Experiment Research of Autonomous Driving Valve for Pulse Detonation Rocket Engine

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Keywords: valve, pulse detonation engine, pulse detonation rocket engine, PDE, PDRE, PDR

Abstract

As pulse detonation engine (PDE) does not need compression mechanisms such as compressors because self-sustained detonation waves are able to compress propellant gases by their incident shock waves, the PDE can have a simple straight-tube structure.

In this study, we propose an autonomous driving valve system of the PDE, which fill premixed gases into the PDE tubes at high frequency with high mass flow rate. The proposed valve is composed of only three parts: a piston, a cylinder, and a spring. This valve system can produce intermittent flow at high mass flow rate, and also can keep stable reciprocal motion by using the propellant-gas enthalpy. When the cylinder content product is assumed to be constant, experimental results of the mass flow rate were approximately equal to the calculation model. We confirmed the autonomous driving valve performance by experiments, and concluded that this extremely simple valve with no electrical power and controller can be used as the PDE propellant supply system.

Introduction

Pulse detonation engine[1-2] (PDE) obtains thrust by generating detonation wave intermittently. There are many PDE review papers (Kailasanath[3-4], Bazhenova and golub[5], Roy et al.[6]). The PDE for aerospace propulsion obtains thrust by blowing the detonated high-pressure gas down. Typical shape of PDE is straight tube. One end of this tube is closed and the other is opened. After filling the propellant gas in this tube, the gas is ignited at the closed end of the tube and the detonation is initiated. Self – sustained detonation wave, which compress the propellant by shock wave, propagates toward open end of the tube. The engine can be operated even if there are no compression mechanism such as compressors and pistons. Sufficient specific impulse (200-350sec) can be obtained even by the same fill pressure as ambient air (Zitoun and Desbordes[7], Morris[8], Endo and Fujiwara[9], Endo et al.[10], Wintenberger et al.[11], Cooper et al.[12]). The rocket engine with an extremely low combustor fill pressure becomes possible[8] (pulse detonation rocket engine, PDRE). The flow as simplified PDE[9-10] can be achieved because in the combustor of PDRE, there is no interaction with the air-breathing mechanism (intake and compressor) install before the combustor (the air breathing PDE are studied by many researchers: Tally and Coy[15], Wintenberger and Shepherd[16], Harris et al.[17], Ma et al.[18], Kojima and Kobayashi[19]). Moreover, it is easy to increase the specific impulse by using the mechanism (an extension tube for partial filling[18], an ejector[19-29], or a nozzle[8]) installed after the combustor.

Our research[21-23] did verification test of thrust and the system model building for PDR system, and it showed that performance is able to forecast. It is necessary to increase mass flow rate for thrust increase. However, the existing magnetic valve need electronic power supply, and mass flow per unit mass is low. It is consider that the existing rotary valve suitable for PDE compared with the magnetic valve because mass flow per unit mass is high, but it needs driving parts.

This research develops the autonomous driving valve that extremely simple and mass flow per unit mass is high. This valve composed of only three parts: a piston, a cylinder, and a spring. In this valve, enthalpy of propellant gas makes a piston to vibrate. Thereat, it does not need the driving parts such as controller and power supply. This paper shows schematic diagram of the valve, principle of the valve operation, measurement experimentation of mass flow, and we show that this valve is approved as a supply system for PDRE.

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Autonomous driving valve

Schematic diagram of the valve

It shows the cross-section diagram in Figure 1-1 and the piston photograph in Figure 1-2. As shown in Fig.1, the Autonomous driving valve composed of mainly three parts: a piston, a cylinder, and a spring. The cylinder material is stainless steel material (SUS304), and the shape is a cube (160 mm×50 mm ×60 mm). The cylinder has a hole for the piston insertion that is 30 mm in diameter and 145 mm in depth. It has the intake port with 5mm in diameter for oxidizer or fuel at 105 mm from the cylinder open end. It has the exhaust port with 5mm in diameter at 67 mm from the cylinder open end. It has both the intake and the exhaust ports with 5mm in diameter for purge gas at 47 mm from the cylinder open end. The piston material is aluminum material (AL5056) to work easily because the piston is worn out by vibrate. The piston entire length is 155 mm. The piston has eight penetration holes with 3 mm diameter and four grooves for O-ring as shown in Fig.1-2. Moreover, in order to soften the collision by the piston vibration, the cushioning is attached to both ends. The spring is connected to the piston and the spring fixed board.

