Numerical Analysis and Experimental Validation on Energy Efficiency of Pneumatic Booster Valves with Energy Recovery

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Abstract This paper describes the result of numerical and experimental analysis on energy efficiency of boost valve with energy recovery. Pneumatic systems are widely applied to 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 used for increasing air pressure where high pressure is still necessary. However, pneumatic booster valves waste some energy by exhausting to 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 widely utilized for cleanliness, safety and low cost in all industries such as automobile production lines. Recently, because energy conservation became one of popular topics due to global warming or oil depletion, pneumatic systems has also been developed to be energy saving. Because the electric energy consumption of compressors has risen to 30% of total industrial electric energy consumption in many countries, manufacturing plants such as an automobile production line have reduced supply pressure [1][2][3]. This is effective for reduction of energy consumption, but some problems occur locally where it needs high pressure, although most processes in the production line has no problem with reduced supply pressure. To solve these problems, researchers have tried to amplify air pressure locally instead of making supply pressure back, and a Pneumatic Booster Valve (PBV), which can amplify air pressure by twice without any energy including electricity, has been developed. However, because PBV amplifies air pressure with wasting high-pressure air, it is considered to be inefficient in terms of energy. To improve the efficiency of PBV, a Pneumatic Booster Valve with Energy Recovery (PBV-R), which recovers and reuses high-pressure air that existing PBVs would waste, has been proposed by Japanese patent [4]. Also, numerical simulations of previous studies show that a PBV-R is more efficient than a PBV [5][6]. However, this finding is still not confirmed by a real experiment. In this study, therefore, we compare performances of PBV-R method with that of PBV method by making and using an experimental apparatus, as well as numerical analysis with real parameters.

2 Principle of PBV and PBV-R

PBV and PBV-R work by resultant force acting on a piston and piston rod. The piston moves by the force of air pressure in each chamber, and it pushes a button of mechanical valve when it reaches the end of each chamber. When the button is pushed, a position of mechanical valve changes and the piston moves toward the opposite direction. In other words, PBV and PBV-R boost air pressure by the back-and-forth motion. For the convenience of description, we define the movement to the right side as ‘mode 1’ and the movement to the left side as ‘mode 2’.

Fig. 1 shows the inside of PBV. In mode 1, supply air flows into Drive Chamber 1, Boost Chamber 1 and Boost Chamber 2, while Drive Chamber 2 is open to the atmosphere. Then, due to the resultant forces, the piston moves to the right side and the air in Boost Chamber 1 is compressed. When the piston reaches the end of the chamber, mode 1 changes into mode 2. In mode 2, Supply air flows into Drive Chamber 2, Boost Chamber 1 and Boost Chamber 2, while Drive Chamber 1 is open to the atmosphere. For the same reason above, the piston moves to the left side and the air in Boost Chamber 2 is compressed.
Fig. 1 Schematic graphic of PBV

Fig. 2 Schematic graphic of PBV-R

Fig. 2 shows the inside of PBV-R. In mode 1, supply air flows into Drive Chamber 1, Boost Chamber 1 and Boost Chamber 2, while Expansion Chamber 2 is open to the atmosphere and Expansion Chamber 1 is connected to Drive Chamber 2. Then, due to the resultant forces, the piston moves to the right side and the air in Boost Chamber 1 is compressed. Unlike PBV, PBV has Expansion Chamber that is connected to Drive Chamber. Because supply air of previous mode remains in Drive Chamber 2, Expansion Chamber 1 can use the remaining air for pushing the piston, and we call this process ‘energy recovery’. When the piston reaches the end of the chamber, mode 1 changes into mode 2. In mode 2, Supply air flows into Drive Chamber 2, Boost Chamber 1 and Boost Chamber 2, while Expansion Chamber 1 is open to the atmosphere and Expansion Chamber 2 is connected to Drive Chamber 1. For the same reason above, the piston moves to the left side and the air in Boost Chamber 2 is compressed, while Expansion Chamber 2 recovers energy from Drive Chamber 1.

