Experimental Study on Energy Efficiency of Pneumatic Booster Valves with Energy Recovery

Jongha LIM**, Kohei IIDA**, Kotaro TADANO**, Toshiharu KAGAWA**

Pneumatic systems are widely used in facilities such as automobile production lines. Recently, many factories have reduced supply pressure in such systems to reduce energy consumption. Instead, pneumatic booster valves are applied to increase pressure where high pressure is still necessary. However, pneumatic booster valves consume some energy by exhausting to the atmosphere the compressed air that is used to drive the boost process. For this reason, we propose a pneumatic booster valve with energy recovery, which recovers the energy by reusing the previously exhausted compressed air. Furthermore, numerical simulation analysis on this new-type pneumatic booster valve is ongoing. Thus, in this study, we experimentally analyze a pneumatic booster valve with energy recovery.

Keywords: Pneumatics, Pneumatic Booster Valve, Air Power, Energy Recovery, Energy Efficiency

1. Introduction

Pneumatic systems are extensively used for cleanliness and low cost in industries such as automobile production lines. Despite the merits of pneumatic systems, the electric energy consumption of compressors has risen to 30% of total industrial electric energy consumption in many countries1-3). In recent years, many factories have been trying to reduce the energy consumption of pneumatic systems. One method that is often considered is to decrease the air pressure of the compressor. Some automobile manufacturing plants save 20% on air compressor energy consumption by decreasing supply air pressure from 0.6 MPa to 0.45 MPa. However, this causes some problems in cases where factories need a high force e.g. a production process, short takt time, or press system. For these reasons, pneumatic booster valves (PBV), which amplify air pressure, have been developed and researched4). Because a pneumatic booster valve can double air pressure without additional electricity, using one can save energy where high pressure is still needed. Moreover, several studies have proposed asymmetric PBV structures that amplify air pressure three or four times, while symmetric PBV only doubles it5-7). However, PBV exhausts part of the compressed air during the process, which wastes energy. Many studies have been done on improving energy efficiency. For example, an expansion energy used booster, which cuts off the air supply before the piston reaches the end of the chamber, was proposed for saving energy8). Furthermore, some energy savings are proposed by changing the pneumatic circuit or recovering exhaust air. However, these can be difficult to apply because they make a circuit more complex or use electricity9-10). To solve this problem, a pneumatic booster valve with energy recovery (PBV-R), which has a similar principle to the previous booster valve but includes one additional air cylinder called an expansion cylinder Fig. 1, was proposed11). The expansion cylinder recovers the air that existing PBVs would exhaust to the atmosphere, so that the compressed air can be reused in the PBV-R. Also, according to Cai, et al.12), the energy of the air accompanying both pressure and flow is defined, i.e. we can calculate efficiency easily in pneumatic systems. Furthermore, Yang and colleague’s numerical simulations show that a PBV-R is from 5%–10% more efficient than a PBV13-14). However, this

![Fig.1 Concept of PBV and PBV-R](image-url)
finding is still not confirmed by a real experiment that can be easily influenced by unexpected factors such as friction or volume of pipes and dead space.

In this study, we make an experimental apparatus for examining both PBV and PBV-R. Then, using the apparatus, we compare efficiency, boost ratio, and air consumption of PBV and PBV-R. In addition, because PBV-R has one additional cylinder for recovering and reusing energy, we investigate how much efficiency is increased by the expansion cylinder.

