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Design and test of a compressed air driven hydraulic motor system with compress air booster

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Abstract. In this study a highly efficient compressed air driven hydraulic motor system is designed, developed and tested. The basic concept of using a hydraulic motor to transform the energy of compressed air (which compressing the hydraulic oil) to mechanical energy is developed, which can use the energy in compressed air more efficiently than the traditional piston type air engine. However, due to the air pressure exhale from the converter still has some energy. To recover the energy, a booster is used to recover the energy. In this study, both theoretical model and experiment device of the system are developed; several experiments to validate the theoretical model are made. It was found that the efficiency of the system is good when using the booster.

1. Introduction

Compressed air is one of the candidates to power the engine without pollution emissions at usage. To transform the energy of the compress air to the mechanical energy, there are a lot of research works have been done. In 1973, Brown [1] filed a pattern which modified a multi-cylinder four stroke engine to a hydraulic engine. Otto [2] also presented a patent which used compress air to push the hydraulic oil and the oil push the pistons which driving a crane shaft. A flywheel is connected with the crank shaft to stabilize the rotating speed of the crank shaft. Through this way; the energy in compress air becomes kinetic energy. The intake and expiration of the air was controlled by the air valves according the angle of the crank shaft. Shen et al [3] and Castro_Alves et al [4] used the piston type air engine to drive a motor cycle was an example of using the air engine. Several research works [5-7] about piston type air engine were published. However, due to the pressure of expiration air is high; the efficiency of the piston type air engine is not so good, therefore, several researches used the compress air to compress the hydraulic oil and this oil was used to drive the hydraulic motor were presented. The reasons for the efficacy of a piston type air engine is not as high as that of the hydraulic motor are (1) The hydraulic oil is incompressible and the exhaust pressure of the oil is the same as that of the atmosphere (even though the pressure is higher than the atmospheric pressure, the energy stored in the hydraulic oil is low); (2) The hydraulic motors’ high efficiency can enhance the total efficiency of the system. In 2006, Lemofouet and Rufer [8] used compress air to push the hydraulic oil into two air/oil converters to generate the pressurized oil. The pressurized oil was used to drive a hydraulic motor. The 4-way 3 position solenoid valve was used to control the direction of air flow. In their research, a flywheel was used to stabilize the rotating speed of the shaft. The use of the flywheel reduce the efficiency of the system due to at the point of changing the direction of oil flow, there is no enough torque and speed to rotate the flywheel. This makes the flywheel drives the hydraulic motor and makes
some energy in the flywheel wasted due to the resistant from the motor. To overcome this deficiency, in 2013, D. Shaw et al [9] presented a system that used two air/oil converters to convert the energy in compressed air to high-pressure oil. The high-pressure oil then used to drive a hydraulic motor. Usually, the efficiency of the hydraulic motor is higher than piston type compress air engine. To make the motor rotate continuously, an accumulator is used to reserve some amount of the compressed air and the air is used when the input oil is changed from one convertor to another convertor. The use of the accumulator increased the efficiency of the system. The volume of air in the air/oil convertor at each stage of air expansion is larger than the piston type air engine for one cycle. It is found that the longer the expansion duration, the less the energy loss. It is also noted that the longer duration of expansion also let the surrounding heat transferred into the air/oil convertor to make the temperature of the system close to the atmosphere temperature and increase the efficiency more.

In reference [9], the energy of compressed air (which compressing the hydraulic oil) is transformed by using a hydraulic motor to mechanical energy. There are two ways to use the compress air in the air/oil convertor. One is the isobaric mode (air in the convertor keep in a constant pressure and the exhaust air pressure is same as the input air, therefore, the energy in the compress air is wasted) and the other is expansion mode (the air into the convertor is keep in constant for some instance, after some certain volume compressed enter the convertor, the air is stop to enter the convertor and the air start to expand to lower pressure). In the expansion mode, the residual pressure of exhaust air is smaller than isobaric mode. However, even in the expansion mode, the exhaust air pressure is not equal to atmosphere pressure due to the hydraulic motor character. There are energy still not been used. To overcome this weakness of reference [9], in this study, a booster is used to recover the energy of exhaust air. Some energy of exhaust air is recovered to increase the pressure of exhaust air. After the exhaust air pressure is increased to certain value, the air is then import to the convertor and converts the energy into kinematic energy to increase system efficiency.

