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Energy conversion characteristics of a hydropneumatic transformer in a sustainable-energy vehicle

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HIGHLIGHTS

- Mathematical model of the HP transformer was set up and verified through experimental study.
- A compressed air-powered hydraulic system with a HP transformer was set up and studied.
- Methods to improve the output power and efficiency of the HP transformer were obtained.
- The research lays a foundation for the optimization of the HP transformer.

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ABSTRACT

As a type of sustainable energy, compressed air energy can be used to drive vehicles, which is applicable to situations requiring explosion prevention and no pollution emissions, including chemical plants and airports. As a key component of an air-driven hydraulic vehicle, an air-driven hydraulic transformer, which is called a hydropneumatic (HP) transformer, is used to pump high-pressure oil for such a vehicle's hydraulic system. To improve the power and efficiency of the HP transformer, in this paper, firstly, a mathematical model of its working process was developed. Secondly, to verify the mathematical model, a dedicated test bench for the HP transformer was established and studied. Through experimental and simulation of the designed HP transformer when the input air pressure, output oil pressure and area ratio are regulated within the ranges of 0.625–0.75 MPa, 1.7–2.2 MPa and 3–5 respectively, it can be concluded that the mathematical model developed in this study is accurate. Furthermore, to improve the output power of the HP transformer, the input air pressure, output oil pressure and area ratio should be increased. Additionally, decreasing the input air pressure from 0.75 MPa to 0.625 MPa may improve the efficiency of the transformer by 14%, increasing the output pressure from 1.7 MPa to 2.2 MPa may improve the efficiency of the transformer by 3%, and decreasing the area ratio of the pistons from 5 to 3 may improve the efficiency of the transformer by 10%. This study can be referred to as the performance and design optimization of air-driven hydraulic HP transformers.

1. Introduction

Due to its low cost, easy access, recyclability, and higher energy storage density, compressed-air energy-storage technology has attracted the attention of scientists and engineers in recent years [1–3]. Compressed-air energy-storage technology provides a sufficient method for energy utilization of certain intermittent renewable power source, such as wind power, solar power, and tidal power [4–6].

To prevent the explosion of a compressed-air energy-storage system, safety codes that make it a rare occurrence are used; however, these codes increase weight and require additional safety features, such as pressure relief valves. The codes may limit the legal working pressure to less than 40% of the rupture pressure of steel bottles (i.e., a safety factor of 2.5), and less than 20% for fiber-wound bottles (i.e., a safety factor of 5). Commercial designs typically adopt the ISO 11439 standard. High-pressure bottles are strong and generally do not rupture in vehicle crashes.

As an energy conversion method used with compressed air, an air-powered engine is applicable to situations requiring explosion prevention and no pollution emissions, including chemical plants and airports. Many researchers have studied these engines. Huang and Hu et al. performed experiments on a compressed-air-driven piston engine that was modified from a commercially available internal-combustion engine (IC engine). That engine could be

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operated at an air pressure between 5 and 9 bar, and provided 0.96 kW of power output [7]. Dimitrova and Maréchal studied a gasoline hybrid pneumatic engine that combines a conventional IC engine and a pneumatic, short-term storage system to achieve lower fuel consumption [8,9]. Currently, certain companies have developed products or prototypes that run on compressed air, such as the famous AIR Pod by MDI, Ku: Rin by Toyota, and a pneumatic motorcycle by Sentead [10,11].

Because the volume of the compressed air tank is restricted by the vehicle's space, a high-efficiency compressed air engine is critical. However, due to air leakage, friction and the incomplete expansion of compressed air, the energy efficiency and output power of compressed air engines are limited, which restricts its popularization [12,13].

In 2009, Shen and Hwang [12] proposed an air-powered motorcycle with a vane-type motor that ran at its highest efficiency at 20 km/h. Vane-type motors have been used in modern factories, and their efficiencies can reach 19% [13]. In 2012, Hu [14] proposed a piston-type air motor and examined its performance; the highest engine efficiency was found to be 13% at 4 bar and 1200 rpm.

In Ref. [15], a compressed air-powered hydraulic system was proposed to improve the power and efficiency of a compressed air-powered vehicle. Shaw et al. designed an air/oil converter with an equal-area cylinder, which was driven by compressed air. Based on the authors' energy evaluation method, the efficiency of the power system was shown to be approximately 50% at 200 rpm via calculations and experimental study; this result was higher than the efficiencies of absolute pneumatic power systems [7–15]. However, due to the equal-area cylinder of the air/oil converter, the pressure of the compressed air must be higher than the pressure of the output oil, and higher residual air pressure in the converter may lead to a lower efficiency. Additionally, the transformer designed by Shaw must be installed vertically, which restricts its application and popularity.

In this study, a hydropneumatic (HP) transformer was proposed to improve the efficiency of a compressed air-powered hydraulic system. The HP transformer is driven by compressed air to pump oil at a higher pressure. Compared to the air/oil converter designed by Shaw, the proposed HP transformer has certain advantages, such as a higher efficiency, a higher power output and free installation.

To study the performance of the HP transformer, a mathematical model of its functionality was developed and verified experimentally. Additionally, a new type of energy evaluation criterion for compressed air, called "air power", was briefly introduced. This energy evaluation criterion for compressed air has been formulated as a National Standard of China (GB/T 30833-2014) and has been proposed to be used as an International Standard in 2015.

Based on this study of key parameters that effect the output power and efficiency of compressed-air systems, the proposed method to develop an HP transformer is demonstrated to be effective.

2. Configuration of a compressed-air-powered hydraulic system

The configuration of a compressed air-powered hydraulic system, which is shown in Fig. 1, is composed of a compressed air tank, a hydraulic motor/pump, an HP transformer and a gearbox. The HP transformer consists of a pressure regulator, a silencer, a solenoid directional valve, an accumulator, a pneumatic cylinder, a floating connector, four check valves and a hydraulic cylinder.

