the dynamic pressure response experiment. In this experiment, the upstream pressure was set to 50 kPaG, and the downstream pressure was maintained at 2.8 kPaG using a second-stage regulator KLS-5B. The pressure in front of the pipe was recorded with a pressure sensor $P_f$ and that at the back of the pipe was recorded with $P_b$. The steps of the experiment are illustrated as follows:

1) Discharge process:
   a. Slowly shut control valve 2, hold the downstream pressure at 2.8 kPaG.
   b. Shut control valve 1.
   c. Open control valve 2 quickly and record the data until the pressure is stable.

2) Charge process:
   a. Shut control valve 1, wait till the downstream pressure decreases to the atmospheric pressure and stabilizes.
   b. Shut control valve 2.
   c. Open control valve 1 quickly and record the data until the pressure is stable.

5.2. Results and discussion

Figures 9 and 10 show the results of the pressure response in the discharge and charge processes, respectively, with various gases. The black curve represents the pressure response $P_f$ in front of the pipe, and the blue curve represents the pressure response $P_b$ at the back of the pipe.

In the discharge process, it can be observed that there is some time delay in the pressure response curve of $P_f$ with air, methane, and propane, but the time delay with hydrogen is very small. This is thought to be because the time taken for the pressure wave to travel from the back to the front of the pipe with hydrogen is way lesser than that with the other gases. The speed of sound is determined by $c = \sqrt{kT}$. Therefore, the speed of sound in hydrogen is way faster than that in the other three gases because of their large gas constants. On the other hand, the large gas constant means that the molecular weight of hydrogen is very small, and that of propane is large. That is, propane is very heavy and hence

![Figure 9. Pressure response in pipe (Discharge)](image-url)
has a large inertia. In Figure 9(d), it seems that there is a large vibration in $P_f$ with propane when the pressure reaches the atmospheric pressure, while a slight vibration is observed with hydrogen in figure 9(c).

The time delay phenomenon also occurs in the charge process, but the delayed pressure is $P_b$ because of the reverse flow direction. A pressure vibration which likes the water hammer is occurred at the back of the pipe because of the propagation of the pressure wave. The period of the pressure vibration is determined by $T = \frac{4L}{c}$. Here, $L$ is the length of the pipe. The pressure vibration periods for air, methane, propane and hydrogen are 0.23 s, 0.17 s, 0.29 s, and 0.06 s, respectively. From the form of the pressure wave in Figure 10, the results roughly accord with the calculations. The amplitude of the pressure wave demonstrates the vibration intensity. In figure 10(d), when the propagation medium is propane, the amplitude of the pressure wave at the back of the pipe is larger than that of the other three gases. Meanwhile, the pressure wave owns the smallest amplitude in hydrogen, and the vibration time is extreme short that no more than one period. Similar to the phenomenon of the water hammer, the maximum amplitude $A_P$ of the pressure vibration at the back of the pipe is determined by

$$A_P = \rho c u$$

(16)

Therefore, the maximum amplitude of pressure wave in hydrogen is certainly small, because the density of hydrogen is only 0.068 times that of air, even though its sound speed is larger than the other gases. On the contrary, the pressure vibration owns a large amplitude in propane due to its large density. Of course, many other factors, such as friction at the pipe’s inner wall and the boundary condition affect the pressure response and the pressure wave propagation. Therefore, a high-precision simulation needs to be performed in a future study.

6. Conclusions
In this study, a static flow rate characteristic experiment using an orifice was performed with various gases. The effect of the viscosity and gas constant of the gases on the flow rate measurement and $P-Q$
characteristic curve was understood. Two dynamic pressure response experiments with a pneumatic resistance capacitance system and a pipe were performed to verify the effect of the gas constant of various gases on the pressure response speed. Finally, the following conclusions were obtained:

(1) The flow rates can be calculated by only considering the gas constant of the various gases in an orifice with a constant area under a certain pressure difference because the influence of \( \kappa \) is negligible when its value is from 1.13 to 1.4.

(2) The time constant of the various gases is equal to the reciprocal of the square root of the gas constant. That is, the pressure response speed of hydrogen is 3.82 times that of air in a pneumatic resistance capacitance system.

(3) The pressure response speed in a pipe with hydrogen is much faster than that with the other three gases, and a large pressure vibration does not easily occur because of its small density. In contrast, propane has a large pressure vibration.