In this study, both the theoretical efficient analysis and experimental study will be introduced in following sections. The equations of efficiency of isobaric mode, expansion mode and booster are introduced. Experiment devices of measuring the booster and system efficiency were developed and the efficiencies of the system under different air pressure and rotating speed were tested.

2. Layout of compressed air engine and its operating processes
In this section, the system layout of compressed air engine and its operating processes are introduced. The system layout is shown in figure 1. The system is composed of a tank, 5 pneumatic ball valves, 2 air/oil converters, a booster to recover the residue energy in the exhaust, 5 check valves, several air pipes and oil pipes, a hydraulic motor, a pressure regulator, a booster, an air tank for filter of the hydraulic oil in the system.

![Figure 1. Compressed air engine system layout.](image)
In the system, hydraulic oil only flow from high pressure to low pressure. Check valve only allow hydraulic oil flow into the motor in one direction. The compressed air is stored in the air tank; while the air is released; high pressure is regulated to working pressure using the pressure regulator. After the air enters the converter, the converter converts air pressure into hydraulic pressure and pushes the hydraulic oil to drive the hydraulic motor and finally goes into another converter (In figure 1, the oil of the red converter flow into the blue converter). According to oil flow direction the system is divided into phase A and phase B. As shown in figure 1, red is the high pressure oil, blue is the low pressure oil. In phase A, the compressed air goes to the left converter and the oil in left converter goes to the right converter through hydraulic motor. In phase B, the compress air goes to the right converter and the oil in the right converter goes to left converter. It is noted that when at the time the phase changed from one phase to another phase, there is an oil flow interrupt and this makes the motor cannot provide any output torque. To prevent this, an accumulator is used to keep the oil continuously enter the motor. To complete one cycle of operation, the hydraulic oil must flow back and forth between two converters, but the direction of the oil enter the hydraulic motor must be the same. To operate the system continuously relies on the oil in the accumulator which will provide the oil at the time the converters under phase change. Due to the energy in exhaust air is still not zero, the exhaust air input to a booster to increase the pressure of exhaust air, when the air in the booster has enough pressure, than enters the converter which pushes the oil into the motor.

In this study, there are two ways to use the energy in the compressed air. The easiest way is isobaric condition (we call it isobaric mode). Under that condition, the air continuously enters the converter with constant pressure till the air fully fills the converter. The air is then release to the booster. Under this condition, a lot of energy in the exhaust air is still not used. To use the energy in the compressed air more, we can control the amount of compressed air enter the converter by closing the ball valve. After closing the valve, let the air in the converter expand and do more work. This process reduces the pressure of the exhaust air (we call this expansion mode). Though using the expansion mode has higher efficiency, there still needs isobaric operation mode. Under this mode, the output torque of the motor is constant; this mode is suitable for the condition which requires high torque, etc.

3. The development of theoretical efficiency equations of the system
Due to the complexity of the hydraulic motor, the efficiency of the motor follows the chart provided by hydraulic motor manufacture. The theoretical efficiency of the system can be calculated by product of the theoretical efficiency of the subsystem includes converter and the booster with the efficiency of the hydraulic motor. Therefore, in following sections, we will discuss the efficiency of the booster, the efficiency of the isobaric mode and expansion mode of the subsystem includes converter and the booster. Finally, the equation of theoretical efficiency will be introduced.

