The Impact of Geometric Design on Energy Efficiency of Pneumatic Booster Valves with Energy Recovery

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***Abstract*—Pneumatic Booster Valves (PBV), which amplify air pressure without any electricity or air compressor, has commonly applied to facilities such as automobile production lines. However, because PBV is still not efficient enough, Pneumatic Booster Valve with Energy Recovery (PBV-R), which has one additional function that recovers energy, has been proposed and validated by previous studies. Nonetheless, a parametric study of the optimal shape of PBV-R has not been experimentally studied yet. Thus, in this paper, we experimentally investigate performance of PBV-R under various conditions such as a stroke length and an area ratio to find out the optimal parameters of PBV-R and discuss the results by calculations.**

***Index Terms*— pneumatics, pneumatic booster valves, air power, energy efficiency, energy recovery**

I. Introduction

Pneumatic systems are commonly used for its safety, cleanliness and low cost in overall industry, such as automobile production lines. Despite the merits of pneumatic systems, these are mainly operated by air compressors, of which electricity energy consumption has risen to 30 % of the whole industrial electric energy consumption in many countries [1-3]. Also, a report has shown that up to 9 % of electric energy consumption can diminish by reducing every 0.1 MPa supply pressure [4]. Therefore, many automobile manufacturing plants have cut down their supply pressure. However, low pressure in the plants causes lack of force, which are essential for efficient production process such as short takt time. For these reasons, pneumatic booster valves (PBV), which amplify air pressure, have been developed and studied [5]. Because PBV can double air pressure without additional electricity, applying one to the processes where high pressure is necessary can not only save the electric energy consumption, but also solve the problems caused by reduced supply pressure. Moreover, some studies have suggested asymmetric PBV structures that can amplify air pressure much higher than original PBV [6-8]. However, in terms of energy efficiency, PBV is not efficient by reason of that PBV includes the process of wasting high-pressure air. Many researchers have tried to improve the energy efficiency of PBV, such as controlling air supply or pneumatic circuit [9-11], but (these are difficult to apply because) they make the pneumatic circuit complex or use electricity. To solve this problem, a pneumatic booster valve with energy recovery (PBV-R), which has a similar structure to PBV but has one additional cylinder called ‘expansion cylinder’, was proposed by a patent [12]. Because PBV-R reuses the high-pressure air that existing PBVs would exhaust, it has been considered that energy efficiency of PBV-R is higher than that of PBV, and in reality, improvement of energy efficiency of PBV-R is numerically and experimentally validated under certain conditions by previous researches [13-15]. According to the previous researches, however, it is already proved that not every shape of the expansion cylinder improves the energy efficiency, but rather decreases on some occasions. Thus, in this study, we experimentally investigate performance of PBV-R under various conditions such as a stroke length and an area ratio to find out the optimal parameters of PBV-R.

II. Principle of PBV-R

As shown in Fig. 1, PBV-R mainly comprises three cylinders: two drive cylinders and an expansion cylinder; three pistons in each cylinder; two mechanical valves that change the pneumatic circuit of PBV-R; and a piston rod that connects the pistons. Also, each cylinder has two chambers: a drive chamber and a boost chamber included in the drive cylinders, two expansion chambers in the expansion cylinder. The pistons move by the force of air pressure in each chamber. When it reaches the end of a stroke, it pushes a button that changes the position of a mechanical valve, then the pistons move to the opposite direction. There are two modes in PBV-R; the movement of the piston either to the left or right.

In mode 1, as shown in the left side of Fig. 1(b), piston moves to the right. First, supply air flows into drive chamber 1, boost chamber 1 and boost chamber 2. Then, because the air in drive chamber 1 and boost chamber 2 presses pistons, the air in boost chamber 1 is compressed.

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In this process, the supply air that remains from mode 2 in drive chamber 2 flows 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, the piston moves to the left. The right side of Fig. 1(b) presents mode 2, and the principle is basically the same as mode 1. Supply air flows into drive chamber 2, boost chamber 1 and 2. For the same reason of mode 1, boost chamber 2 emits air at higher than supply pressure.

