Proceedings of the 7th JFPS International
Symposium on Fluid Power, TOYAMA 2008
September 15-18, 2008

P1-40

AN APPROACH TO ENERGY CONSERVATION FOR AIR MOTOR

Eisuke SUMIDA*, Masaki GOTO* and Hiroshi MUTOH**

*Department of Applied Mechanics
Graduate School of Fundamental Science and Engineering, Waseda University
3-4-1 Ookubo,Shinjyuku-ku, Tokyo,169-8555 Japan
(E-mail: z-chiyo-add-z@asagi.waseda.jp)
** Department of Applied Mechanics and Aerospace Engineering
School of Fundamental Science and Engineering, Waseda University
3-4-1 Ookubo,Shinjyuku-ku, Tokyo,169-8555 Japan

ABSTRACT

There are many methods to improve actuator efficiency in pneumatic systems. In this research, the authors remodeled rotary valve of radial piston type air motor. During forward rotation, increasing Cut-off ratio of rotary valve which controls supply and exhaust timing can increase expansion process in this motor. As a result, air consumption was reduced, torque was increased and efficiency that we define as the ratio of air consumption to torque was improved. And the authors clarified the existence of an optimum angle in Cut-off ratio.

Considering practical utilizations, performance of this motor is demanded for the same forward rotation as backward rotation. But actually, increasing Cut-off ratio increases compression process and derives efficiency worse.

So the authors have proposed to remodel the casing of this motor in addition to increasing Cut-off ratio. This remodeling makes this motor the same performance forward rotation as backward rotation, but clearance volume expands. So the rate of increasing efficiency under this condition is less than under only remodeling Cut-off ratio. But we directed to possibility of improving efficiency.

KEY WORDS

Key words: Actuator, Rotary valve, Cylinder, Cut-off angle, Expansion energy

NOMENCLATURE

E_I	:	Supplied energy
P_C	:	Cylinder pressure
τ	:	Torque
V_C	:	Cylinder volume
ω	:	Angular velocity
h	:	Efficiency
θ_{ex}	:	Cut-off angle

INTRODUCTION

The characteristic of the pneumatic actuator depends mainly on the compressibility of air as its operating medium. The advantages include the easy storage of energy, the small size and lightweight per output, and the good explosion-proof performance.

The disadvantages include the low energy conversion efficiency, the low controllability caused by the compressibility of air, and the loud exhaust noise, which a variety of researches have been developed to improve. The energy conversion efficiency can be improved by reducing pressure loss or fluid resistance due to air leaks or restrictions, or by using supplied energy efficiently. This research attempted higher energy conversion efficiency by using the expansion energy of compressed air. The subject is a radial piston type air motor. Remodeling its rotary valve for utilizing the characteristic of air in the cylinder was applied to reduce the supplied and exhaust energy. The problems of the remodeling were shown, which led to the proposal of new remodeling. The validity was examined by simulation.

THE PRINCIPLE

Figure 1 illustrates a radial piston type air motor in section. Supplied air passes through the inside of the rotary valve indicated by the shaded area, pushes the piston down, passes through the inside of the rotary valve again, and then lets out. Figure 2 (a) illustrates a genuine rotary valve in section which is an important part to decide supply and exhaust timing in driving.

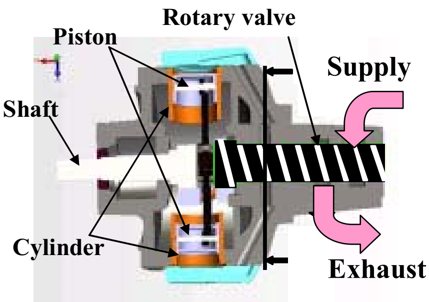
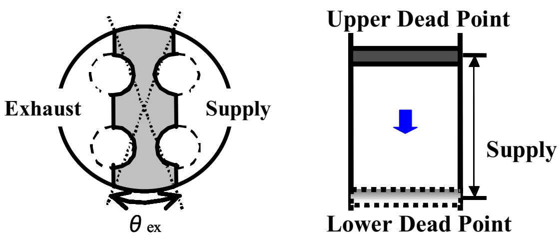


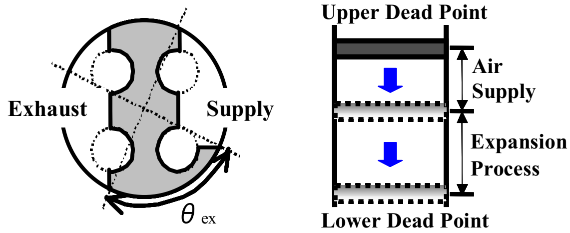
Figure 1 Radial piston type air motor in section



(a) In section (b) Cylinder

Figure 2 Genuine valve

As shown in Figure 2 (b), the genuine valve supplies air during the piston travels from the upper to the lower dead point. This mechanism does not make full use of the expansion energy of air. To improve this, remodeling the rotary valve for using the expansion energy of air was applied. Figure 3 illustrates the remodeled valve in section.