3.1. The efficiency of booster
Due to the manufacturer does not provide the efficiency of the booster. Experiments have to be done to know the efficiency of the booster. The experimental setup of measuring the efficiency of booster is lineup of a big air tank as compress air source, a booster (SMC VBA-11A-02) and a small air tank as the reservoir of the compressed air from booster. The compressed air is first stored in the big air tank and release to the booster. When the compressed air enters booster, it increases the pressure of the air and then the high pressure air stored in small air tank. The booster can increase the pressure of small air tank up to four times of that of the air of big air tank. The efficiency of the booster is calculated by dividing the energy of the air in the small air tank with the initial energy of big air tank as shown in equation (1). In equation (1), the energy equation can be found in [10]. The efficiency can be calculated by dividing the energy of air in small tank by the energy of air come out from big tank.
Where, \( \eta_b \) is the efficiency of the booster, \( \gamma \) is heat capacity ratio, \( p_t \) is the pressure in the small tank, \( p_b \) is the pressure in the big tank, \( V_t \) is volume of small tank and \( V_b \) is volume of big tank. The results of the experimental efficiency of the booster used in this study in different pressure are almost a constant. The efficiency used in the theoretical efficiency calculating is 22.3%.

3.2. The efficiency of the subsystem includes converter and the booster for isobaric operation

Before analyze the efficiency of converter, the conversion follows 5 assumptions.

- The real air complies with the ideal gas equation.
- The hydraulic oil is the incompressible fluid.
- Ignore the impact velocity of the fluid and the height variation.
- Each valve not to cause pressure drop.
- The experiment of expansion is under isothermal condition.

As shown in the study of Cai et al [11], the energy in the compressed air is divided into two parts. The first part represents the transmission power, which addresses the power required to push the air downstream. The second part represents the expansion power, which addresses the available work in the air. The basic equations of thermodynamic can be found in [11].

Definitions pressure conversion efficiency \( \eta_{cp} \) is:

\[
\eta_{cp} = \frac{E_{use}}{E_{Total}}
\]

(2)

Where

\[
E_{Total} = E_e + E_c
\]

(3)

\[
E_{use} = E_e + E_b
\]

(4)

**Figure 2.** Ideal P-V diagram of isobaric operation.

In above equations, the total energy of the compressed air for the air tank into system is the \( E_{Total} \). The \( E_{Total} \) combines the energy of hydraulic oil which drives the hydraulic motor \( E_e \) and the energy of the residual pressure in converter \( E_c \). The \( E_{use} \) combines the energy of hydraulic oil which drives the hydraulic motor \( E_e \) and the energy of the energy comes from booster \( E_b \). Figure 2 shows a compressed air of converter P-V diagram for constant pressure operation. Where \( P \) is the pressure of
the air and $P_{\text{atm}}$ is the pressure of atmosphere. The total volume of the conversion is $V_c$, and area of the dotted line is $E_e$.

It follows the equation to calculate the $E_e$:

$$E_e = \int (P - P_{\text{atm}})dV = (P - P_{\text{atm}}) V_c$$  \hspace{1cm} (5)

The energy of the residual pressure of the air in the converter $E_c$ is not used to drive the hydraulic motor. Energy $E_c$ defined as when a gas pressure $P_{\text{atm}}$ and volume $V_{\text{atm}}$ from an atmospheric pressure environment to pressure $P$ and volume $V_c$ in adiabatic compression mode. The different between $E_c$ and $E_e$ is the energy of power output to motor and $E_e$ is under isothermal process because the process for system is very slow and no significant change in temperature. $E_c$ is under adiabatic process because when the compressed air stored in air tank, it is not considered the energy come from ambient environment. $E_c$ follows the equation (6).

$$E_c = \frac{PV_c}{1-\gamma} \left[ \left( \frac{P}{P_{\text{atm}}} \right)^{\frac{1}{\gamma}} - 1 \right] - P_{\text{atm}}(V_{\text{atm}} - V_c)$$  \hspace{1cm} (6)

The energy $E_b$ is the energy recovers from the exhaust air which can be defined as following:

$$E_b = E_c \eta_b \frac{V_c}{V_c + V_b}$$  \hspace{1cm} (7)

Pressure conversion efficiency $\eta_{\text{exp}}$ rewrite to

$$\eta_{\text{exp}} = \frac{(P - P_{\text{atm}})V_c + \eta_b V_c}{(V_c + V_b) \left( \frac{PV_c}{(1 - \gamma)} \right) \left( \frac{1}{\gamma} \right) - 1} - P_{\text{atm}}(V_{\text{atm}} - V_c)$$  \hspace{1cm} (8)

3.3. The efficiency of the subsystem includes converter and the booster for expansion mode

Expansion mode is a high efficient mode. This section develops the formulas by using assumptions as and thermodynamic equations [11] in Section 3.2. The difference of this section is established a variable $N$. The $N$ is the ratio of the total stroke and the intake stroke.