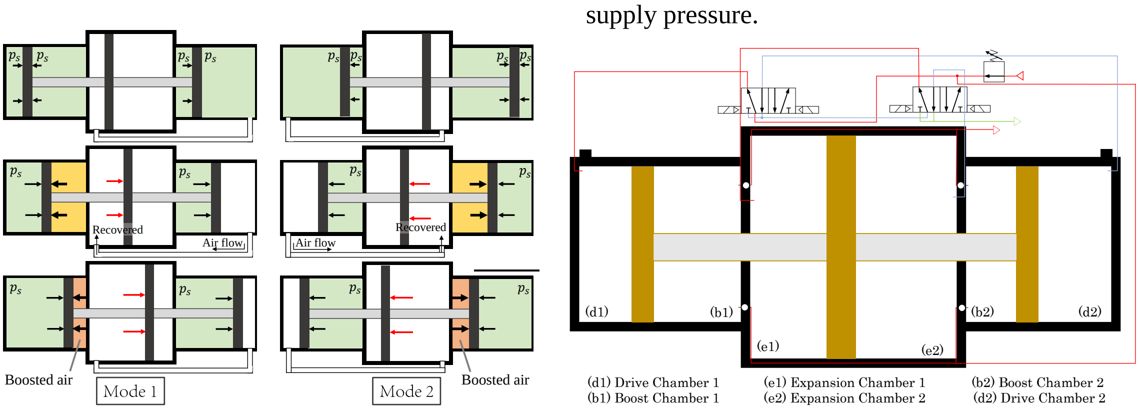


Figure 1. (a) Schematic graphic of PBV-R and (b) principle of PBV-R.

III. Experimental Setup and Procedure

As mentioned previously, not every shape of PBV-R improves the energy efficiency, so it is necessary to investigate the performances of the PBV-R under several conditions. In this study, we carry out an experiment with three different area ratios and four different strokes and see how the energy efficiency, the boost ratio and the air consumption rate change.

A. Experimental Setup

Fig. 1 presents the pneumatic circuit of the experimental apparatus in this study. The experimental apparatus includes a filter-regulator-lubricator (F.R.L); two air power meters (APM) that can measure air power, pressure, temperature, and flow rate; two air cylinders with a 40 mm diameter for drive cylinders; three air cylinders with a 50 mm, 63 mm, 80 mm each for an expansion cylinder; and a 10 dm3 tank. Each diameter has four different stroke; 25 mm, 50 mm, 75 mm and 100 mm, so total number of air cylinders we prepare is twenty. Direction control of pneumatic circuit is operated by two 5-way/2-position solenoid valves and a solid-state timer that has a function of a relay. The pressures of inflow, outflow and each chamber; the air power of inflow and outflow; and the flow rate of inflow and outflow are measured during operation. All data is acquired by converting analog signals to digital signals with a sampling rate of 1000 Hz. Table I shows a list of components included in the experimental apparatus and their main specification. Fig. 2 is the actual experimental apparatus with the components described above. Two drive cylinders and one expansion cylinder are included for an experiment. Because every end of piston rod of air cylinder has a female screw, we connect the rods by a shaft that has male screws on both ends. Also, a U-shaped button pusher is fixed on the shafts and pushes switch buttons when the pistons reach to the end of the stroke.

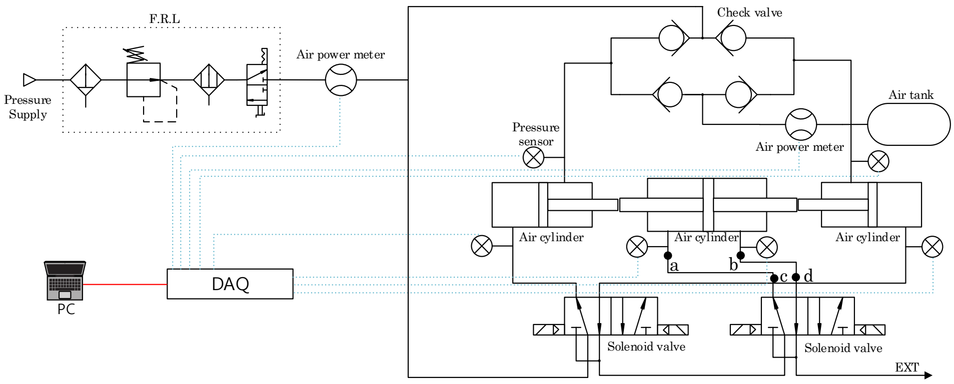


Figure 2. Circuit diagram of PBV-R.

B. Experimental Procedure

The purpose of this study is to investigate the performance of PBV-R under different area ratio and stroke length. Accordingly, we first fix the stroke length of 25 mm and carry out the experiment for each area ratio cylinder and then we carry out the same experiment on the other stroke lengths. We set supply pressure of 300 kPa, 400 kPa and 500 kPa using a regulator. Also, the experiment is carried out 5 times at each supply pressure.