3 Numerical Analysis

In this paper, we mainly carry out numerical analysis of energy efficiency and boost ratio. To simplify the calculation, the following assumptions are valid.  
(1) Air in the system is considered as ideal gas;  
(2) No leakage occurs in the system;  
(3) No temperature changes and no heat transfer occurs in the system;  
(4) Dead volume in air cylinders and volume of pipes are neglected.
First, we calculate boost ratio. Boost ratio, which is one of important performance of PBV, is the ratio of output pressure and supply pressure. In this study, because the air boosted by PBV or PBV-R is accumulated in an air tank, air pressure of the air tank can be considered as output pressure. The forces acting on piston is shown in Fig. 3. When resultant force is zero, it means that the air boosted to the maximum. Sum of forces can be written as Eq. 1.

\[
p_{d1}A_{d1} - p_{b1}A_{b1} + p_{b2}A_{b2} - p_{d2}A_{d2} - 2f_d = 0
\]

(1)

Fig. 3 Forces acting on each piston of PBV and PBV-R

Because pressure in boost chamber \( p_{b1} \) or \( p_{b2} \) is boosted, boosted air pressure can be found by solving Eq. 1 for \( p_{b1} \). In this case, \( p_{d1} \) and \( p_{b2} \) are the same as supply pressure, and \( p_{d2} \) equals to \( p_a \). Therefore, final air pressure boosted by PBV can be derived as Eq. 2.

\[
p_{PBV} = \frac{p_a(A_d + A_b) - p_aA_d - 2f_d}{A_b}
\]

(2)

Likewise, final air pressure boosted by PBV-R can be presented as Eq. 3.

\[
p_{d1}A_{d1} - p_{b1}A_{b1} + p_{e1}A_{e1} - p_{e2}A_{e2} + p_{b2}A_{b2} - p_{d2}A_{d2} - 2f_d - f_e = 0
\]

(3)

In mode 1, Drive Chamber 2 includes supply air that was used in mode 2 and, assuming that the maximum air pressure is gained when the piston reaches end of the stroke, \( p_{e1} \) equals to \( p_eA_d/A_e \). Therefore, boosted air pressure by PBV-R can be derived as Eq. 4.

\[
p_{PBV-R} = \frac{p_a(A_d + A_b) + p_eA_d(A_e - A_d)/A_e - p_aA_e - 2f_d - f_e}{A_b}
\]

(4)

Boost ratio of PBV and PBV-R can be calculated by ratio between supply pressure and boosted pressure of each case.

Next, Air consumption rate is commonly used for evaluating air energy, but in this study, we use air power that quantifies the energy of flowing compressed air [7]. On the assumption that temperature does not change, air power can be presented as Eq. 5.

\[
P = pQ \left[ \ln \frac{p}{p_a} + \frac{k}{k-1} \left( \frac{T}{T_a} - 1 \right) \right]
\]

(5)

According to the assumption (3), Eq. 5 can be simplified as Eq. 6.

\[
P = pQ \ln \frac{p}{p_a} = p_aQ_a \ln \frac{p}{p_a}
\]

(6)

Because air power denotes energy per unit time, input energy or output energy of the system can be calculated by integrating air power. The input energy of PBV and PBV-R is the supply air flowing into drive chamber 1 and boost chamber 2, then the input energy of each stroke can be presented as Eq. 7.
\[ E_{in} = \int_0^t p_a Q_a \ln \frac{p_z}{p_a} \, dt = p_z l (A_b + A_d) \ln \frac{p_z}{p_a} \] (7)

By using Boyle’s law, we can calculate how many stroke occurs as Eq. 8.

\[ N = \frac{(p - p_z)V_t}{p_z A_b} \] (8)

\( p \) is \( p_{PBV} \) or \( p_{PBVR} \). Next, the output energy can be calculated as Eq. 9.

\[ E_{out} = (p - p_z)V_t \ln \frac{p}{p_a} \] (9)

Thus, the energy efficiency can be written as Eq. 10.

\[ \eta = \frac{E_{out}}{NE_{in}} = \frac{A_b \ln \frac{p}{p_a}}{(A_d + A_b) \ln \frac{p_z}{p_a}} \] (10)

4 Experimental Setup and Procedure

The pressure 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. 3 indicates the pneumatic circuit of the experimental apparatus in this research. The apparatus includes an air compressor, a filter-regulator-lubricator, two air power meters that can measure air power, as well as pressure, temperature, and flow rate; two air cylinders with a 63 mm diameter and a 100 mm stroke; one air cylinder with an 80 mm diameter and a 100 mm stroke; and a 0.01 m³ air tank. Also, instead of using mechanical valves, we use two 5-way/2-position solenoid valves and change the position by a solid-state timer. We acquire data with a sampling rate of 1000 Hz. Experiment is carried out with supply pressure of 200 kPa, 300 kPa, 400 kPa, 500 kPa.