Definitions pressure conversion efficiency $\eta_{\text{exp}}$ is:

$$\eta_{\text{exp}} = \frac{E_{\text{use}}}{E_{\text{Total}}}$$  \hspace{1cm} (9)

Where,

$$E_{\text{Total}} = E_c + E_e$$  \hspace{1cm} (10)

$$E_{\text{use}} = E_e + E_b$$  \hspace{1cm} (11)

Figure 3 shows the $P$-$V$ diagram of the compressed air of converter for expansion mode. N is the fraction of the converter volume when the external air enter the amount of fraction of N, the valve is closed to stop the external air import. The area of the dotted line is $E_e$, and it following the equation.
\[ E_e = (P - P_{atm}) \frac{V_c}{N} + (P_{atm}) \ln \left( \frac{V_c}{V_c} - \frac{V_c}{N} \right) - P_{atm} \left( V_{atm} - \frac{V_c}{N} \right) \]  

(12)

**Figure 3.** Ideal P-V diagram of expansion mode.

And \( E_e \) is rewritten as

\[ E_e = \frac{P}{N} \left( \frac{V_c}{1 - \gamma} \right) - 1 - P_{atm} \left( V_{atm} - \frac{V_c}{N} \right) \]  

(13)

Finial, the pressure conversion efficiency \( \eta_{exp} \) can be rewritten to

\[
\eta_{exp} = \frac{(P - P_{atm}) \frac{V_c}{N} + (P_{atm}) \ln \left( \frac{V_c}{V_c} - \frac{V_c}{N} \right) + \frac{V_c}{V_c + V_h} \left[ \left( \frac{P}{P_{atm}} \right)^{\frac{1}{\gamma}} - 1 \right] - P_{atm} \left( V_{atm} - \frac{V_c}{N} \right)}{(P - P_{atm}) \frac{V_c}{N} + (P_{atm}) \ln \left( \frac{V_c}{V_c} - \frac{V_c}{N} \right) + \frac{V_c}{V_c + V_h} \left[ \left( \frac{P}{P_{atm}} \right)^{\frac{1}{\gamma}} - 1 \right] - P_{atm} \left( V_{atm} - \frac{V_c}{N} \right)}
\]  

(14)

3.4. The theoretical efficiency of the system

In the system, there are two major subsystems which dominate the efficiency of the system. The subsystem includes converter and hydraulic motor. We assume the efficiency of the system is the product of the efficiency of these two subsystems. It is noted that the effect of the pipe, valves etc. are not considered in the theoretical efficiency. The theoretical efficiency of the system can be defined as:

Efficiency of system = efficiency of converter (included the efficiency of booster)\( \times \) efficiency of hydraulic motor

(15)

DANFOSS OMM 50 is the hydraulic motor used in this system. The efficiency of hydraulic motor for different pressure can be found from manufacture’s manual [12].

4. Experimental set up

4.1. Configuration of the experimental set up

The developed compressed air driven hydraulic motor system is shown in figure 4. The configuration of the experiment device can be found in figure 1. The parts used are list in Appendix. The measurement of the torque variation with time is at a fixed speed. The reason for that is the difference between this system and other pneumatic engines is that the expansion time is longer. If used the fixed
torque to measure the power output, there is a chance of the output torque being too small to be measured due to expansion of the system. The speed is measured and fed back to the brake to keep the speed of the hydraulic motor near the set value. The configuration of dynamo meter test device is shown in figure 5. The speed of the hydraulic motor is measured by the tachometer and the signal goes to the controller. After the PID signal is processed in the controller, the signal is output to the brake actuator to control the voltage input from the power supply to the brake to control the rotation speed.