We investigate efficiency, boost ratio and air consumption rate, which are mainly considered as performance of PBV-R. First, we employ air power for evaluating the energy of air. Air power is a concept that quantify the energy of flowing compressed air, according to the paper [16]. Air power can be presented as Eq.1.

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

Based on Eq.1, we investigate the energy efficiency of PBV-R. As shown in Fig. 1, because input and output air power are measured by each APM, the energy efficiency, η, during the time $[0,\infty]$ can be calculated with Eq.2.

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

Next, we also investigate boost ratio of PBV-R. Boost ratio means a ratio between inlet pressure and outlet pressure. Generally, while PBV-R is operating, inlet pressure, p_{in}, and output pressure, p_{out}, are fluctuant. However, if there is no air consumption at downstream, the pistons of PBV-R stop their movement finally when p_{out} reaches the maximum pressure. Then, after sufficient time has elapsed, p_{in} and p_{out} become constant. Thus, we define the boost ratio, k_p, with the p_{in} and the p_{out} as Eq.3.

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

In this case, ∞ means the time when p_{in} and p_{out} do not fluctuate anymore.

Finally, we also investigate air consumption rate, which indicates the percent of air consumed. The air consumption rate, k_v, during the time $[0,\infty]$ can be defined with inlet flow rate, Q_{in}, and outlet flow rate, Q_{out}, as Eq.4.

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

IV. RESULTS

In this study, we changed stroke length L, area ratio k_r as well as supply pressure p_s. Therefore, first, we show the results when the stroke length is constant, and then, we show the results when the area ratio is constant.

A. The Results with Constant Stroke Lengths

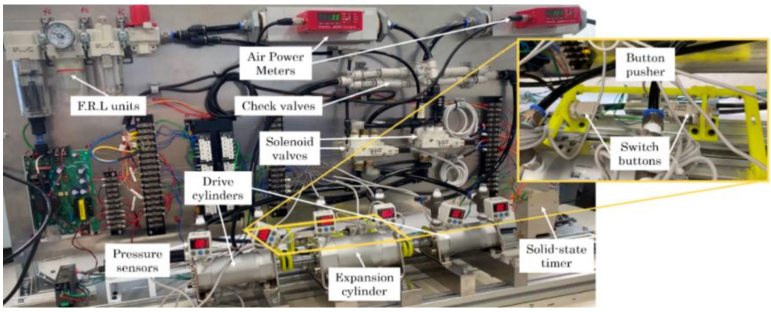
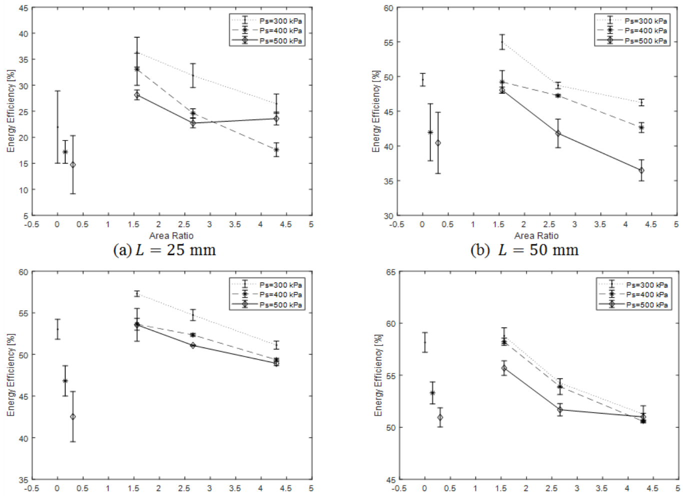


Figure 3. Experimental apparatus of PBV-R.

Fig. 3 illustrates the energy efficiency of each area ratio. The dotted line indicates the energy efficiency at $p_s = 300$ Pa, the dashed line indicates the energy efficiency at $p_s = 400$ kPa, and the solid line indicates the energy efficiency at $p_s = 500$ kPa. Also, the dots at around k_r = 0 are the results with no expansion cylinder (PBV method). Regardless of the stroke length, the energy efficiency is the greatest where $k_r = 1.56$. When the stroke length and the supply pressure are fixed, the energy efficiency is up to 10 % different between $k_r = 1.56$ and $k_r = 4.30$. In some cases where $k_r = 2.66$ and$k_r = 4.30$, the energy efficiency is lower than PBV method although the expansion cylinder recovers energy.



(a) $L = 25$ mm (b) $L = 50$ mm (c) $L = 75$ mm (d) $L = 100$ mm

Figure 4. Relations between energy efficiency and area ratio at various stroke lengths.