The cylinder and the spring fixed board are fixed on the same foundation.

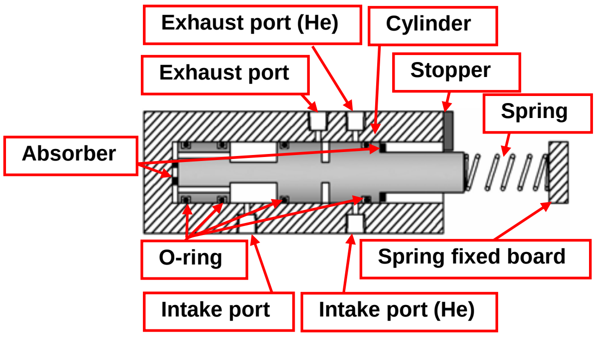


Fig.1-1 Cross-section diagram of the valve

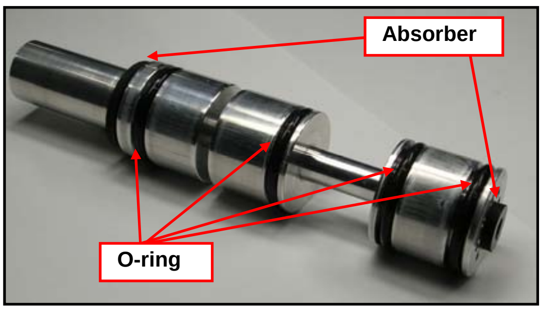


Fig.1-2 Piston photograph

Principle of the valve operation

Figure 2-1 shows principle of the valve operation and the gas state point in a pressure-position plane. As shown in Fig.2-1, the piston and the cylinder are simplified. The volume A means a gas filling volume. The piston displacement x sets displacement of the state [1] to 0, and the cylinder opening end side is positive direction. In the state [1], a gas flows into the valve from the intake port. In the volume A, the pressure increases from the ambient pressure to the supply pressure momentarily ($p_a \rightarrow p_s$). The piston moves positive direction of x because dynamic equilibrium doesn't keep (because the piston has penetration hole and the cylinder is fixed.). Secondly, when the state [1] goes on to the state [2], it has already gone up to the supply pressure in the state [1]. Therefore, the state point moves to positive direction of x. In addition, the initial state from the second cycle is the state [2]. Next, the state [2] goes on to the state [3] that the intake port is closing and the exhaust port is just before opening. When moving to the state [3] from the state [2], the volume A increases. However, the increasing volume is vanishingly small compare with the total of the volume A, so the state point moves to positive direction of x with constant pressure. Next, the state [3] goes on to the state [4] that the intake port is closing and the exhaust port is opening. In the volume A, the pressure decreases from the supply pressure to the ambient pressure momentarily ($p_s \rightarrow p_a$). The piston moves to the state [5] because of the inertia force, and the repulsion force of the spring pushes at the piston. Finally, it returns to the state [2].