(a) In section (b) Cylinder

Figure 3 Remodeled valve(Forward rotation)

As shown in Figure 3 (a), increasing Cut-off angle θ_{ex} on the supply side cuts air supply off halfway, and the supplied air expands in the rest of its stroke. This may give lower air consumption and higher efficiency. Three remodeled valves were made for the research. Table 1 shows the Cut-off angles and the expansion process rate of the genuine and all remodeled valves. The expansion process rate is defined only for forward rotation. Consideration to backward rotation is in another chapter.

Table 1 Remodeled values of Rotary valves

Valve	Cut-off angle rad	Expansion process rate
Genuine	0.262 π	0.001
Remodeled #1	0.479 π	0.121
Remodeled #2	0.631 π	0.307
Remodeled #3	0.750 π	0.487

EXPERIMENTAL SETUP

Figure 4 illustrates the outline of the experimental setup used in this research. The method is to change the angular velocity by controlling the exciting current of the magnetic particle brake at 0.5[MPa] of supplied air pressure.

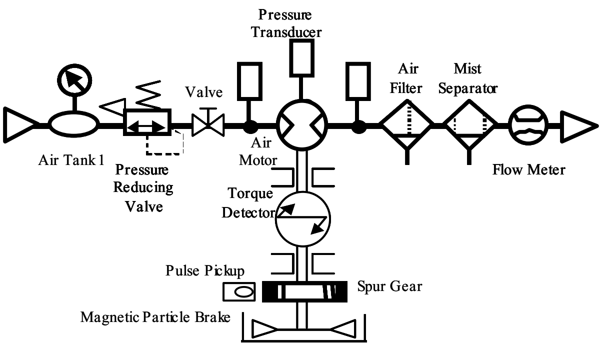


Figure 4 Outline of Experimental setup

EXPERIMENTAL RESULTS AND CONSIDERATIONS

Figure 5 illustrates the *P-V* diagram of the cylinder inside for each valve at 80[rad/s] of angular velocity. Figure 6 illustrates The *P-V* diagram in changing angular velocity for the remodeled #2.

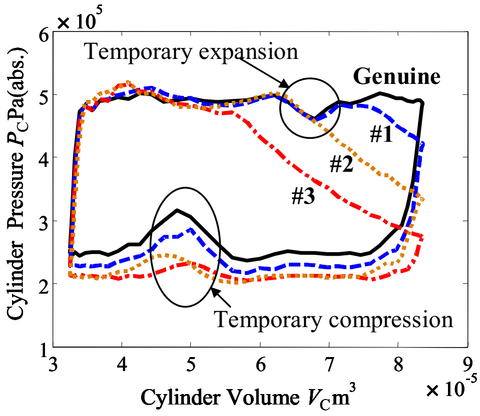


Figure 5 *P-V* diagram (80[rad/s])

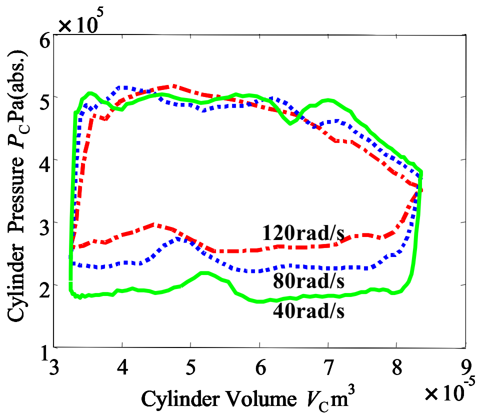


Figure 6 *P-V* diagram(Remodeled #2)

As shown in Figure 5, this process in which the expansion process rate increases as the Cut-off angle increases is categorized into adiabatic expansion. The higher exhaust pressure than atmospheric pressure is caused by the equipment of the air filter, mist separator, and flow meter on the exhaust side.