Fig. 4 illustrates the boost ratio of each area ratio. All boost ratio shows a similar tendency that has the highest boost ratio at $k_r = 2.66$. The boost ratio of $k_r = 2.66$ is up to 0.4 higher than that of $k_r = 4.30$, up to 0.2 higher than that of $k_r = 1.56$.

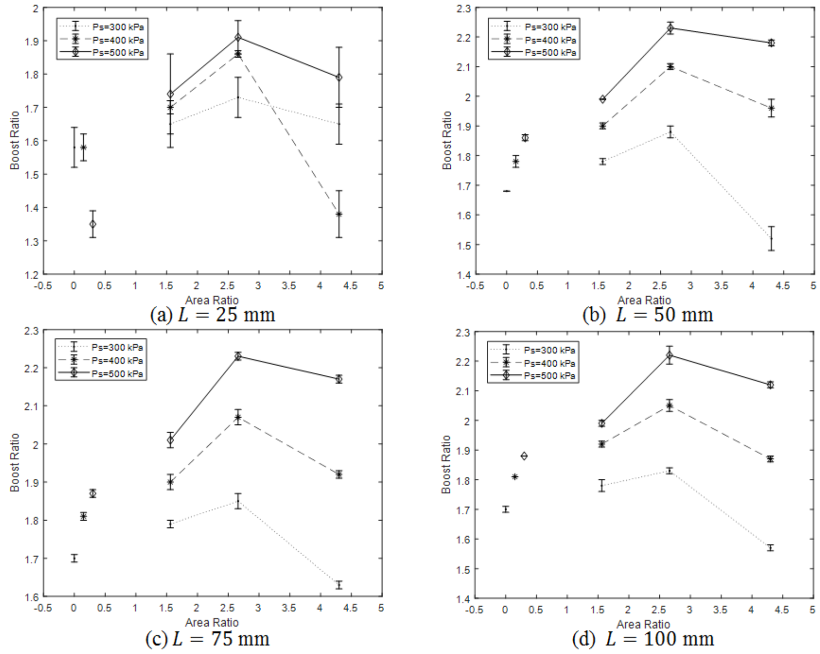


Figure 5. Relation between energy efficiency and area ratio at various stroke lengths.

Fig. 5 illustrate the air consumption rate of each area ratio. Regardless of the stroke length, air consumption rate is the greatest where $k_r = 1.56$ at all supply pressures. Also, the air consumption rate of $k_r = 1.56$ is up to 5 % higher than that of $k_r = 2.66$, up to 10 % higher than that of $k_r = 4.30$.