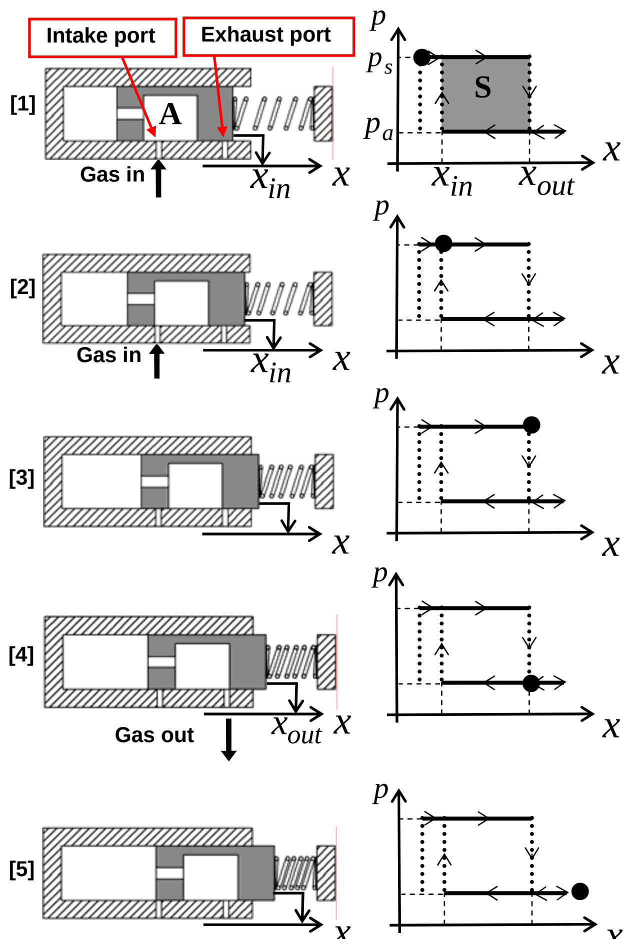


Fig. 2-1 Principle of the valve operation and a gas state point in a pressure-position plane

The area S in a pressure-position plane shows the work that a gas was made piston per unit the piston cross-section area. It turns out that the enthalpy of a gas is changed into the kinetic energy of the piston. In addition, since the piston displacement is controlled with the stopper by the actual valve, the intake port does not open.

Calculation model for mass flow

The calculation mass flow rate can be obtained from the principle of the valve operation. The mass flow is calculated in 10 cycles because the experiment measured mass flow per 10 cycles. The meaning of a subscript is as being shown below respectively: *e* is experimental values, *c* is calculation values, *A* is a gas filling volume in the valve, *T* is tank, *i* is the number of the cycle, *ave* is average in the experiment.

Let $p_{e,T,i}$ of the experimental result be the initial condition. We can obtain the gas mass in the tank and the mass flow per 1 cycle in first time from the state Eq. (1) and Eq. (2) (the pressure in the volume A is $p_{e,T,i}$ at this time). Therefore, we can obtain the mass in the tank after 1 cycle from Eq. (3). Next, we can obtain mass flow per 1 cycle in the second time from Eq. (4)-(5). By repeating the above work, We can obtain the mass flow per 10 cycle from Eq. (7), and It changes into the mass flow rate from Eq.(8). The frequency f_{ave} is the average operation frequency of 10 cycle obtained in the experiment.

In addition, since the tank volume is small and there is little mass flow rate, it assumes the temperature in the tank is average temperature T_{ave} at before and after the experiment

$$m_{c,T,i} = \frac{MV_T\, p_{e,T,i}}{\Re T_{ave}} \tag{1}$$

$$m_{c,A,i} = \frac{MV_A\, p_{c,A,i}}{\Re T_{ave}} \tag{2}$$

$$m_{c,T,i+1} = m_{c,T,i} - m_{c,A,i} = \frac{Mp_{c,A,i}(V_T - V_A)}{\Re T_{ave}} \quad (p_{e,T,i} = p_{c,A,i}) \tag{3}$$

$$p_{c,T,i+1} = \frac{m_{c,T,i+1}\Re T_{ave}}{V_T M} = \frac{p_{c,T,i}(V_T - V_A)}{V_T} \tag{4}$$

$$m_{c,A,i+2} = \frac{MV_A\, p_{c,T,i+1}}{\Re T_{ave}} \tag{5}$$

$$\vdots$$

$$m_{c,A,i+10} = \frac{MV_A\, p_{c,T,i+10}}{\Re T_{ave}} \tag{6}$$

$$\Delta m_c = \sum_{i}^{i+10} m_{c,A,i}$$

(7)