Compressed air is stored in the air tank. The input pressure of the pneumatic cylinder is adjusted by the regulator based on the feedback of the output pressure of the hydraulic cylinder. The accumulator is used to decrease the fluctuation of the output pressure.

When the left pneumatic chamber is connected to the air tank, and the right pneumatic chamber is connected to the atmosphere, the air in the right pneumatic chamber is discharged to the atmosphere through the reversing valve. Concurrently, the compressed air charged from the air tank flows into the left pneumatic chamber through the regulator and the solenoid directional valve successively. The compressed air in the left pneumatic chamber drives the piston to move toward the right. The oil charged from the hydraulic reservoir flows into the left hydraulic chamber. The oil pressure in the right hydraulic chamber rises until the pressure is higher than that of the output side. Thereafter, the high-pressure oil is pumped from the right chamber to the hydraulic motor.

When the piston reaches its rightward travel destination, the solenoid valve changes its state, and the air in the left pneumatic chamber flows to the atmosphere. The air charged from the air tank flows into the right pneumatic chamber through the regulator and the solenoid valve. The oil charged from the hydraulic reservoir flows into the right hydraulic chamber. The air in the right pneumatic chamber then drives the piston to move toward the right, while the pressure in the left hydraulic chamber increases. Finally, the pressurized oil in the left hydraulic chamber is discharged to the output side. The HP transformer continues to deliver high-pressure oil by repeating the process discussed above.

Compared to the air/oil converter designed by Shaw, the proposed HP transformer has certain advantages. First, the input air pressure of the HP transformer is adjusted automatically to save the energy in the compressed air based on the feedback of the output pressure. The area of the hydraulic cylinder is smaller than the area of the pneumatic cylinder, which could improve the efficiency and power of the HP transformer. In addition, compared with the air/oil converter, compressed air and hydraulic oil in the HP transformer is isolated, and that effectively prevent compressed air discharging to hydraulic motor. Therefore, the HP transformer has more installation options, which are beneficial to its application and popularity.

3. Mathematical modeling of the HP transformer

Because an HP transformer and an air-driven pneumatic booster, which is proposed in Refs. [16,17], have similar working processes, the mathematical model of the HP transformer was developed using the mathematical model of an air-driven pneumatic booster, which was verified by the authors' experimental study [16,17]. This model is described below.

3.1. Energy equation of the pneumatic system

In this study, compressed air is considered to be an ideal gas; thus, it follows all ideal gas laws:

$$C_p - C_v = R \tag{1}$$

where

C_p: heat capacity at constant pressure;
C_v: specific heat at constant volume;
R: gas constant, 287 J/(kg K).

Because it is assumed that no leakage occurs in the pneumatic driving chambers, the driving chambers do not charge and exhaust air simultaneously. Consequently, the energy equation for the charge and discharge side of the left pneumatic chamber can be described as follows:

$$C_v W_{dA} \frac{d\theta_{dA}}{dt} = S_{dA} \cdot h_d(\theta_a - \theta_{dA}) + Rq_{dA}\theta_{dA} - p_{dA}A_{dA}u \tag{2}$$

$$C_v W_{dA} \frac{d\theta_{dA}}{dt} = (S_{dA} \cdot h_c + C_v \cdot q_{dA})(\theta_a - \theta_{dA}) + Rq_{dA}\theta_a - p_{dA}A_{dA}u \tag{3}$$

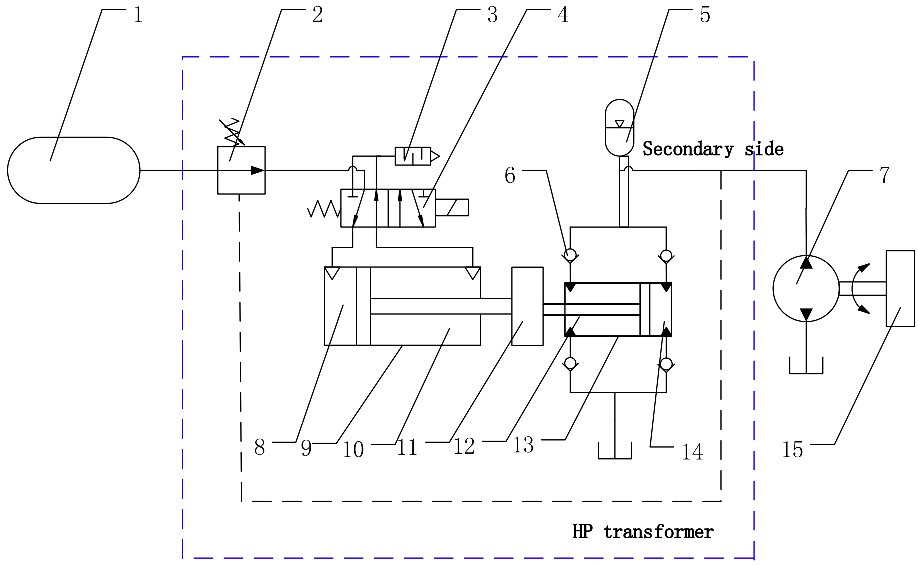


Fig. 1. Structure of the compressed-air-powered hydraulic system. 1. Air tank; 2. Pressure regulator; 3. Silencer; 4. Reversing valve; 5. Accumulator; 6. Check valve; 7. Hydraulic motor/pump; 8. Left pneumatic chamber; 9. Pneumatic cylinder; 10. Right pneumatic chamber; 11. Floating connector; 12. Left hydraulic chamber; 13. Hydraulic cylinder; 14. Right hydraulic chamber; 15. Gear box.

where
t: time (s);
θ_a: atmospheric temperature (K);
u: velocity of piston (m/s);
h_c: heat transfer coefficient of the charge side (W/(m^2 K));
h_d: heat transfer coefficient of the discharge side (W/(m^2 K));
S_{dA}: heat transfer area of the left pneumatic chamber (m^2);
q_{dA}: air mass flow of the left pneumatic chamber (g/s);
W_{dA}: air mass of the left pneumatic chamber (g);
θ_{dA}: temperature of the left pneumatic chamber (K);
p_{dA}: pressure of the left pneumatic chamber (Pa);
A_{dA}: area of a piston of the left pneumatic chamber (m^2);
W_{dA}: air mass of the right pneumatic chamber (g).