B. *The Results with Constant Area Ratios*

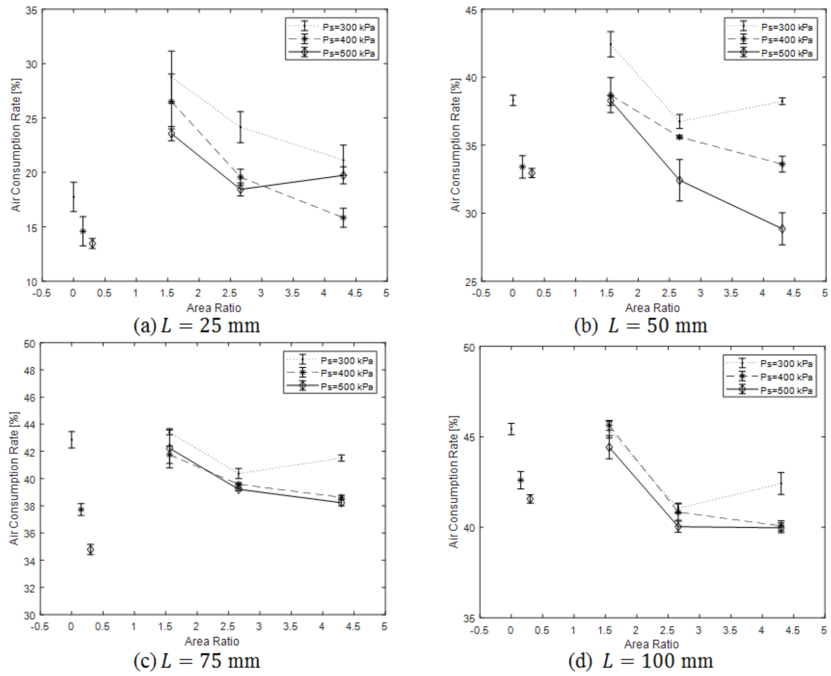
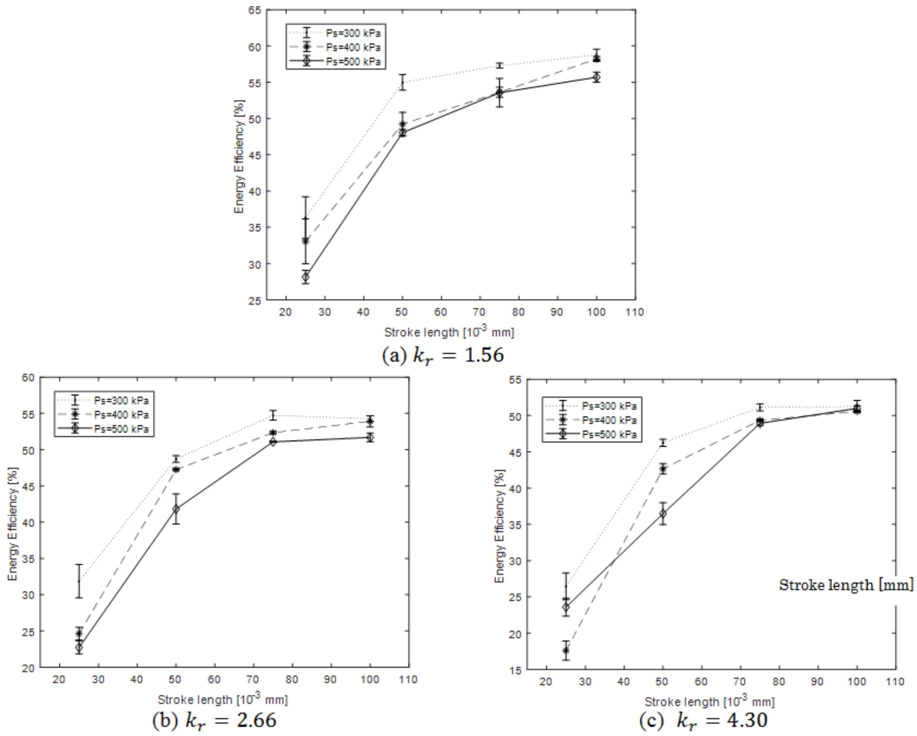


Figure 6. Relation between air consumption rate and area ratio at various stroke lengths.

Fig. 6 illustrates the energy efficiency of each stroke length. When supply pressure is fixed, the energy efficiency tends to increase as the stroke length increases for all area ratio. Especially, the energy efficiency at $L = 100$ mm is from 50 % to 55 %, whereas the efficiency at $L = 25$ mm is around 20 % for all area ratios.



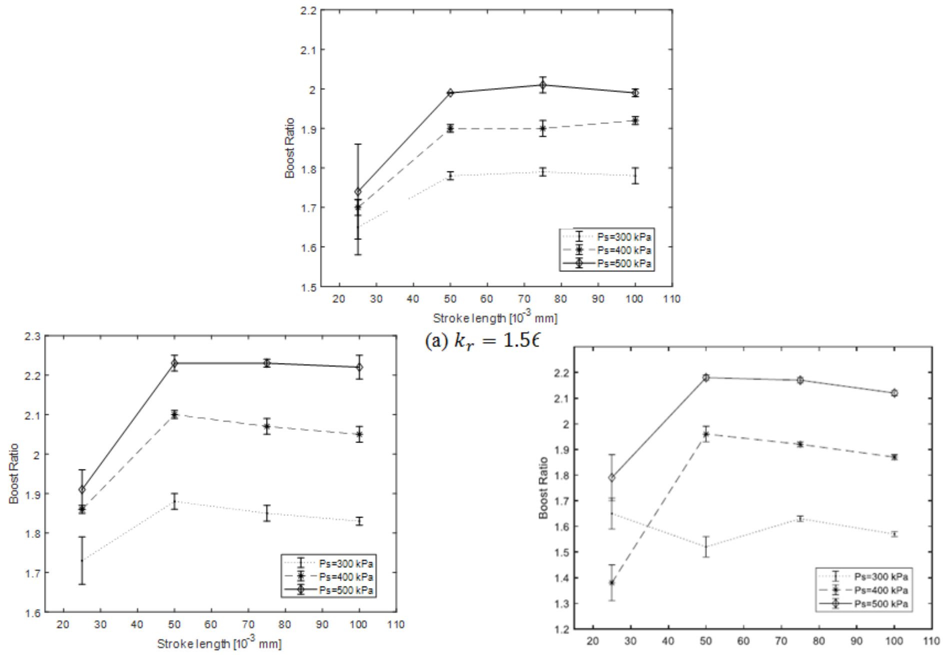
(a) $k_r = 1.56$

(b) $k_r = 2.66$

(c) $k_r = 4.30$

Figure 7. Relation between energy efficiency and stroke length.