$$\dot{m}_c = \Delta m_c \times \frac{1}{10} \times f_{e,ave} \tag{8}$$

Experimental overview and apparatus

Experimental measurement of mass flow

Figure 3-1 shows schematic diagram of the mass flow measurement experimental. It fills up with the nitrogen gas into the tank (3.785L, manufactured by swagelok) temporarily from high pressure tank, and it exhausts to the atmosphere by way of autonomous drive valve. As shown in Fig.3-1, in order to measure the pressure in the tank and the pressure in the valve, the diaphragm type pressure gauge (VPRNP-A2-1000kPa, manufactured by VOLCOM) is installed. Moreover, in order to check opening-and-closing of intake and exhaust port, specify start point of the piston for the cycle, the piston displacement is measured using the laser displacement meter (LK-G 3000V, LK-G400 manufactured by KEYENCE). As shown in Fig.3-4, the piston weight can be arbitrarily changed by putting weight on the rail guide installing both the sides of the valve.

The initial pressure $p_{e,T,i}$ in the tank where the piston displacement become the maximum and the pressure after 10 cycle $p_{e,T,i+10}$ measure from the experimental result. We can obtain the mass flow per 10 cycle from Eq. (9), and It changes into the mass flow rate from Eq.(10). In addition, it assumes the temperature in the tank is average temperature T_{ave} at before and after the experiment.

In this experiment, the supply pressure p_s=1MPa, the spring constant k=9800N/m, k=4900N/m, k=2940N/m, and the piston weight m=12.80kg, m=3.88kg.

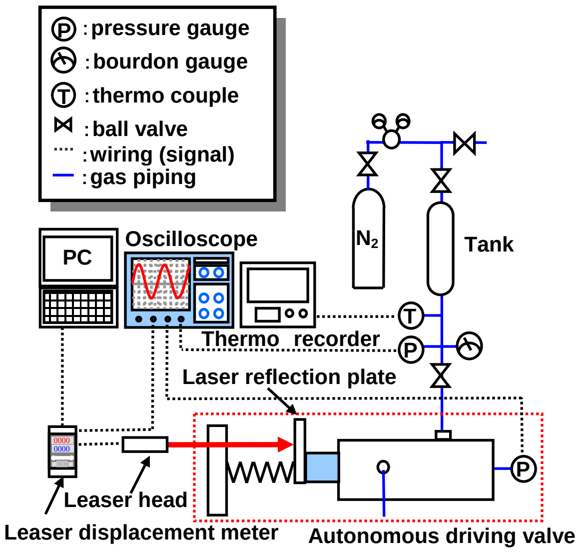


Fig. 3-1 Schematic diagram of a mass flow measurement experimental

$$\Delta m_e = m_{e,T,i} - m_{e,T,i+10} = \frac{MV_T p_{e,T,i}}{\Re T_{e,T,i}} - \frac{MV_T p_{e,T,i+10}}{\Re T_{e,T,i+10}}$$

$$= \frac{MV_T \left(p_{e,T,i} - p_{e,T,i+10} \right)}{\Re T_{ave}} = \frac{MV_T \Delta p}{\Re T_{ave}} \qquad (9)$$

$$\dot{m}_e = \Delta m_e \times \frac{1}{10} \times f_{e,ave} \qquad (10)$$

Experiment of Valve Steady Operation

What is important to operate this valve system for PDRE is the timing to a supply propellant gas and a purge gas into the PDE tube and ignite. In this study, we devise two of autonomous driving valve are combined which is including ignition system. Fig.3-2 shows schematic diagram of purge gas exhausting. Both the exhaust and the intake ports for purge gas are placed in same phase. At the state [1] in Fig.3-2, the purge gas can flow through the valve when both the intake and exhaust ports are opening while the propellant gas ports are closing. The piston geometry like this makes it possible to certainly exhaust purge gas after exhaust of a fuel or an oxidizer. Also, because a purge gas is exhausted twice at each cycle, mass flow rate of purge gas becomes larger which is supposed to be important for continuous operation of PDE. Figure.3-3 shows schematic diagram with the experiment of valve steady operation. Three tanks with nitrogen are used instead of an oxidizer, a fuel and a purge gas. In order to measure the pressure after exhaust, the diaphragm type pressure gauge is installed as shown in figure. About ignition, the proximity sensor is used which can ignite detecting the piston displacement. Figure.3-4 shows the photograph of the double autonomous driving valve with experiment of valve steady operation. These two pistons have taken the synchronization by joining together with the metal plate. In this experiment, the supply pressure p_s=1MPa, the spring constant of k=9800N/m, and the piston weight m=3.88kg.