The energy equation for the charge and discharge sides of the right pneumatic chamber can be given by the following equations:

$$C_v W_{dB}\frac{d\theta_{dB}}{dt} = S_{dB}\cdot h_d(\theta_a - \theta_{dB}) + Rq_{dB}\theta_{dB} + p_{dB}A_{dB}u \tag{4}$$

$$C_v W_{dB}\frac{d\theta_{dB}}{dt} = (S_{dB}\cdot h_c + C_v\cdot q_{dB})(\theta_a - \theta_{dB}) + Rq_{dB}\theta_a + p_{dB}A_{dB}u \tag{5}$$

where
t: time (s);
S_{dB}: heat transfer area of the right pneumatic chamber (m^2);
q_{dB}: air mass flow of the right pneumatic chamber, (g/s);
W_{dB}: air mass of the right pneumatic chamber (g);
θ_{dB}: temperature of the right pneumatic chamber (K);
p_{dB}: pressure of the right pneumatic chamber (Pa);
A_{dB}: Area of piston of the right pneumatic chamber (m^2).

3.2. Continuity equation of the pneumatic system

Based on the ratio P_l/P_h, the air mass flow equation for the flow through a restriction can be written as follows [18]:

$$q = \begin{cases} \frac{A_e p_h}{\sqrt{\theta_h}}\sqrt{\frac{2\kappa}{R(\kappa-1)}}\left[\left(\frac{p_l}{p_h}\right)^{\frac{2}{\kappa}} - \left(\frac{p_l}{p_h}\right)^{\frac{\kappa+1}{\kappa}}\right] & \frac{p_l}{p_h} > 0.528 \\ \frac{A_e p_h}{\sqrt{\theta_h}}\left(\frac{2}{\kappa+1}\right)^{\frac{1}{\kappa-1}}\sqrt{\frac{2\kappa}{R(\kappa+1)}} & \frac{p_l}{p_h} \leqslant 0.528 \end{cases} \tag{6}$$

where
A_{ep}: effective area of the intake and exhaust ports (m^2);
p_h: pressure of the upstream side (Pa);
p_l: pressure of the downstream side (Pa);
κ: specific heat ratio (null);
θ_h: temperature of the upstream side (K).

3.3. State equation of the pneumatic system

The changes in air pressure in each driving chamber can be obtained by deriving the state equation of ideal gases:

$$\frac{dp}{dt} = \frac{1}{V}\left[\frac{pV}{\theta}\cdot\frac{d\theta}{dt} + R\theta q - pAu\right] \tag{7}$$

where
V: volume (m^3);
p: pressure of the compressed air (Pa);
θ: temperature of the compressed air (K);
A: area of the piston of the pneumatic chamber (m^2);
u: velocity of the piston (m/s).

3.4. Motion equation

The velocity of the piston is calculated from Newton's Second Law of Motion. In this study, the friction force is considered to be the sum of the Coulomb friction and the viscous friction. The viscous friction force is considered to be a linear function of the piston velocity. The forces on the piston of the HP transformer are shown in Fig. 2.

The right side was considered to be the positive direction, and the motion equation of the piston can be given by the following equations:

$$\frac{d^2x}{dt^2} = \begin{cases} \frac{1}{M}(p_{dA}\cdot A_d - p_{dB}\cdot A_d + p_{bA}\cdot A_b - p_{bB}\cdot A_b - F_f) & x \neq 0, L \\ 0 & x = 0, L \end{cases} \tag{8}$$

$$F_f = \begin{cases} F_s & u = 0 \\ F_c + Cu & u \neq 0 \end{cases} \tag{9}$$

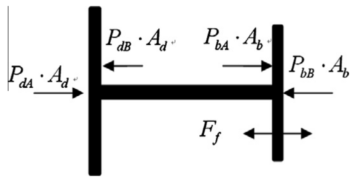


Fig. 2. Forces on the piston of the HP transformer.

where
x: displacement of the piston (m);
M: mass of the piston (kg);
p_{dA}: pressure of the left pneumatic chamber (Pa);
A_d: area of the piston of the pneumatic chambers (m^2);
p_{dB}: pressure of the right pneumatic chamber (Pa);
p_{bA}: pressure of the left hydraulic chamber (Pa);
p_{bB}: pressure of the right hydraulic chamber (Pa);
p_a: atmosphere pressure (Pa);
A_b: area of the piston of hydraulic chambers full filled with hydraulic oil (m^2);
A'_b: area of the piston of hydraulic chambers full filled with air (m^2);
F_f: friction force (N);
F_s: maximum static friction force (N);
F_c: Coulomb friction force (N);
C: viscous friction coefficient (N/(m/s));
L: stroke (m).