Fig. 7 illustrates the boost ratio of each stroke length. For all area ratio, the boost ratio is almost constant at all stroke length, exclusive of $L = 25$ mm. The boost ratio has difference of less than 0.1 at $L = 50$ mm, $L = 75$ mm, $L = 100$ mm, although these are around 0.6 different from the boost ratio at $L = 25$ mm.



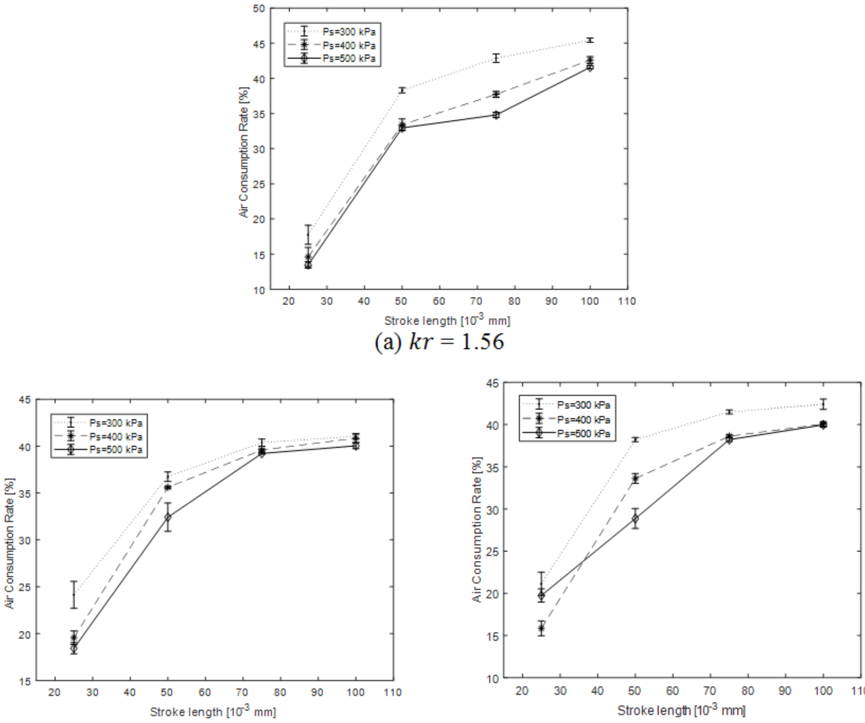
(a) $k_r = 1.56$

(b) $k_r = 2.66$

(c) $k_r = 4.30$

Figure 8. Relation between boost ratio and stroke length.

Fig. 8 illustrates the air consumption rate of each stroke length. For all area ratio, the air consumption rate tends to increase as the stroke length increases when supply pressure is fixed. The air consumption rate is averagely from 40 to 45 % at $L = 100$ mm, whereas it is from 20 to 25 % at $L = 25$ mm.



(a) $kr = 1.56$

(b) $kr = 2.66$ (c) $kr = 4.30$

Figure 9. Relation between air consumption rate and stroke length.

V. Discussion

The most interesting thing in the results is that a stroke length affects the energy efficiency of PBV-R, although it was numerically proved that there is no relationship between them. It is assumed that one of the reasons is a dead volume. Thus, we discuss how big an influence of the dead volume is. First, in this paper, we define the dead volume as the whole volume except a chamber of an air cylinder, i.e., the dead volume includes, pipes, etc. Then, we also define and use 'dead volume rate' that indicates a ratio of the dead volume to the whole volume. The whole volume, V_{whole}, can be presented by using an ideal volume of a chamber which is considered that no dead volume exists, V_{ideal}, and the dead volume rate, α, as Eq.5.

$$V_{whole} = V_{ideal}(1+\alpha) \tag{5}$$

Using the dead volume rate, we calculate the energy efficiency of PBV-R both with and without a dead volume. To simplify the calculation, we assume that air is an ideal gas and it satisfies the ideal gas state equation. Also, temperature change is neglected during state changes, and the pressure in a chamber is constant as supply pressure while air flows in and out. Then, according to the definition of air power, Eq.1, energy can be simplified with pressure, p, volume, V, mass, m, temperature, T, and gas constant, R, as Eq.6.

$$E = pV\ln\frac{p}{p_a} = mRT\ln\frac{p}{p_a} \tag{6}$$

As presented in Eq.6, only pressure and mass are necessary for calculating energy of air. However, the outlet pressure and the outflow mass is not constant but changeable according to the number of stroke, n. Thus, we need to generalize the pressure and the mass equation in terms of n.