References
[1] Zuttel A, Remhof A, Borgschulte A and Friedrichs O 2010 Hydrogen: the future energy carrier Philosophical Transactions of the Royal Society A 368 3329–3342.
[2] Kler A M, Tyurina E A, Potanina Y M and Mednikov A S 2015 Estimation of efficiency of using hydrogen and aluminum as environmentally-friendly energy carriers International Journal of Hydrogen Energy 40(43) 14775-14783.
[3] Hwang Y G 2016 Technical trends of hydrogen manufacture, storage and transportation system for fuel cell vehicle Journal of The Korean Institute of Resources Recycling 25(1) 48-59.
[4] Wong J and Gambone L, 2006 70 MPa fueling station for hydrogen vehicles 16th World Hydrogen Energy Conference Lyon France.
[5] Takeuchi T and Kagawa T, 2013 Applicability of frequency response test for stability evaluation of gas pressure regulator Transactions of the Society of Instrument and Control Engineers 49(8) 747-754.
[6] Nakano A, Maeda T, Ito H, Masuda M, Kawakami Y, Tange M, Takahashi T and Nishida K 2012 Study on absorption/desorption characteristics of a metal hydride tank for boil-off gas from liquid hydrogen International Journal of Hydrogen Energy 37(6) 5056-5062.
[7] Mizuno T, Youn C, Nakamura Y and Kagawa T 2013 A simulation study of radial slits pressure regulator for hydrogen gas AsiaSim 2013: 13th International Conference on Systems Simulation (Singapore) Tan G, Yeo G K, Turner S J and Teo Y M pp 288-297.
[8] Kagawa T and Shimizu M 1988 Nondimensional pressure responses of pneumatic RC circuits considering heat transfer Hydraulics & Pneumatics 19(4) 308-311.
[9] Kagawa T 1982 Transient pressure response of pneumatic nozzle flapper Transactions of the Society of Instrument and Control Engineers 18(6) 617-621.
[10] Kagawa T, Kitagawa A and Takenaka T 1984 An analysis of transient response of a pneumatic transmission line terminated by volume using characteristics method Transactions of the Society of Instrument and Control Engineers 20(11) 1014-1018.
[11] Brown F T, Margolis D L and Shah R P 1969 Small-amplitude frequency behavior of fluid lines with turbulent flow ASME, Journal of Basic Engineering 91(4) 678-693.
[12] Zielke W 1968 Frequency-dependent friction in transient pipe flow. Trans. ASME, Journal of Basic Engineering 90(1) 109-115.
[13] Kitagawa A, Kagawa T, Sanada K and Okada T 1997 A study on the transient characteristics of the flow in pneumatic transmission line Transactions of the Society of Instrument and Control Engineers 33(4) 227-233.
[14] Yoshida M, Kawato T, Fujita T, Kawashima K and Kagawa T 2003 Modeling of Gas Transmission Systems Considering Heat Transfer Transactions of the Society of Instrument and Control Engineers 39(3) 253-258.
[15] Takeuchi T and Kagawa T 2013 Applicability of frequency response test for stability evaluation of gas pressure regulator Transactions of the Society of Instrument and Control Engineers
49(8) 747-754.

[16] Rahman F 2015 Pressure and Temperature Response of Pneumatic System with Thermal Consideration Global Journal of Research In Engineering 15(4) 23-27.

[17] Li S, Wu P, Cao L, Wu D and She Y 2017 CFD simulation of dynamic characteristics of a solenoid valve for exhaust gas turbocharger system Applied Thermal Engineering 110(5) 213–222

[18] Lee T S 1994 Numerical modelling and computation of fluid pressure transients with air entrainment in pumping installations International Journal For Numerical Methods In Fluids 19 89–103.

[19] Lee T S 1998 A numerical method for the computation of the effects of an air vessel on the pressure surges in pumping systems with air entrainment International Journal For Numerical Methods In Fluids 28 703-718.

[20] Shin C H 2013 A numerical study on the characteristics of transient flow in a pressure regulator resulting from closure of the pressure control valve Journal of Mechanical Science and Technology 27(2) 443-449.

[21] Kagawa T, Saisu Y, Nishimura R and Youn C, 2009 Development of high speed response laminar flow meter for air conditioning 10th International Conference on Fluid Control, Measurements, and Visualization (Moscow, Russia)

[22] Oertel H 2004 Prandtl’s Essentials of Fluid Mechanics, 2nd ed (Springer, New York, USA) pp 190-193.

[23] Kawashima K, Kagawa T and Fujita T 2000 Instantaneous flow rate measurement of ideal gases Transactions of the ASME Journal of Dynamic Systems, Measurement, and Control 122 174-178.