3.5. Pressure equation of the hydraulic system

The continuous equations of hydraulic chambers A and B can be written as:

$$\frac{dp_{dA}}{dt} = \frac{\beta}{V}(Q_{Ain} - Q_{Aout} - Au) \tag{10}$$

$$\frac{dp_{dB}}{dt} = \frac{\beta}{V}(Q_{Bin} - Q_{Bout} + Au) \tag{11}$$

where
β: effective bulk modulus (Pa);
Q_{Ain}: input volume flow of the left hydraulic chamber (m^3/s);
Q_{Aout}: output volume flow of the left hydraulic chamber (m^3/s);
Q_{Bin}: input volume flow of the right hydraulic chamber (m^3/s);
Q_{Bout}: output volume flow of the right hydraulic chamber (m^3/s).

3.6. Flow equation of the hydraulic system

The volume flow of oil through a throttle can be described as:

$$Q = C_d A_{eh}\sqrt{\frac{2(p_h - p_l)}{\rho}} \tag{12}$$

where
C_d: flow coefficient of the throttle (null);
ρ: oil density (kg/m^3);
A_{eh}: effective area of the hydraulic orifice (m^2);

Based on Eq. (9), when the effective areas of the intake and exhaust ports were fixed, the output flow of oil could increase by increasing the pressure in the working boosting chamber or by decreasing the output oil pressure.

3.7. Power of the pneumatic system

In this study, a new energy-consumption evaluation criterion for a pneumatic system, called "air power", is briefly introduced. With air power, the output power efficiency of the HP transformer was studied with regard to the optimal performance of the HP transformer.

The available energy of flowing compressed air could theoretically be converted into mechanical work at atmospheric pressure and was discussed in the authors' previous research [19]. The available energy of flowing compressed air can be expressed as:

$$E = p_a V_a\left[\ln\frac{p}{p_a} + \frac{\kappa}{\kappa-1}\left(\frac{\theta-\theta_a}{\theta_a} - \ln\frac{\theta}{\theta_a}\right)\right] \tag{13}$$

where P_a is the atmospheric pressure, V_a is the volume of air at the standard state, and θ_a is the atmospheric temperature.

We propose that the available energy represents the energy of the compressed air. The air power was defined as the flux of the available energy that could be extracted from flowing air as it undergoes a reversible process from a given state to the atmospheric state. With this definition, the air power can be described as:

$$P = p_a Q_a\left[\ln\frac{p}{p_a} + \frac{\kappa}{\kappa-1}\left(\frac{\theta-\theta_a}{\theta_a} - \ln\frac{\theta}{\theta_a}\right)\right] \tag{14}$$

where Q_a is the flow of air at the standard state (m^3/s).

3.8. Power of the hydraulic system

The power of pressurized oil is described by:

$$P = pQ \tag{15}$$

where
p: the pressure of a hydraulic system (Pa);
Q: the flow of a hydraulic system (m^3/s).

3.9. Algorithm

Based on the mathematical equations above and the parameters shown in Table 1 below, the following mathematical model was built using the Matlab/Simulink S function. The Simulink diagram is shown in Fig. 3.

4. Experimental verification of the mathematical model

To verify the accuracy of the mathematical model, a compressed-air-powered hydraulic system was developed. Its schematic structure is shown in Fig. 4. The compressed air was charged from the air source and flowed through a regulator (IR3010-03BG, SMC, Japan), which reduced its pressure to a fixed value of approximately 0.6 MPa. When the compressed air was supplied to the hydropneumatic transformer (SWB-100D-5, SIWELL Supercharger Technology, China), pressurized hydraulic oil was pumped from the HP transformer. To stabilize the output pressure of the HP transformer, an accumulator (GXQA-0.35/25-L-A,AOQI, China) and a relief valve (DBDS6P1X/315, Rexroth, Germany) were installed downstream of the compressed air-powered hydraulic system. A pressure sensor (AK-4B, 701, China), a data acquisition card (USB4711, Advantech, Taiwan) and a computer (X430, Lenovo, China) were used to measure the output pressure of the HP transformer, whose parameters, provided by its manufacturer, are shown in Table 1.

A dedicated test bench for the HP transformer, which is shown in Fig. 5, was designed and built to measure the output pressure of the HP transformer. In this experiment, the compressed-air source

Table 1
Parameters of the HP transformer investigated in this study.

R (J/(kg K))	θ_a (K)	h_c (W/(m^2 K))	h_d (W/(m^2 K))	A_d (m^2)	A_b (m^2)	A_{ep} (m^2)	κ	C_d
287	293	30	20	0.0079	0.002	1.26×10^{-5}	1.4	0.6
M (kg)	F_s (N)	F_c (N)	C (N/(m/s))	L (m)	β (Pa)	ρ (kg/m^3)	A_{eh} (m^2)	p_a (Pa)
2	20	10	10	0.09	7×10^8	900	4.91×10^{-6}	1.01×10^5