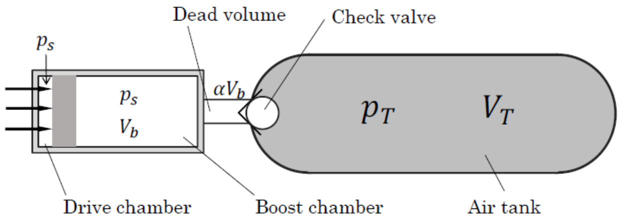


Figure 10. Schematic diagram of a drive cylinder, dead volume and an air tank.

A. The General Term of Pressure

First, we find a general term of pressure without dead volume. Inlet pressure is the same as supply pressure, p_s, regardless of n, whereas outlet pressure changes by n. Because, as shown in Fig. 10, the boost chamber and the air tank can be considered as a closed system and the initial pressure in the boost chamber is p_s, Eq.7 is established according to the general gas equation.

$$p_sV_b + p_T(n-1)V_T = p_T(n)V_T \tag{7}$$

In Eq.7, p_T is the pressure of the air tank. From Eq.7, the general term of p_{T} can be presented as Eq.8.

$$p_T(n) = p_s\left(1+\frac{V_b}{V_T}n\right) \tag{8}$$

If final outlet pressure, p_{PBVR}, is already known, it is possible to calculate the number of strokes, N, that occur until the piston stops. Let $p_T = p_{\mathrm{PBVR}}$, then N can be presented as Eq.9.

$$N = \frac{(p_{PBVR} - p_s)V_T}{p_s V_b} \tag{9}$$

Next, we find a general term of pressure with dead volume. Similarly, inlet pressure is the same as supply pressure, p_s, regardless of n, whereas outlet pressure changes by n. Because of the same reason above, Eq.10 is established.

$$p_s V_b(1+\alpha) + \hat{p}_T(n-1)V_T = \hat{p}_T(n)(V_T + \alpha V_b) \tag{10}$$

From Eq.10, the general term of $\hat{p}_T$ can be presented as Eq.11.

$$\hat{p}_T(n) = \frac{p_s}{\alpha}\left[\alpha + 1 - \left(\frac{V_T}{V_T + \alpha V_b}\right)^n\right] \tag{11}$$

Also in this case, if final outlet pressure, $\hat{p}_T$, is already known, we can calculate the number of strokes, $\hat{N}$, that occur until the piston stops. Let $\hat{p}_T = p_{\mathrm{PBVR}}$, then $\hat{N}$ can be presented as Eq.12.

$$\hat{N} = \frac{ln(\alpha + 1 - \frac{\alpha \hat{p}_T}{p_s})}{ln\, V_T - ln(V_T + \alpha V_b)} \tag{12}$$

In Eq.9 and Eq.12, if the other conditions are equal, the $\hat{p}_T$ has the same value whether or not dead volume exists because, according to the study [15], the final outlet pressure of PBV-R is presented as Eq.13.

$$p_{PBVR} = [p_s(A_d + A_b) + p_s A_d(A_e - A_d)/A_e - p_a A_e - 2f_d - f_e]/A_b \tag{13}$$

By using Eq.9, Eq.12 and Eq.13, N and $\hat{N}$ can be determined.

B. The General Term of Mass

In Fig. 6, the piston of the air cylinder moves to the right side, boosting the pressure in the boost chamber while the check valve is closed. When the pressure in the boost chamber reaches to the tank pressure, the air in the boost chamber starts to flow into the tank. Therefore, first, we find a distance, x, that the piston moves until the check valve opens. Because initial pressure is p_s and the pressure when the check valve opens is $\hat{p}_T(n)$, Eq.14 is established according to the general gas equation.

$$p_s V_b(1+\alpha) = \hat{p}_T(n) V_b \frac{L - x(n)}{L} \tag{14}$$

In Eq.15, L is the length of a stroke. From Eq.14, the general term of x can be written as Eq.15.

$$x(n) = L(\alpha+1)(1 - \frac{p_s}{\hat{p}_T(n)}) \tag{15}$$

Because we assume that the pressure is constant, the ratio of the mass that actually flows into the tank is $1 - x/L$ out of $1 - x/L + \alpha$. Therefore, by using Eq.15, m_n can be presented as Eq.16.

$$m_n = \frac{1 - x/L}{1 - x/L + \alpha} m_b = \left[1 - \frac{\alpha \hat{p}_T(n)}{(\alpha+1)p_s}\right] m_b \tag{16}$$

In Eq.16, m_b is the initial mass in the boost chamber. By Eq.16, both cases with and without dead volume can be explained. In the case without dead volume, m_n is always equal to m_b.