**Figure 4.** Experimental set up. **Figure 5.** The configuration of the experimental set up.

4.2. *Equation of the experimental efficiency of the system*

The experimental efficiency of the system is defined as the ratio of the output shaft energy to the energy consumption of pneumatic system as following:

\[
\eta_{\text{system}} = \frac{\tau \times \omega}{P_{\text{filter}} \times q_{\text{air}} + E_{\text{ex}}} 
\]  

\[
E_{\text{ex}} = \frac{P_{\text{filter}} \times q_{\text{air}}}{1 - \gamma} \left[ \left( \frac{P_{\text{filter}}}{P_{\text{atm}}} \right)^{\frac{1}{\gamma}} - 1 \right] 
\]

where \( \tau \) is the torque of the hydraulic motor (N-m), \( \omega \) is the rotating speed of the hydraulic motor (rpm), \( P_{\text{filter}} \) is the air pressure enter the converter (Pa), \( q_{\text{air}} \) is the flow rate of the air enter converter (m\(^3\)/s) and \( E_{\text{ex}} \) is the energy of air expansion (J).

5. Results of analysis and experiment

One may use equations (8) and (14) to calculate the efficiency of the converter. Before calculating the efficiency of the converter, one should know the effect of the booster volume on the efficiency of the converter. In figure 6, the effect of the different ratio of the booster and converter volume on the efficiency of converter is presented. It is found that although the volume ratio does not affect the efficiency much (in figure 6, only about 2%), we still can find that the smaller the volume ratio, the higher the efficiency of the converter. In this study, 2% volume ratio is used in all cases.

Figure 7 is the results of efficiency of the converter for different air pressure of isobaric mode. It is found that the booster can increase the efficiency of the system compares with the system without booster. The efficiency of the converter with booster can be as high as 70% at 5 Bar. The improvement of the efficiency when using the booster is around 9% to 11.5%. However, the efficiency is higher as the pressure is lower. At low pressure the efficiency is almost 70%, but the help comes from the booster is not as much when using the air with higher air pressure.
Figure 6. Effect of booster volume ratio efficiency of converter.

Figure 7. Efficiency of converter (Isobaric operation).

Figure 8. Efficiency of converter (Expansion mode, \( N=2 \)).

Figure 9. Theoretical efficiency of system (Isobaric operation).

Figure 10. Efficiency of system (Isobaric operation).

The system efficiencies are calculated by using equation (15). As shown in figure 9, the efficiency of the system of isobaric mode can be found. The Optimum efficiency occurs in 20 bar to 40 bar for isobaric operation. The maximum efficiency of this mode is 0.32 without booster and 0.41 with booster.

As shown in figure 10, the efficiency of the system in expansion mode can be found \((N=2)\). The Optimum efficiency occurs in 20 bar to 40 bar for isobaric operation. The maximum efficiency of this mode is 0.55 without booster and 0.64 with booster.

It shows the optimum efficiency occurs in 10 bar to 40 bar, however, considering the mechanical affordability and durability, the majority pressures of experiments are set to 10 and 20 bar. As shown in figure 11, the experimental efficiency of expansion mode is around 30.15% to 42.01% for expansion mode with booster and 25% to 32.32% for isobaric. It is also note that the efficiency of...
motor system decreases when the RPM of the motor increases.

![Figure 10. Theoretical efficiency of system (Expansion mode, N=2).](image)

**Figure 10.** Theoretical efficiency of system (Expansion mode, $N=2$).

![Figure 11. Experimental efficiency of system of different speed (Isobaric operation, 10 bar and 20 bar).](image)

**Figure 11.** Experimental efficiency of system of different speed (Isobaric operation, 10 bar and 20 bar).

![Figure 12. Efficiency of the system of isobaric operation for different pressure.](image)

**Figure 12.** Efficiency of the system of isobaric operation for different pressure.

In figure 12, the efficiencies of the system (both theoretical and experimental results) for different pressure of isobaric operation mode are shown. It can be found that the higher the pressure, the higher the efficiency. The difference between experimental and theoretical results increases as the pressure
increase. This may due to the effect of the piping system, the higher the pressure, the more energy loss in the pipe. At 30 bar the efficiency is about 9% higher for the system with booster.