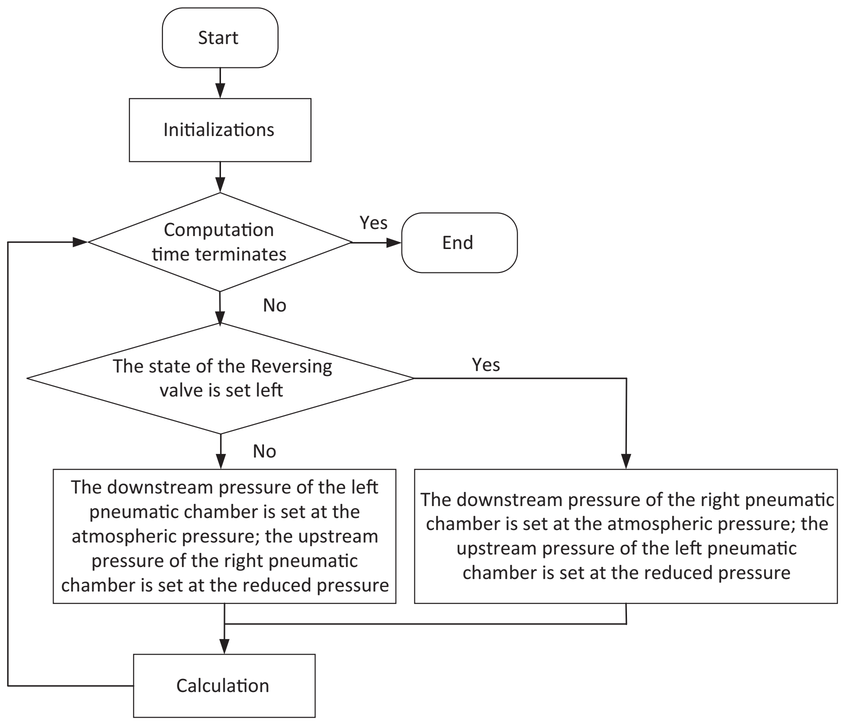
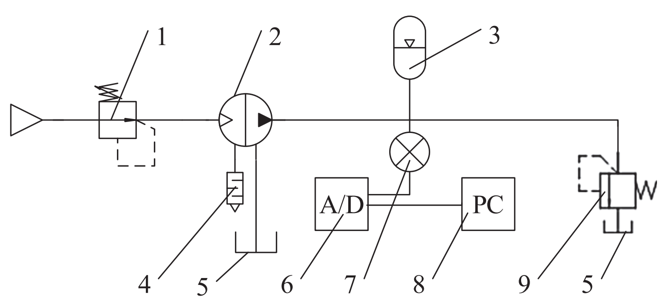


Fig. 3. Algorithm of the mathematical model.



(1) Regulator, (2) HP transformer, (3) Accumulator, (4) Silencer, (5) Tank, (6) Data acquisition card, (7) Pressure sensor, (8) Computer, (9) Relief valve

Fig. 4. Schematic diagram of the experimental system.

was opened, and the air pressure of the regulator was set to a fixed value. Next, the relief valve was adjusted, and the hydraulic oil was pumped steadily to the tank; the output oil pressure varied little at this point in the process. The last stage included data acquisition and preservation. The input air pressure and relief valve were adjusted, and the steps above were repeated.

As the input air pressure and output oil pressure of the HP transformer can be adjusted conveniently, in the experimental study, other parameters were held constant, the input air pressure was set at 0.5 MPa, 0.6 MPa and 0.7 MPa, and the output oil pressure was set at 1.6 MPa, 1.7 MPa and 1.8 MPa. Three groups of experiments with each condition were done, therefore, twenty-seven groups of experiments were carried out totally. A representative experiment and its simulation results are shown in Fig. 6 when the input and output pressures were set to approximately 0.6 and 1.7 MPa.

As shown in Fig. 6, the reported results are consistent in terms of model verification with the range of experimental data collected. However, there are two differences between the simulation results and the experimental results: (1) the output pressure

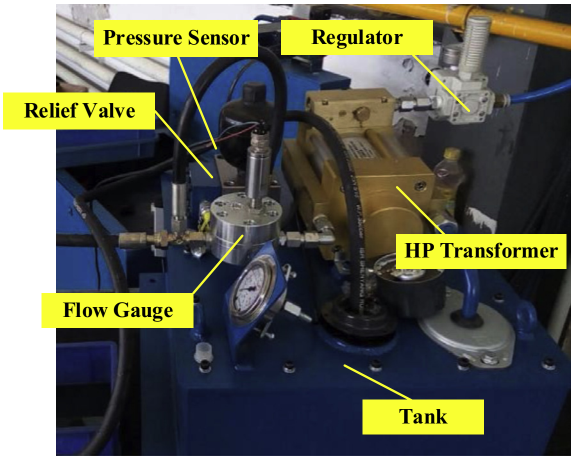


Fig. 5. Experimental bench.

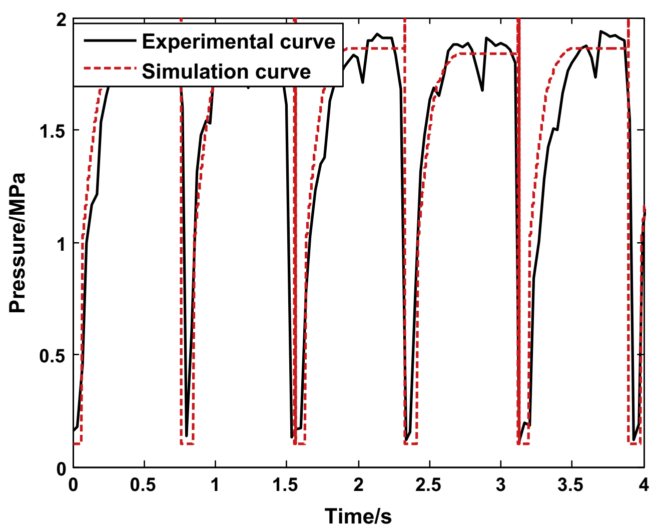


Fig. 6. Simulated and experimental curves of the HP transformer.