C. The General Term of Energy Efficiency

First, we calculate inlet energy. Because supply pressure flows into both drive chamber and boost chamber, and we assume that pressure is constant, the whole inlet energy, E_{in}, is established as Eq.17, based on Eq.6.

$$E_{\mathrm{in}} = n p_s (V_b + V_d) \ln \frac{p_s}{p_a} \tag{17}$$

Next, we calculate outlet energy. During the nth stroke, the pressure changes from p_{n-1} to p_{n}. However, it is much smaller than the supply pressure, so we assume that the pressure during the nth stroke is constant as $(p_{n-1} + p_n)/2$. Then, the whole outlet energy, E_{out}, can be calculated as Eq.18.

$$E_{\mathrm{out}} = \sum_{n=1}^{k} \bar{p}_n (V_b + V_d) \ln \frac{\bar{p}_n}{p_a} \tag{18}$$

In Eq.18, $k = N$ if dead volume exists and $k = \hat{N}$ if dead volume does not exist. Also, $\bar{p}_n = (p_{\mathrm{n}-1} + p_{\mathrm{n}})/2$ where $p_{\mathrm{n}} = p_T(n)$ if dead volume exists and $p_{\mathrm{n}} = \hat{p}_T(n)$ if dead volume does not exist. Thus, with Eq.2, Eq.17 and Eq.18, the energy efficiency with and without dead volume can be calculated.

Fig. 11 indicates the relationship between dead volume rate and the energy efficiency. Overall, the energy efficiency diminishes as the dead volume rate increases. In this study, because we did not change the pipe or tube in the experimental apparatus and the dead volume accounts for the most part of the apparatus, the dead volume rate in the experiment is inversely proportional to the stroke length. In other words, PBV-R with 25 mm stroke length has 4 times greater dead volume rate than PBV-R with 100 mm stroke length. Thus, the differences between the energy efficiency of several stroke lengths can be explained by Fig. 11. In this study, because the dead volume rate at $L = 25$ mm is around 0.25, the efficiency drop is around 30 % according to Fig. 11, which accords closely with the results.

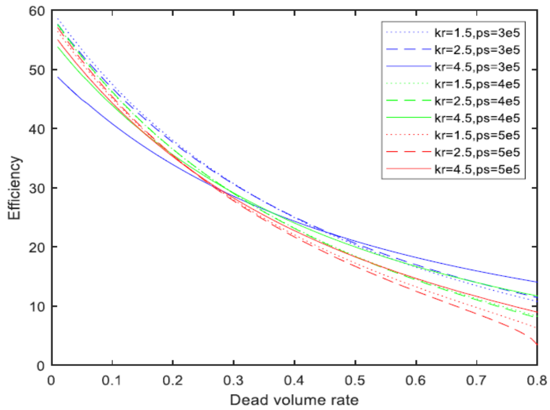


Figure 11. Relationship between the dead volume rate and the energy efficiency.

VI. Conclusion

In this study, we set up an experimental apparatus and investigated how the performances of PBV-R change when an area ratio and a stroke length are different. According to the results of the experiment, the energy efficiency is the greatest where a stroke length is 100 mm and an area ratio is 1.56. Also, the boost ratio is the greatest where an area ratio is 2.66 and a stroke length is 50 mm or more. Moreover, the air consumption rate is the greatest where a stroke length is 100 mm and an area ratio is 1.56. Hence, based on the results and the discussion, we can conclude that a long stroke, which can reduce dead volume rate, and an expansion chamber with proper diameter.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Conceptualization, J. Lim; methodology, J. Lim; validation, J. Lim; formal analysis, J. Lim and K. Tadano; investigation, J. Lim; resources, K. Tadano and T. Kagawa; data curation, J. Lim; writing-original draft preparation, J.Lim; writing-review and editing, K. Tadano and T. Kagawa; supervision, K. Tadano and T. Kagawa; project administration, J. Lim; funding acquisition, K. Tadano and T. Kagawa.

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