2. Nomenclature

\[ A : \text{area} \left[ \text{m}^2 \right] \]
\[ c : \text{viscous friction coefficient} \left[ \text{kg/s} \right] \]
\[ E : \text{energy} \left[ \text{J} \right] \]
\[ f : \text{friction force} \left[ \text{N} \right] \]
\[ G : \text{mass flow rate} \left[ \text{kg/s} \right] \]
\[ k_e : \text{recovery ratio} \left[ - \right] \]
\[ k_p : \text{boost ratio} \left[ - \right] \]
\[ k_r : \text{area ratio} \left[ - \right] \]
\[ l : \text{stroke of cylinder} \left[ - \right] \]
\[ p : \text{absolute air pressure} \left[ \text{Pa} \right] \]
\[ P : \text{air power} \left[ \text{W} \right] \]
\[ Q : \text{flow rate} \left[ \text{m}^3/\text{s} \right] \]
\[ R : \text{gas constant} \left[ \text{N} \cdot \text{m/kg} \cdot \text{K} \right] \]
\[ t : \text{time} \left[ \text{s} \right] \]
\[ T : \text{temperature} \left[ \text{K} \right] \]
\[ v : \text{velocity} \left[ \text{m/s} \right] \]
\[ V : \text{volume} \left[ \text{m}^3 \right] \]
\[ x : \text{displacement of piston} \left[ \text{m} \right] \]
\[ \eta : \text{energy efficiency} \left[ - \right] \]
\[ \kappa : \text{specific heat ratio} \left[ - \right] \]

Subscript
\[ a : \text{atmosphere} \]
\[ b1/b2 : \text{boost chamber 1/2} \]
\[ d : \text{drive cylinder} \]
\[ d1/d2 : \text{drive chamber 1/2} \]
\[ e : \text{expansion cylinder} \]
\[ e1/e2 : \text{expansion chamber 1/2} \]
\[ in : \text{inlet} \]
\[ out : \text{outlet} \]
\[ s : \text{static state} \]
\[ S : \text{supply} \]

3. Principle of PBV and PBV-R

3.1 Principle of PBV

PBV is based on the principle of a resultant force acting on a piston and piston rod. Fig. 2 shows the inside of VBA20A manufactured by SMC Corporation. It is composed mainly of two drive chambers, two boost chambers, two pistons and a piston rod. The piston moves by the force of air pressure in each chamber, and it pushes a button and changes the mode by switching the mechanical valve when it reaches the end of each boost chamber. There are two modes for the VBA; the movement of the piston either to the left or right.

In mode 1, the piston moves to the right. The left side of Fig. 3 presents mode 1. First, supply air flows into drive chamber 1, boost chamber 1 and boost chamber 2. Second, because the air in drive chamber 1 and boost chamber 2 presses pistons to the right, the air in boost chamber 1 is compressed. Finally, boost chamber 1 exhausts air at higher than supply pressure. In this case, drive chamber 2 is open to the atmosphere. In mode 2, as it is presented in the right side of Fig. 3, the principle is the same as mode 1. Supply air flows...
into drive chamber 2, boost chamber 1 and 2, then the piston moves to the left. As a result, the air in boost chamber 2 is compressed.

### 3.2 Principle of PBV-R

PBV-R, which was first proposed in a Japanese patent\(^1\), has a similar principle to PBV but has one additional cylinder, the expansion cylinder, which includes two expansion chambers. As we described in section 3.1, the air in drive chamber 2 in mode 1 or in drive chamber 1 in mode 2, is exhausted to the atmosphere. This means that energy is partly wasted in the process of PBV. To address this waste, PBV-R reuses the air exhausted to the atmosphere in case of PBV. Fig. 4 shows the inside of PBV-R that mainly includes two drive chambers, two boost chambers, two expansion chambers, three pistons and a piston rod. The piston moves by the force of air pressure of each chamber, and the mode is changed by switching the direction of valves. There are also two modes in PBV-R; the movement of the piston either to the left or right.

In mode 1, the piston moves to the right. The left side of Fig. 5 presents mode 1. First, supply air flows into drive chamber 1, boost chamber 1 and boost chamber 2. Second, because the air in drive chamber 1 and boost chamber 2 presses pistons to the right, the air in boost chamber 1 is compressed. Third, in this process, the supply air that remains from mode 2 in drive chamber 2, unlike PBV, moves to expansion chamber 1, where it adds force to the middle piston. Finally, boost chamber 1 emits air at higher than supply pressure. In this case, expansion chamber 2 is open to the atmosphere. In mode 2, as it is presented in the right side of Fig. 5, the principle is the same as mode 1. Supply air flows into drive chamber 2, boost chamber 1 and 2, then the piston moves to the left. Like mode 1, the supply air in drive chamber 1 moves to expansion chamber 2. As a result, the air in boost chamber 2 is compressed.