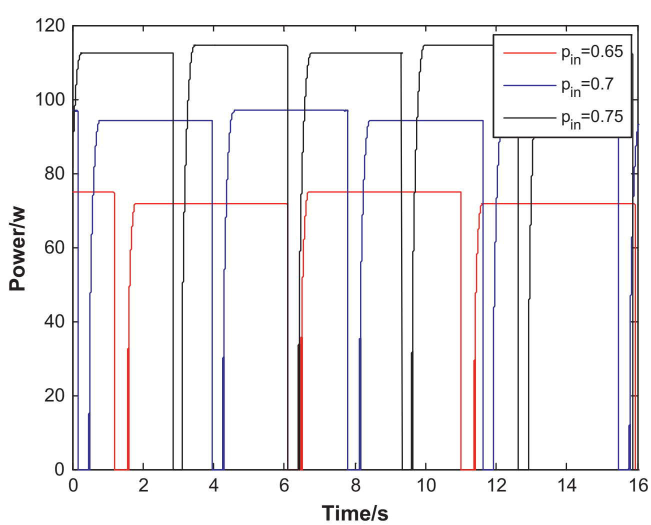
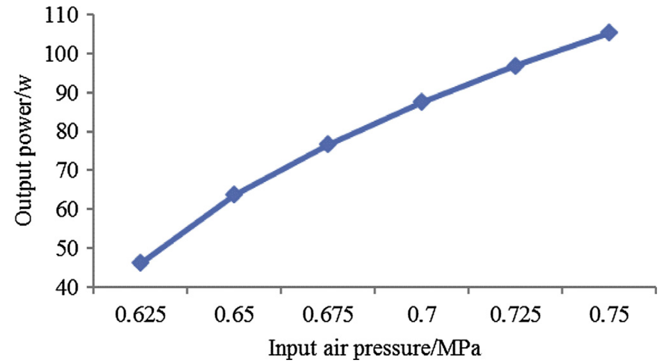
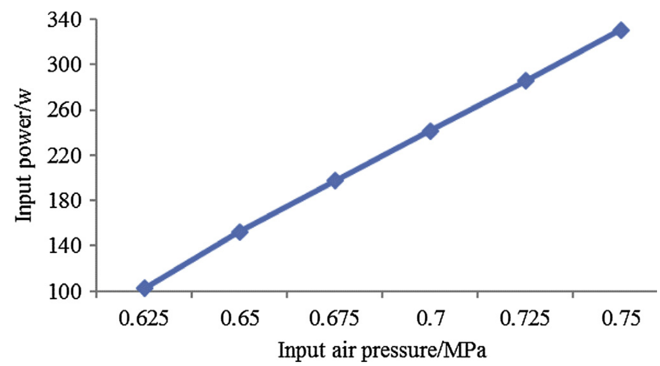


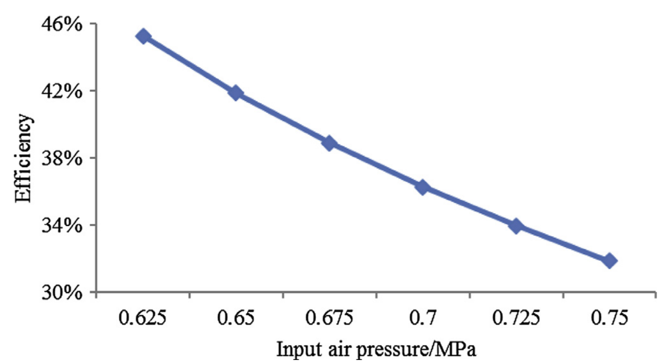
Fig. 7. Output power dynamics of the HP transformer.



(a) Relationship between the average output power and the input air pressure



(b) Relationship between the average input power and the input air pressure



(c) Relationship between the efficiency and the input air pressure

Fig. 8. Relationship between the average output power, input power, efficiency and the input air pressure.

in the experiment results increases less markedly than the output pressure in the simulation results; (2) a fluctuation of ±0.1 MPa in the output pressure of the HP transformer is shown when the output pressure reaches to its maximum value.

The primary causes of these differences are summarized as follows. In the experiment, when the pressurized hydraulic oil was pumped from the HP transformer, a portion of the hydraulic oil flowed into the accumulator, which reduced the rate of increase in the output pressure. Additionally, the size of the opening of the relief valve was not fixed and is larger when the output pressure increases; this resulted in a fluctuation of the output pressure.

5. Study of the output power and efficiency of the HP transformer

Based on the authors' previous study [14], the output flow characteristics of the HP transformer are primarily affected by the input air pressure, output oil pressure and the area ratio of the pistons in the pneumatic and hydraulic cylinders. To illustrate the effect of the three parameters on the output oil flow, a parametric sensitivity analysis was used. According to the pressure range of the compressed air supply, the pressure requirement of the hydraulic motor, and the parameter of the existing HP transformer, the ranges of the input air pressure (p_{in}), output oil pressure (p_{out}) and the area ratio (n) of the pistons are set at 0.6–0.8 MPa, 1.6–2.4 MPa and 3–5 respectively.

To create a valid comparison, each parameter was changed while the other parameters were held constant. This sensitivity analysis could be the basis for further multi-objective optimization to determine the trade-off between the output net power and the efficiency.

5.1. Effect of the input air pressure

The input air pressure of the HP transformer is typically used to adjust the output oil flow of the HP transformer. To ensure output power is always available, the input air pressure should be sufficiently high to drive the HP transformer. When the output oil pressure (p_{out}) and the area ratio (n) equaled 2.0 MPa and 4, respectively, the input pressure (p_{in}) was set to 0.625, 0.65, 0.675, 0.700, 0.725, and 0.750 MPa in successive tests; the output power, input power and efficiency of the HP transformer were then studied. Fig. 7 shows the output power dynamics of the HP transformer. Fig. 8(a) describes the relationship between the average output power (i.e., the average value of output power in an entire cycle) and the input air pressure. Fig. 8(b) shows the relationship between the average input power (i.e., the average value of input power in an entire cycle) and the input air pressure. Fig. 8(c) shows the relationship between the efficiency (i.e., the ratio of average output power and average input power) and the input air pressure.

As shown in Figs. 7 and 8, as the input air pressure increases from 0.625 MPa to 0.75 MPa, the average output power and input power increase, but the efficiency decreases. These results occur because the proportion of the expansion power increases when the pressure of the compressed air in the driving chambers increases. When the compressed air at higher pressure is discharged from the driving chambers, more expansion power is wasted.