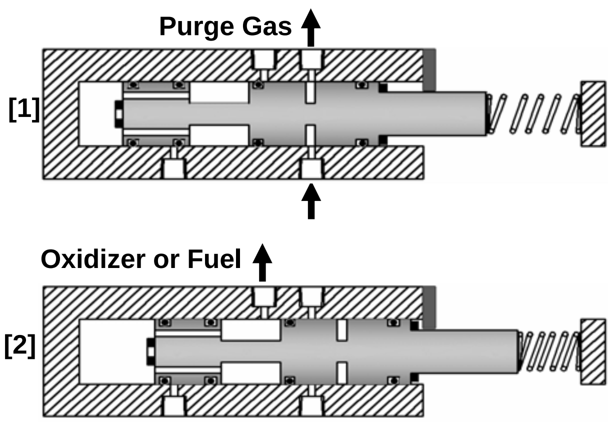


Fig. 3-2 Schematic diagram of purge gas exhausting

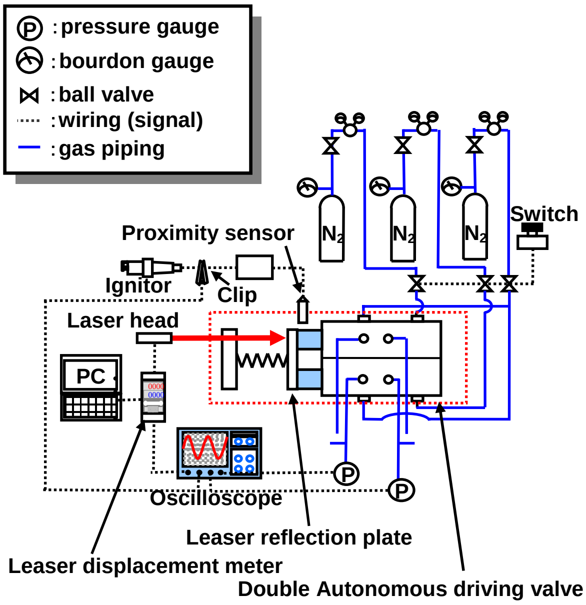


Fig. 3-3 Schematic diagram with the experiment of valve steady operation

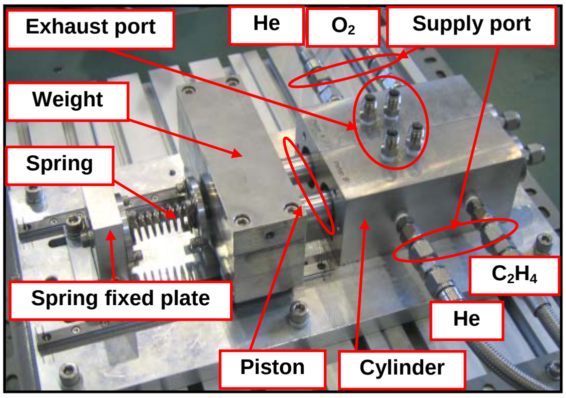


Fig. 3-4 Photograph of the double autonomous driving valve with experiment of valve steady operation