### 4. Experimental Setup and Procedure

#### 4.1 Experimental Setup

The pressures of inflow, outflow, and each chamber; the flow rates of inflow and outflow; and the air power of inflow and outflow are measured during operation. Fig. 6 presents the pneumatic circuit of the experimental apparatus in this study. The experimental apparatus consists of an filter-regulator-lubricator (FRL), two air power meters that can measure air power in real time, as well as pressure, temperature, and flow rate; two air cylinders with a 63 mm diameter; one large air cylinder with an 80 mm diameter; two solenoid valves; and a 10 dm\(^3\) tank. Since, according to the previous study, energy efficiency gets the maximum where the diameter ratio of drive chamber to expansion cylinder is around 1.25, we use the two
air cylinders with a 63 mm diameter as drive cylinders, the air cylinder with an 80 mm diameter as an expansion chamber. 14)

Pressure gauges are attached at each chamber of the cylinders. We acquire data with a sampling rate of 1000 Hz. A solid-state timer controls the solenoid valves. Table.1 shows a list of components included in the apparatus and their main specification.

### 4.2 Experimental Procedure

The purpose of the following experiments is to investigate the differences between PBV and PBV-R. More precisely, because our design of PBV-R incorporates an expansion cylinder on the PBV for reusing energy that existing PBVs exhaust, we verify the effect of the expansion chamber. Using this experimental apparatus, we test both PBV and PBV-R; the former is carried out without the expansion chamber and the latter is with the expansion chamber. In other words, the latter can be built by leaving the apparatus as Fig. 6 represents, and the former can be built by disconnecting (a) and (b) and removing the expansion cylinder while connecting (c) and (d). In this case, both rods are connected by a metal bar so that the pistons can move together.

First, we investigate efficiency of both PBV and PBV-R. To do that, we need to set an evaluation method for measuring the energy of compressible air. For compressible air, air power is usually employed for evaluating the energy of air. Air power is a concept that, according to Cai and Kagawa 12), quantifies the energy of flowing compressed air. Air power can be presented as Eq. 1.

$$ P = \frac{GRT_a}{p_a} \ln \frac{p}{p_a} + \frac{\kappa}{\kappa-1} \left( \frac{T}{T_a} - 1 - \ln \frac{T}{T_a} \right) $$  (1)

Based on Eq. 1, we investigate the energy efficiency of both PBV and PBV-R. If input and output air power are already known, the energy efficiency, $\eta$, during the time $[0,\infty]$ can be calculated with Eq. 2.

$$ \eta = \frac{E_{out}}{E_{in}} = \frac{\int_0^\infty P_{out} dt}{\int_0^\infty P_{in} dt} $$  (2)

Next, we also investigate boost ratio, which is one of the significant characteristics of PBV and PBV-R. Because the expansion chamber recovers and reuses high-pressure air, it is expected that the boost ratio of PBV-R is higher than that of PBV. Generally, while PBV or PBV-R is working, inlet pressure, $p_{in}$, and tank pressure, $p_{out}$, are fluctuant. However, if PBV or PBV-R are on condition that there is no air consumption at downstream, the pistons stop their movement when $p_{out}$ reaches the maximum pressure, then both $p_{in}$ and $p_{out}$ finally become constant after sufficient time has elapsed. Thus in this study, we define the boost ratio, $k_p$, with the $p_{in}$ and the $p_{out}$ as Eq. 3.

$$ k_p = \frac{p_{out}(\infty)}{p_{in}(\infty)} $$  (3)

In this case, $\infty$ is the time when $p_{in}$ and $p_{out}$ converge and do not fluctuate anymore.