The lower exhaust pressure of the remodeled valves than the genuine valve appears as the Cut-off angle increases. This is caused by the reduction of air supply at the same revolution. The temporary compression is observed in exhaust. This is considered as the effect of the four cylinders motor in that when the measured cylinder comes at 270[deg] of phase, another cylinder running 90[deg] behind starts exhausting. The temporary expansion in supply is caused by the similar effect. The results of air consumption and output are shown in Figure 7 and Figure 8.

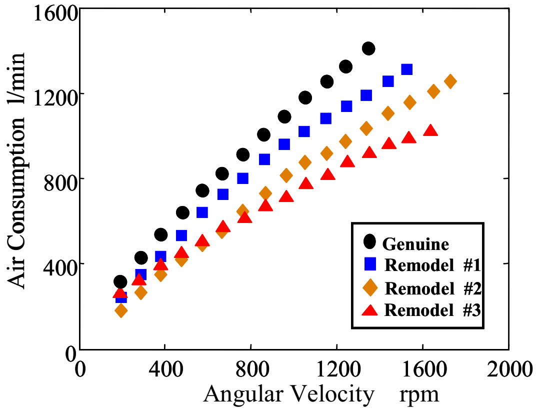


Figure 7 Air consumption

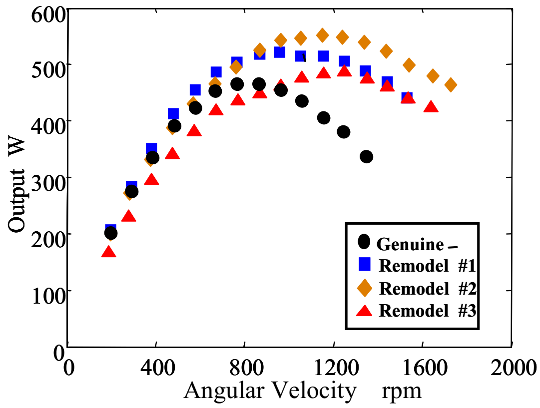


Figure 8 Output

Focusing on the air consumption, it decreases in the high and middle revolution range as the Cut-off angle increases.

The output of all remodeled valves is generated more than the genuine valve. Theoretical torque is represented as the area of *P-V* diagram. In Figure 5, the reduction, in the expansion process, of the *P-V* diagram area for the remodeled valves seems worse than the genuine valve. But the lower exhaust pressure of the remodeled valves than the genuine valves allows the higher torque.

The following equation calculates efficiency. The input is supplied energy and the output is shaft output.

$$\eta = \frac{\tau\omega}{E_1} \times 100 \tag{1}$$

Figure 9 shows the efficiency calculated by this equation. All remodeled valves improve the efficiency in Figure 9. The remodeled #2 which show the highest efficiency improves it by approximately 4[%] in all revolution ranges. The remodeled #1 and #2 show no peaks. This is considered to be caused by the dispersion of revolution on the effect of stick-slip in the low revolution range. The Cut-off angle of each valve increases as the remodeled number, and the efficiency of #2 is higher than #1 while that of #3 is not the highest. This shows that an optimum Cut-off angle giving a maximum efficiency should exist.

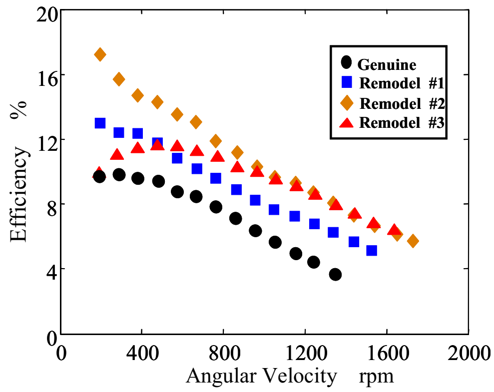


Figure 9 Efficiency

PROBLEMS OF REMODELING

Performance in backward rotation

The improvement of the efficiency in forward rotation was examined in previous chapter. But in backward rotation, the compression process doesn't improve the performance, the expansion process does. Figure 10 and 11 shows the results.