Experimental result and consideration

Result of Mass Flow Measurement

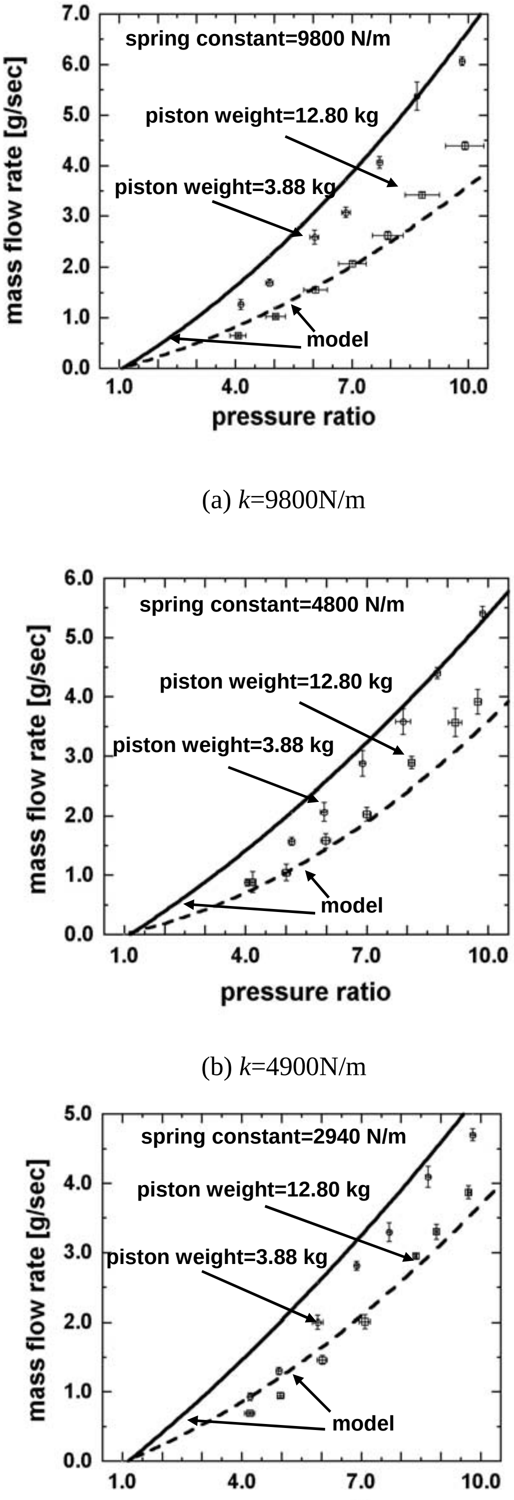
Figure 4-1 shows comparison of experimental values and the calculated values with different spring constant. Horizontal axis shows pressure ratio which is made dimensionless by ambient pressure, and note that the experimental plotted data means average the supply pressure of 10 cycles. These shows the experimental values are well correspond with the calculated values in the model calculation. Fig.4-2 shows comparison of frequency ratio with different spring constant. In Fig.4-2, frequency ratio on vertical axis is dimensionless values by the characteristic frequency which is calculated by mass of the piston and the constant of spring. In other words, the frequency ratio means velocity ratio of the velocity in simple harmonic oscillation and the velocity in forced oscillation. This autonomous driving valve is in forced oscillation model containing the term meaning of external pressure (external force). The piston reciprocates converting enthalpy into kinetic energy effectively. This kinetic energy is given by the velocity and mass of the piston when supplied gas pushes the piston. This piston velocity depends on spring constant, mass of the piston, and the viscous friction. In the comparison as same mass of the piston, the frequency ratio is larger value with smaller the spring constant even if the supply pressure is constant. It is considered that it is because the one where a spring constant is smaller has taken out kinetic energy efficiently, when the piston carries out a forced oscillation by the same power. Also, in the comparison as same the spring constant, the frequency ratio is larger with the larger mass of the piston even if the supply pressure is constant. It is considered that it is because the one where the piston mass is larger has taken out kinetic energy efficiently, when the piston carries out a forced oscillation by the same power. In fact, Low frequency can take out high movement energy compares with the kinetic energy in single vibration. However, it is necessary to optimize because the work per unit time is small in low frequency. Figure 4-3 shows comparison of flow ratio with different spring constant. The flow ratio of a vertical axis is the dimensionless values by calculation mass flow, and flow ratio=1 means ideal flow ratio. From these results, The flow ratio was changing from these graphs among 70% - 120% percent, and it can be said that the result as a calculation model came out.

Thrust prediction can calculate easily using Eq. (11) because it can be proved that mass flow can be predicted by a calculation model.

$$F = I_{sp}\, g\left(m_f + m_o\right) \tag{11}$$

In Eq.(11), m_f is a mass of fuel and m_o is a mass of oxidizer. Mixing rate is m_f: m_o=1:3. Figure 4-4 shows the relation of thrust and the cylinder volume. We assume specific impulse I_{sp}=170sec, operating frequency f=25Hz. In Fig.4-4, the volume on horizontal axis is gas filling volume A at state3 in Fig.2-1. According to Fig.4-4, it is thought possible to take out the thrust of about 25N with A=70.8 cm^3 as internal volume and p_s=1MPa as the supply pressure.