Finally, air consumption rate, which indicates the percent of air consumed, is a typical index that can indirectly evaluate how much energy is used. The air consumption rate, $k_v$, during the time $[0,\infty]$ can be calculated as the ratio between volumes of input air and output air, Eq. 4.

$$ k_v = \frac{V_{out}}{V_{in}} = \frac{\int_0^\infty Q_{out} dt}{\int_0^\infty Q_{in} dt} $$  (4)

Because we need to investigate at various supply pressures, we change supply pressure from 200 kPa to 500 kPa at intervals of 100 kPa using a regulator. Also, the experiment is carried out 5 times at each supply pressure and each case of PBV and PBV-R, then we calculate average values. Through the equations and methods above, we investigate and compare performance of PBV and PBV-R in terms of efficiency, boost ratio, air consumption and pressure response.

![Fig.7 Energy efficiency of PBV and PBV-R](image-url)
5. Results

First, Fig. 7 illustrates the energy efficiency of each supply pressure. The dashed line indicates the energy efficiency of PBV, and the solid line indicates that of PBV-R. The energy efficiency of PBV-R is from 5 % to 8 % higher than that of PBV. Also, the energy efficiencies of both PBV and PBV-R tend to decrease as the supply pressure increases, except at 200 kPa.

Second, boost ratios of each supply pressure are shown in Fig. 8. The boost ratio of PBV-R is up to 20 % higher than that of PBV at all supply pressures. Boost ratios of both PBV and PBV-R tend to decrease as the supply pressure increases.

Third, air consumption at each supply pressure is shown in Fig. 9. The air consumption rate for PBV-R is around 4 % higher than that of PBV at 200 kPa, 300 kPa, 400 kPa and 5 % at 500 kPa. Also, both tend to decrease as the supply pressure increases.

Fourth, the pressure response is shown in Fig. 10. The pressure responses of both PBV and PBV-R do not differ until \( t = 13 \) s or an outlet pressure of 600 kPa; the pressure increases linearly for the first 13 seconds. Then, these two lines separate: the speed of PBV-R becomes faster than that of PBV after \( t = 13 \) s. As a result, both converge according to the boost ratios that are shown in Fig. 8.

Finally, the pressure responses of each chamber for PBV-R are shown in Fig. 11. For lack of space, we only deal with pressure behaviors of drive chamber 1, boost chamber 1 and expansion chamber 1. As described in the legend, each line indicates a pressure behavior of a chamber. Because the lines overlap when the time range is large, Fig. 11 shows the time range of \([0,7]\) seconds. The pressure of each chamber fluctuates with the cycle set by the solid-state timer. We can see that the lines of the boost chamber increase incrementally, which in turn increases the tank pressure. We also see that the expansion chamber always has an air pressure of approximately 250 kPa recovered from the drive chamber.

6. Discussion

Because PBV-R has one more cylinder than PBV, it affects several characteristics e.g. boost ratio and energy efficiency. However, we cannot ensure that every form of the additional
cylinder will contribute to the improvement of PBV. Thus, we investigate how much energy is reused by an expansion chamber with various parameters. In this paper, because area ratio is one of the influential parameters, we discuss the energy efficiency focusing on the area ratio $k_r$.

As mentioned previously, the method of PBV-R energy recovery is to let high-pressure air of the previous mode in the drive chamber move to the expansion chamber by connecting both chambers with a tube. Then, the supply pressure is shared by both chambers. Because the area of the piston in the expansion chamber is greater than the area of the piston in the drive chamber, the high-pressure air works toward the motion direction of the piston. However, although recovered air consequently works in the positive direction, the air in the drive chamber causes the force to reverse direction, i.e., some of the energy is used for negative work. Therefore, to investigate how much recovered air is actually used for positive work, we make a calculation as follows: First, valid energy of the high-pressure air in the drive chamber can be written as Eq. 5.

$$E = pV \ln \frac{p}{p_u}$$  \hspace{1cm} (5)

Next, the high-pressure air is divided into two forces; a force acting in the forward direction and a force acting against the forward direction. The air in each chamber does work, so we first calculate pressure in both chambers. From now on, we only consider the case of mode 1. To simplify calculation, we assume that air is an ideal gas. Also, we assume that there is no temperature change and no heat transfer through the wall of the air cylinders. According to the general gas equation, Eq. 6 is established.