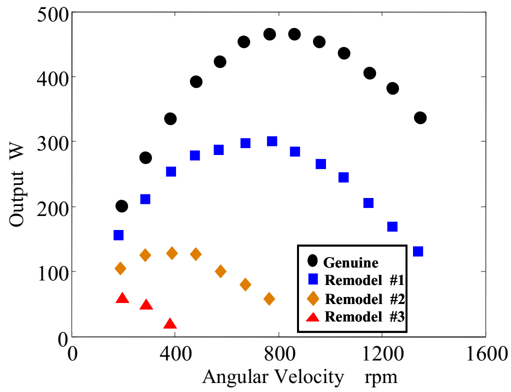


Figure 10 Output(backward rotation)

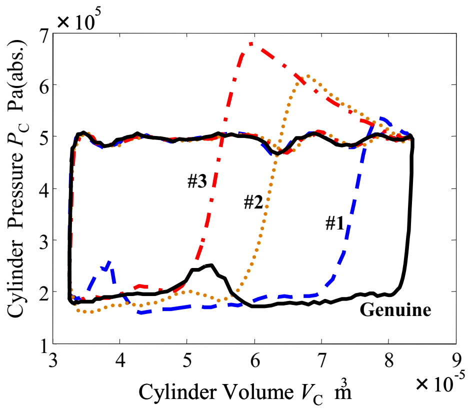


Figure 11 *P-V* diagram(backward rotation 40[rad/s])

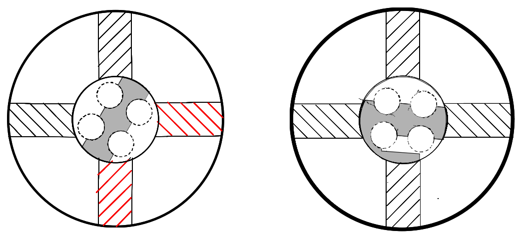
Increasing the Cut-off angle expands the compression process to lower the output. The torque output was almost lost at 90[rad/s] for the remodeled #2 and at 40[rad/s] for the #3 of revolution to prevent higher revolution. While the remodeled #1 has much lower torque and output, it can rotate more than at 120[rad/s] of revolution so that it has enough performance to be used even in backward rotation.

Starting torque

Changing the Cut-off angles showed the existence of some specific Cut-off angles at which the upward tendency of starting torque changes into downward or the motor cannot start theoretically.

Figure 12 explains the reason. Air passes through the inside of the rotary valve and the ducts, and is supplied to the cylinder inside. The four ducts connected to each cylinder are used for air supply and exhaust.

In Figure 12(a) air was always supplied to the cylinder, but in (b) air is not supplied. While the experimental estimation of starting torque is difficult on the effect of air leaks, the torque was at approximately 10.5[Nm] in supplying air to two cylinders and 6.8[Nm] in supplying air to one cylinder, at 0.5[MPa] of air supply pressure. The classification of the cut-off angles, the number of cylinders, and the valve types is shown below.



(a)2 cylinders supplied (b)Not supplied

Figure 12 Starting Torque

(1) $\theta_{ex} < 0.244\pi$ [rad]

2 cylinders supplied

(2) $0.244\pi < \theta_{ex} < 0.500\pi$ [rad]

1 or 2 cylinders supplied (genuine, remodeled #1)

(3) $0.500\pi < \theta_{ex} < 0.745\pi$ [rad]

1 cylinder supplied (remodeled #2)

(4) $0.745\pi < \theta_{ex}$ [rad]

0 or 1 cylinder supplied (remodeled #3)

In some cases of the remodeled #3, air was not supplied so that it doesn't rotate theoretically. Actually, the leaked air may come into the cylinder to rotate it. But practical use should be restricted. For the remodeled #1 and #2, air is always supplied to the cylinders, but the starting torque is lower than the genuine valve.

Starting characteristic

Figure 13 shows the experimental results for the starting characteristic of the genuine valve and remodeled #3 applying the step input of air supply pressure.

It shows the genuine valve has the better starting characteristic than the remodeled #3. This is caused by the number of cylinders supplied air. For the genuine valve, two cylinders are usually supplied and for the #3, just one cylinder is. For the other remodeled types, the ducts connected to the cylinders are shut off longer than the genuine valve by increasing the Cut-off angles so that the amount of air supply reduces when step input begins. This makes the starting characteristic worse.