Figure 4-5 shows the experimental result and diagram with the valve of valve steady operation. A purge gas was exhausted right after exhaust of the propellant gas. The ignition noise came out after the propellant gas was fully exhausted. In addition, the valve worked f=18.58Hz operating frequency on average. However, it is supposed that ideal ignition should be done at the exhaust port closing. Although a time interval is necessary between the propellant gas exhaust and a purge gas exhaust, it is possible by changing a piston form.

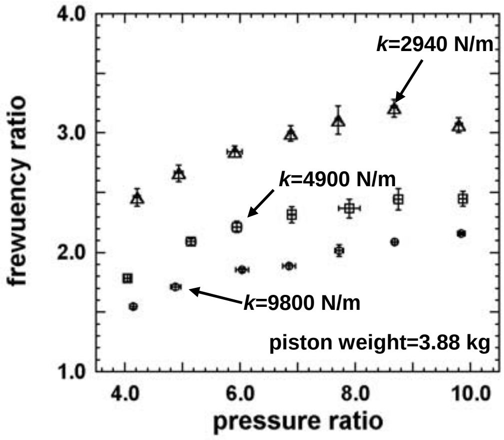


(a) k=9800N/m

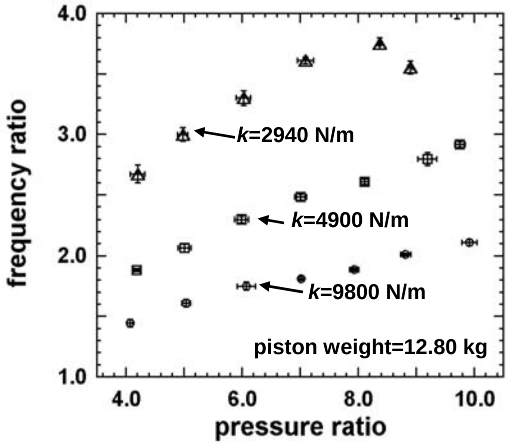
(b) k=4900N/m

(b) k=2940N/m

Fig. 4-1 Comparison of experimental values and the calculated values
with different spring constant