Therefore, to improve the efficiency of the HP transformer, the input air pressure should be decreased within the range of 0.625–0.75 MPa.

5.2. Effect of the output oil pressure

When the input air pressure (p_{in}) and the area ratio (n) were set to 0.7 MPa and 4, respectively, the output oil pressure (p_{out}) was set to 1.7, 1.8, 1.9, 2.0, 2.1, and 2.2 MPa. The output and input power characteristics of the HP transformer were then studied. Fig. 9

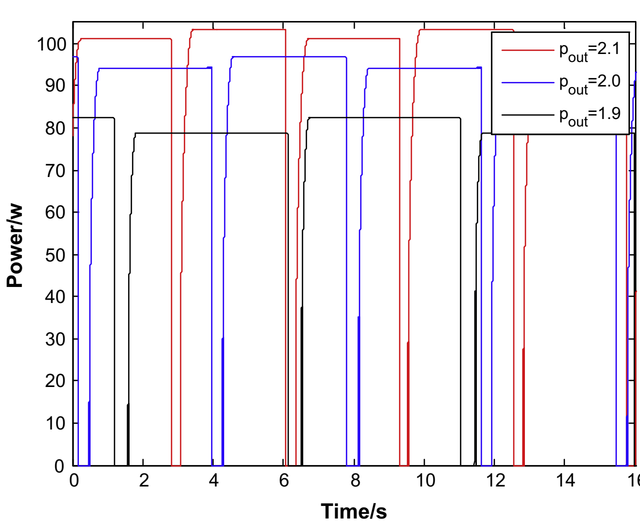
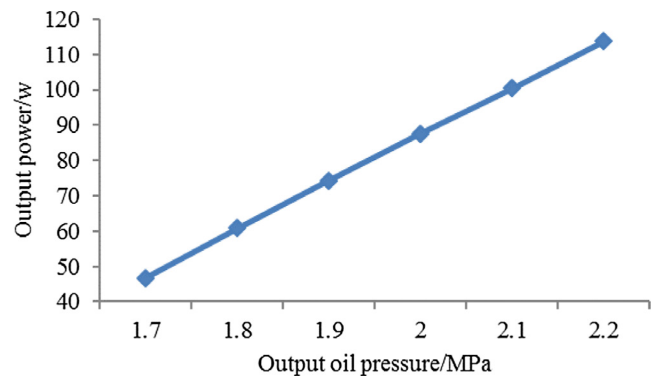
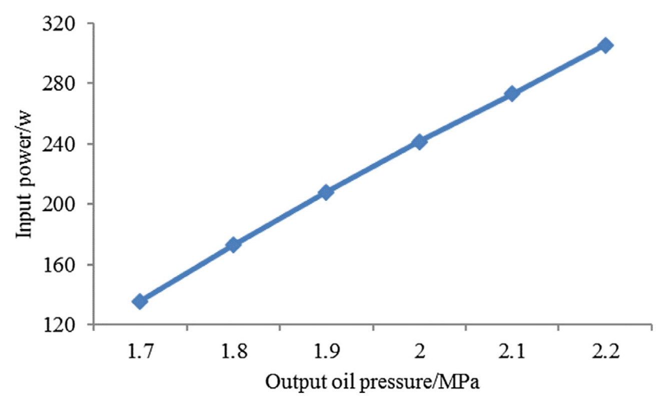


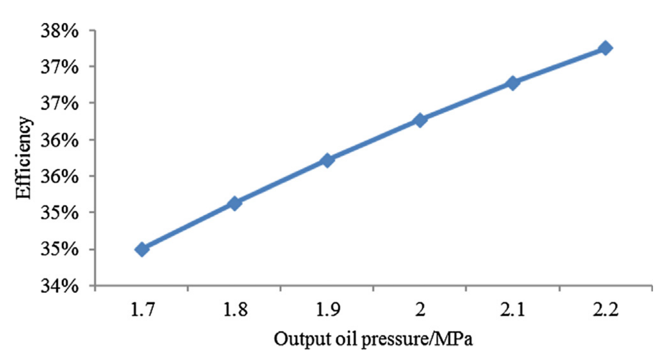
Fig. 9. Output power dynamics of the HP transformer.



(a) Relationship between the average output power and the output oil pressure



(b) Relationship between the average input power and the output oil pressure



(c) Relationship between the efficiency and the output oil pressure

Fig. 10. Relationships between the average output power, input power, efficiency and the output oil pressure.

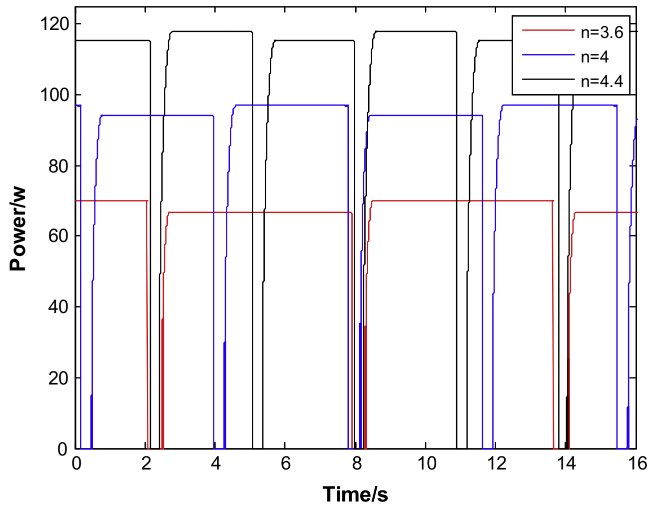


Fig. 11. Output power dynamics of the HP transformer.

shows the output power of the HP transformer; Fig. 10(a) shows the relationships between the average output power and the output oil pressure; Fig. 10(b) describes the relationships between the average input power and the output oil pressure; and Fig. 10 (c) shows the relationship between the efficiency and the output oil pressure.