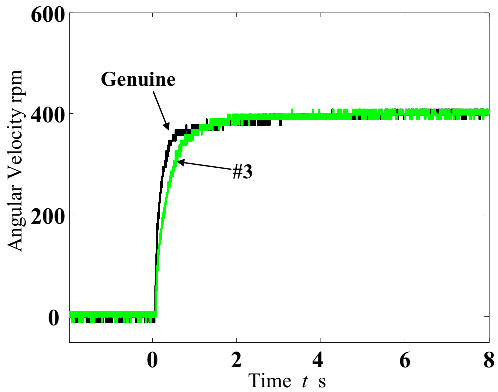


Figure 13 Comparison of Starting Characteristic

PROPOSING NEW REMODELING

The deteriorations due to the remodeling were enumerated in previous chapter. In this chapter, new remodeling for the same level of performance in both rotations is proposed.

Remodeling only rotary valves has limitation for the same level of performance in both rotations. Many practical uses may require the performance of backward rotation so that new design with remodeling casings and rotary valves was developed. The outline is shown in Figure 14 and its casing in section is shown in Figure 15.

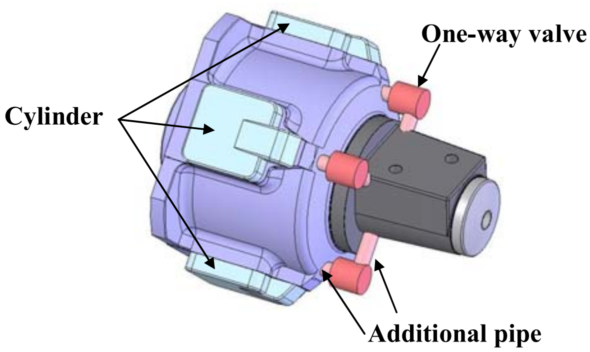


Figure 14 Outline of Casing

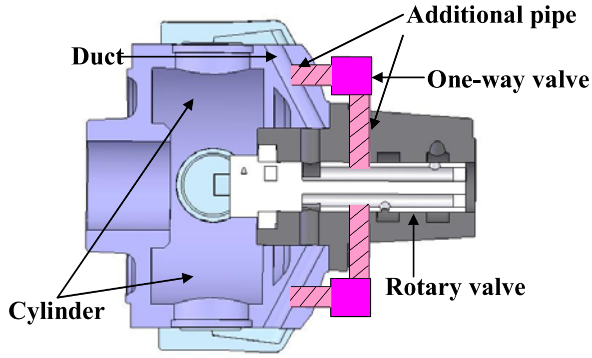


Figure 15 Casing in section

Supplied air usually reaches to cylinders through supply-side pipes inside rotary valves and ducts. After working on pistons, it passes through ducts again and exhaust-side pipes inside rotary valves, and lets out. In backward rotation, however, exhaust grooves do not open immediately so that pistons work on air, which represents the generation of compression process. Additional pipe shown in Figure 15 in section provides another exhaust groove. It is considered that making a hole in the rotary valve along with the phase of the new exhaust groove allows exhaust as compression process occurs. The installation of the one-way valve provides cutting air supply off if expansion process begins during air supply. Without this one-way valve, expansion process may be prevented by supplied pressure air flowing in.

This proposed design is examined by simulation. The two kinds of one-way valve performance used in the simulation are shown in Figure 16. The performance diagrams of the remodeled #2 giving the best efficiency in forward rotation and the specs having the similar Cut-off angle and the one-way valve #1 or #2 are shown.

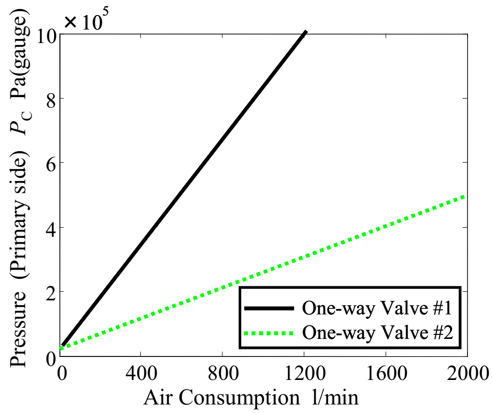


Figure 16 Performance of One-way valves

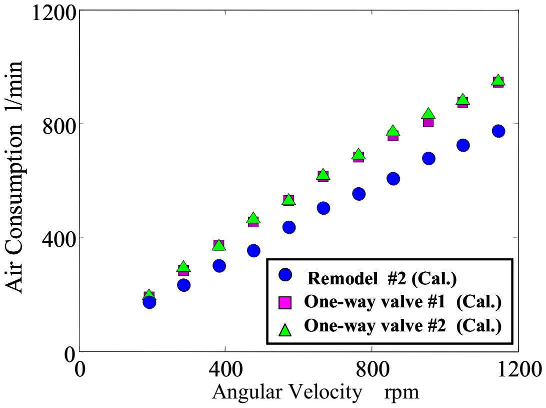


Figure 17 Air consumption(remodeled Casings)