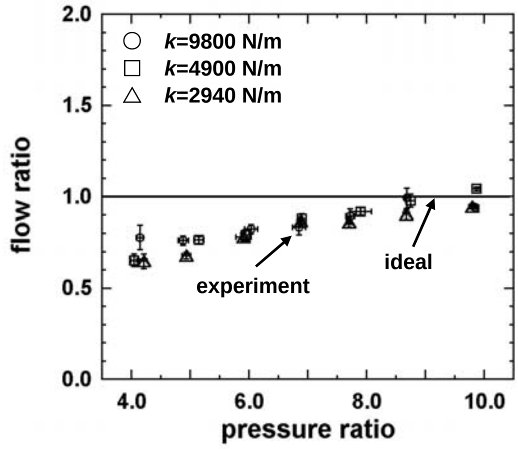


(a) Piston weight=3.88kg

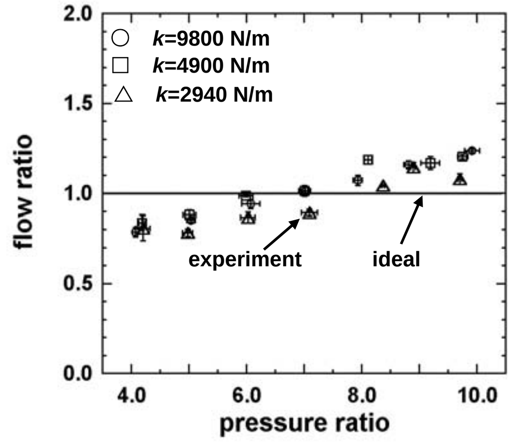


(b) Piston weight=12.80kg

Fig. 4-2 Comparison of the frequency ratio with different spring constant



(a) Piston weight=3.88kg



(b) Piston weight=12.80kg

Fig. 4-3 Comparison of the flow ratio with different spring constant

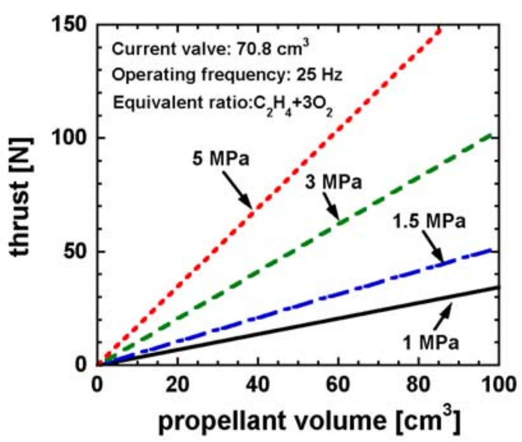


Fig. 4-4 Relation of thrust and the cylinder volume (I_{sp}=170sec, f=25Hz)

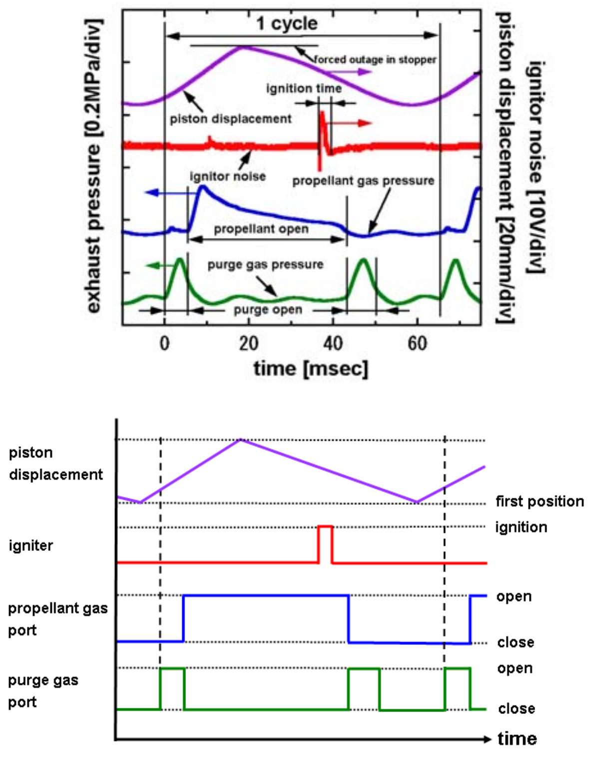


Fig. 4-5 Experimental result and the diagram of valve steady operation
(k=9800N/m)

Conclusion

Steady operation experiment of autonomous driving valve which is generated the intermittent flow by the power of the propellant gas enthalpy and the spring was successful.

The calculation model of mass flow was built. Moreover, the mass flow of experiment was 70%-120% in the ratio to the model calculated value on spring constant k=9800N/m, k=4900N/m, k=2940N/m, the piston mass m=3.88kg, and m=12.80kg conditions.

Steady operation experiment of Valve system combined the double autonomous driving valve and igniter was conducted, and we checked cycle of the propellant gas exhaust, ignition, and the purge gas exhaust on average operation frequency f=18.58Hz.

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Nomenclature

k	: spring constant	[N/m]
Δm	: mass flow per 10 cycle	[kg/10cycle]
$\dot{m}$	: mass flow rate	[kg/sec]
V	: volume	[m^3]
p	: pressure	[N/m^3]
T	: temperature	[K]
M	: molecular weight	[g/mol]
$\Re$	: universal gas constant	[J/kmol･K]
m	: mass	[kg]
F	: thrust	[N]
I_{sp}	: specific impulse	[s]
g	: gravitational acceleration	[m/s^2]

Subscripts

s : supply
a : ambient
A : gas filling volume
T : tank
e : experiment
c : calculation
i : number of cycle
ave : average of 10 cycle
f : fuel
o : oxidizer