![Circuit diagram of PBV-R](image)

**Fig. 4 Circuit diagram of PBV-R**

The purpose of this experiments is to investigate the differences of performance between PBV method and PBV-R method. Thus, using the experimental apparatus, we test both PBV and PBV-R method; the PBV-R method can be operated by the circuit as indicated in Fig. 3, and the PBV method can be built by disconnecting ‘a’ and ‘b’ and connecting ‘c’ and ‘d’.

Energy efficiency of each method can be calculated with using air power acquired by air power meter as Eq. 11.

\[ \eta = \frac{E_{out}}{E_{in}} = \frac{\int_0^\infty p_{out} \, dt}{\int_0^\infty p_{in} \, dt} \] (11)

Boost ratio of each method can be calculated with input pressure and output pressure measured by air power as Eq. 12:

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\[ k_p = \frac{p_{\text{out}}(\infty)}{p_{\text{in}}(\infty)} \]  

(12)

In this case, because sufficient time is needed for \( p_{\text{in}} \) and \( p_{\text{out}} \) to converge and do not fluctuate anymore, we define boost ratio by using \( p_{\text{in}}(\infty) \) and \( p_{\text{out}}(\infty) \).

5 Results and Discussion

Fig. 5 illustrates the energy efficiency at each supply pressure. The dashed lines are numerical and experimental result of PBV method, and the solid line indicates those of PBV-R method. Numerical result shows that the energy efficiency of PBV-R method is from 5% to 20% higher than that of PBV method. Also, experimental result shows that PBV-R method is from 5% to 8% more efficient than PBV method. However, the difference of energy efficiency between numerical results and experimental results exist. Also, according to the numerical analysis, PBV-R method theoretically can be 20% more efficient than PBV method, but experiment could not show the difference. One of the main reason is considered as energy loss by pipe. Because a diameter of the pipe used on experimental apparatus is only 7 mm, it is considered to cause an unnegligible pressure loss and energy loss.

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

Fig. 6 illustrates the boost ratio at each supply pressure. Boost ratios are high when supply pressure becomes high overall. Numerical result shows that the boost ratio the boost ratio of PBV-R method gains from 13% to 20% higher pressure than PBV method at 300 kPa, 400 kPa and 500 kPa; while only 4% is higher at 200 kPa. Also, experimental result shows that PBV-R method gains from 18% to 20% higher pressure than PBV method at 300 kPa, 400 kPa and 500 kPa; while only 6% is higher at 200 kPa. Compared to high supply pressure, at low supply pressure, as we can see in Eq. 4, because friction force of an expansion chamber \( f_e \) is greater than other terms, recovered air in the expansion chamber is not effective enough for boosting air pressure.

6 Conclusion

In this study, first, we carried out numerical analysis of performances of PBV and PBV-R with real parameters. Then, we set up an experimental PBV-R apparatus and investigated performances of the PBV method and the PBV-R method. Although there are differences between the numerical analysis and the experiment, both results show that the PBV-R method is energetically more efficient and gains higher pressure than PBV method. Thus, it may be concluded that PBV-R method is numerically and experimentally validated.
Nomenclature

\( A \) Area of piston
\( E \) Air energy
\( f \) Friction force
\( k_p \) Boost ratio
\( l \) Stroke
\( p \) Pressure
\( P \) Air power
\( Q \) Flow rate
\( T \) Temperature
\( V \) Volume
\( \eta \) Energy efficiency
\( \kappa \) Specific heat ratio

Subscript
\( a \) Atmosphere
\( b \) Boost chamber
\( d \) Drive chamber
\( e \) Expansion chamber
\( \text{in} \) Inlet
\( \text{out} \) Outlet
\( s \) Supply
\( t \) Air tank

References