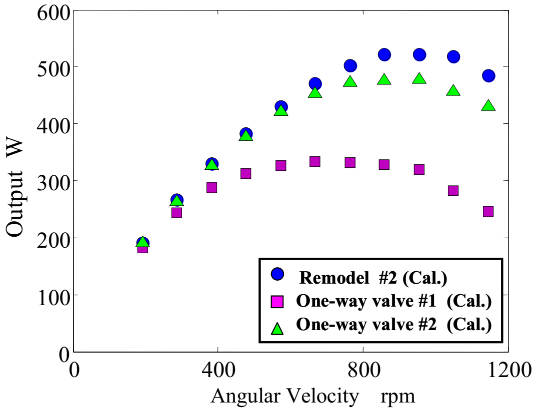


Figure 18 Output (remodeled Casings)

The one-way valve #1 and #2 consumes more air than the remodeled #2. This is caused by increasing the gap volume because of installing the one-way valves and by adding the pipe connecting the one-way valves and the rotary valves. Reducing the additional volume provides the same level of air consumption with the remodeled #2.

The remodeled #2 and the one-way valve #2 have the same level of output in the both low and high revolution ranges. But the one-way valve #1 has much lower output as the revolution increases. Figure 19 shows the *P-V* diagram to explain the reason.

The shift of the diagram toward the right due to the added gap volume is shown. The smaller effective sectional area of the one-way valve #1 than the #2 means no smooth exhaust. When the exhaust route changes from the one-way valve into the original, the higher cylinder pressure keeps the exhaust pressure higher than the remodeled #2 to reduce the output.

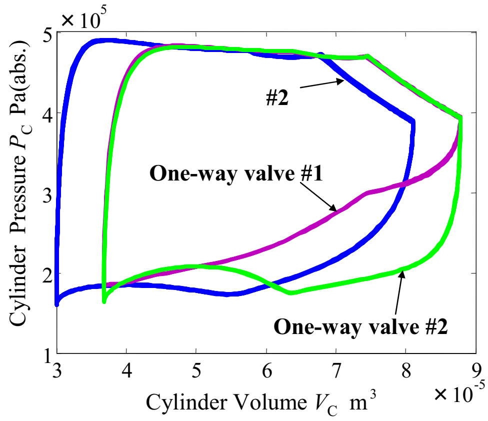


Figure 19 *P-V* diagram (remodeled Casings)

CONCLUSION

While the performance tests progressed, no considering the expansion of air characteristic for the existing pneumatic actuators was proved. Therefore this research was planned to improve the characteristic in forward rotation by remodeling the rotary valves working for the supply and exhaust of pneumatic motors. Comparing the remodeled valves with the genuine valve, all remodeled valves improved the output, the amount of air consumption, and the efficiency in forward rotation. The lower exhaust pressure is also supposed to give lower noise. The possibility of an optimal Cut-off angle giving a maximum efficiency was shown.

The remodeling made the problems of the lower performance relating to backward rotation, starting torque, and starting characteristic. A feature of radial piston type pneumatic motors is changing the rotational direction with a low-cost selector valve so that the same level of performance in both directions is required. Therefore the design including the remodeled rotary valve and casing to give the same performance was developed. The simulation of the design showed the added gap volume and installed one-way valve work as the element of pressure loss so that higher efficiency than remodeling only rotary valve is not given. But a guideline was indicated. Reconsidering the shape of the motor and adapting the design for both rotational directions will reduce gap volume to give the same level of efficiency with remodeling only rotary valve.

REFERENCES

1. Goto, Sumida, Mutoh : System control containing pneumatic actuator（Speed control of pneumatic motor）, Journal of Fluid power System Symposium, 2007, pp52-54

2. Sumida, Nakajima, Goto, Mutoh : System control containing pneumatic actuator （Position control of pneumatic motor）, Journal of Fluid power System Symposium, 2007,pp55-57.