As shown in figure 13, the experiment efficiency of expansion mode for different rotating speed with booster of 10 bar is around 30.15% to 42.01% and the theoretical efficiency of system maximum around 32.32% to 48.97%. The experiment efficiency of 10 bar without booster is around 26% to 38% and the theoretical efficiency of system maximum around 31% to 40%. In all cases, the efficiency of the system decreases when the RPM of the motor increases. The experiment efficiency with booster of 20 bars is around 50% to 52% and the theoretical efficiency of system maximum around 58%. The experiment efficiency of 20 bars without booster is around 44.5% to 49% and the theoretical efficiency of system maximum around 51%. It is very interesting to find that at 20 bar air pressure the efficiency of the system is independent on the speed of the motor. This is due to at that pressure the motor efficiency is not change at speed around 120 rpm to 200 rpm.

Figure 13. Experiment efficiency of system of different speed (Expansion mode, \(N=2\)).

In figure 14, the efficiencies of the system (both theoretical and experimental results) for different pressure of expansion mode are shown (rotating speed is 150 rpm). It can be found that the higher the pressure, the higher the efficiency. The maximum experimental efficiency is 53.67% at 30 bar. The difference between experimental and theoretical results increases as the pressure increase. This may due to the effect of the piping system, the higher the pressure, the more energy loss in the pipe. At 30 bar the efficiency is about 5% higher for the system with booster.

Figure 14. Experiment efficiency of system for different pressure (Expansion mode).

Figure 15. Experiment efficiency of system at different speed, pressure and torque.

Considering that in most cases, the expansion mode is used to keep the system in an efficient state. Therefore, refer to above data we get from the experiments are used to produce the performance curve of the system in figure 15. Figure 15 indicates the operating range of the system operation. One may
uses this chart to find the relation between the torque and the rpm for different air pressure. This can help the designer of the device to design their control system to get best condition of using present engine.

6. Conclusion
In this study, a compressed air driven hydraulic motor system with compressed air booster was proposed, manufactured and tested. The efficiency formulae are more close to the actual situation than the other research such as [7]. In addition, based on the design configuration, a booster was used to recover the exhaust residual energy, the exhaust residual pressure through gas pressurization can increase the pressure to the working pressure which then enters the converter. After the booster was introduced into the system, the system efficiency was increased by 3.1% ~ 6.85% and the highest system efficiency is 53.67%. Finally, a chart of the efficiency of system at different speed, pressure and torque was developed to let the reader can use it as the base of the control of the system. It is also noted that the hydraulic motor used in this study is not suitable for this system due to all the motors in the market not design for our system, we believe if the hydraulic motor can design according the characters of our system; the efficiency will improve more.

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Appendix
Specifications of the parts used in experiment set up:

- High pressure tank: Maker, SERIAN, Material Graphy epoxy, Maximum pressure: 306 bar, Volume: 9 L.
- Air/oil converter: Maker,ASHU, Piston type, Diameter of the piston 100mm, Stroke 580mm, Volume 4.5 L and Maximum operation pressure 50 bar.
- Hydraulic motor: Maker, SAUER DANFOS, Type OMM50, Operation pressure 0-50Bar, Output power 0.2-1 h, Flow rate 3-12 L/min.
- Pneumatic ball valve: Maker, ENOLGA, Type, Single action pneumatic valve, Operation pressure 7 bar, Regulate pressure 60 bar.
- Three position five-way electromagnetic control valve: Maker: MINDMAN, Type: MVSY-188.
- Pressure regulator: 3ARROW, Type: HPR-200V/B, Maximum output pressure 200 bar, Range: 5-200 bar.
- Accumulator: Brand name: HYDAC, Maximum pressure 200 bar.
- Booster: Maker: SMC, Type VBA-11A-02, Maximum boost rate 4, Maximum flow rate: 70 L/min.

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