$$p_e k_r A_{d2} x + p_d A_{d2}(l-x) = C$$  \hspace{1cm} (6)

In Eq. 6, $C$ is constant. Assuming there is no friction or resistance between the drive chamber and the expansion chamber, then $p_e$ and $p_d$ can be considered equal and Eq. 6 can be simplified as Eq. 7.

$$p_e k_r A_{d2} x = C$$  \hspace{1cm} (7)

Then, we need to consider all additional forces that occurred by adding the expansion cylinder. As indicated in Fig. 12, in comparison with PBV, PBV-R has four more forces; $p_e A_{e1}$, $p_{d2} A_{d2}$, $p_a A_{e2}$ and friction force of expansion chambers $f_e$. Thus, the work that these four new forces do can be written as Eq. 8.

$$W = \int_0^l [(p_e - p_a)(k_r - 1)A_{d2} - f_e]dx$$  \hspace{1cm} (8)

There exist many friction models for pneumatic cylinders generally based on Coulomb model, viscous model and Striber model in a pneumatic cylinder, but in this discussion, we only consider the Coulomb model and viscous model as Eq. 915).

$$f_e = f_s + cv$$  \hspace{1cm} (9)

In Eq. 9, since a piston of a pneumatic cylinder moves with almost the same velocity, we assume that $v$ is constant16). Next, we define the recovery ratio, $k_e$, which indicates how much energy from the drive chamber is actually reused, as Eq. 10.

$$k_e = \frac{\int_0^l (p_e - p_a)(k_r - 1)A_{d2} - f_e) dx}{p_a A_{d2} l \ln(p_s/p_a)}$$  \hspace{1cm} (10)

$p_e$ is described by Eq. 7, thus we can find out that the recovery ratio is determined by $k_r$ and $p_r$. In this study, $k_r$ of the cylinders of the apparatus is 1.46 and the recovery ratio is around 10~20 % at every supply pressure. This means that around 10~20 % of the energy, which was supposed to be exhausted in case of PBV, is reused by adding the expansion cylinder.
Next, we investigate the recovery ratio in the case of a different $k_r$. Let $p_z$ from 200 kPa to 500 kPa and $k_r$ from 1 to 6. Fig. 13 indicates the relationship between $k_r$ and recovery ratio. As shown on the graph, the recovery ratio is less than 0 % when $k_r = 1$ because, according to Eq. 8, all pressures do the same work in different directions and friction acts as a backward force, which causes a negative work and a negative term in the numerator of Eq. 10. Also, the recovery ratio gets the maximum with $k_r = 1.9 \sim 3.6$ by up to 45.4 %. In comparison to the recovery ratio at $k_r = 1.46$ which is real value for this experimental apparatus, the maximum value is up to 23 % greater, although the previous study energy efficiency has the maximum at $k_r = 1.46$. One of the reasons is considered that the recovery ratio is calculated under assumption that both $p_e1$ and $p_d2$ are the same. In fact, as shown in Fig. 11, $p_e1$ is not consistent with $p_d2$ due to impedance of the experimental circuit or pressure loss. The difference of the pressure has an effect on the recovery ratio, which needs accurate calculation of fluid dynamics. Therefore, further research about the recovery ratio by numerical analysis of air flowing pipe is necessary.

7. Conclusion

In this study, we set up an experimental PBV-R apparatus and investigated the energy efficiency, boost ratio, and air consumption for both PBV and PBV-R. According to the results of the experiment, the efficiency of PBV-R is up to 8% greater than PBV. Moreover, the boost ratio of PBV-R is up to 17.2% greater than that of PBV. Also, consumption rates of PBV-R are up to 5.4 % greater than those of PBV. Hence, we can conclude that a PBV-R incorporating an additional expansion cylinder offers not only energy efficiency but also higher pressure gains than PBV.

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