As shown in Figs. 9 and 10, as the output oil pressure increases from 1.7 MPa to 2.2 MPa, the average output power, input power and efficiency increase. The relationships between the average output power, input power, efficiency and the output oil pressure are nearly linear because the output flow is only marginally affected by the output oil pressure. When the output oil pressure increases, the output power increases accordingly.

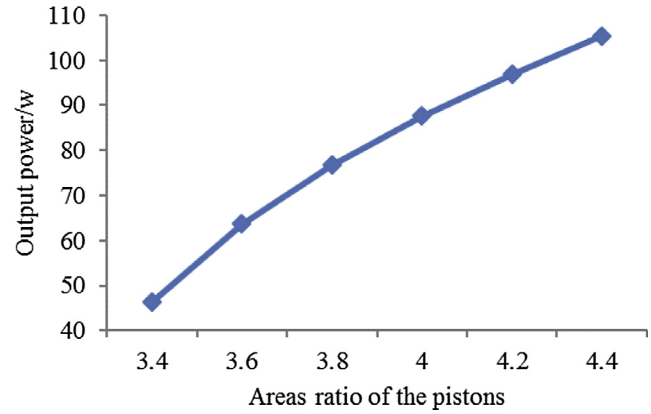
Therefore, to improve the efficiency of the HP transformer, the output oil pressure should be increased within the range of 1.7–2.2 MPa. Note that the efficiency of Shaw's system could not be improved in this manner.

5.3. Effect of the area ratio of the pistons

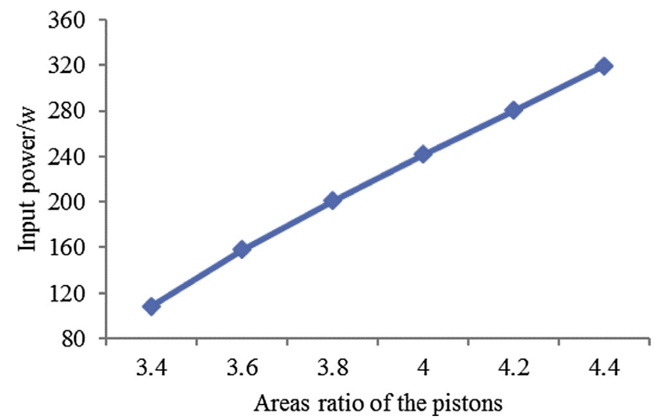
When the input air pressure (p_{in}) and the output oil pressure (p_{out}) were set to 0.7 and 2.0 MPa, respectively, and after increasing the area of the pneumatic cylinder, the area ratio (n) was set equal to 3.4, 3.6, 3.8, 4.0, 4.2 and 4.4. The output oil and input air flow characteristics of the HP transformer were then analyzed. Fig. 11 shows the output power of the HP transformer; Fig. 12(a) shows the relationship between the average output power and the areas ratio; Fig. 12(b) describes the relationships between the average input power and the areas ratio; and Fig. 12(c) shows the relationship between the efficiency and the areas ratio.

As shown in Figs. 11 and 12, as the area ratio increases from 3 to 5, the average output power and input power increase accordingly, but the efficiency decreases. Additionally, the relationships between the average input power, efficiency and the area ratio are shown to be nearly linear; this occurs because when the area of the hydraulic piston remains constant, the areas ratio increases, and the driving chambers may charge more compressed air. When the compressed air at higher pressure is discharged from the driving chamber, more expansion power from the compressed air is dissipated.

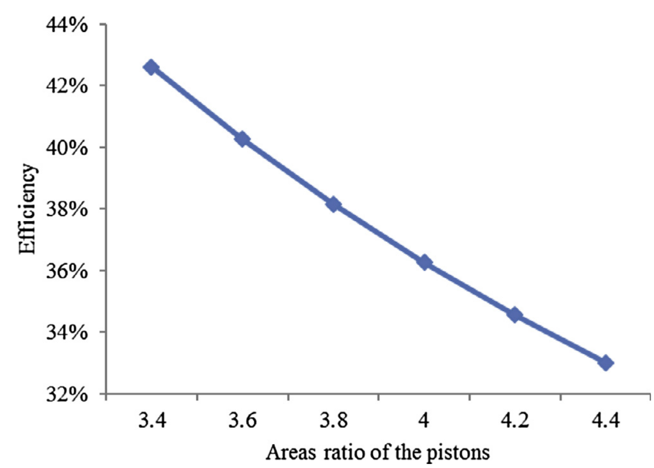
Therefore, to improve the efficiency of the HP transformer, the area ratio of the pistons should be decreased within the range of 3–5.



(a) Relationship between the average output power and the areas ratio



(b) Relationship between the average input power and the areas ratio



(c) Relationship between the efficiency and the areas ratio

Fig. 12. Relationships between the average output power, input power, efficiency and the areas ratio.

6. Conclusions

In this study, a mathematical model of the HP transformer was proposed. To set a foundation for improving the performance of the designed HP transformer, its power and efficiency characteristics were studied when it works at its normal condition according to the practice. The conclusions of this study are listed as follows:

1. The HP transformer was proposed to solve two problems in air-powered vehicles: low power and low efficiency;
2. The simulation results of this study agree with the experimental results; thus, the mathematical model developed in this study is effective and accurate;
3. To improve the output power of the HP transformer, the input air pressure, output oil pressure and area ratio should be increased within the ranges of 0.625–0.75 MPa, 1.7–2.2 MPa and 3–5 respectively.
4. Decreasing the input air pressure from 0.75 MPa to 0.625 MPa may improve the efficiency of the transformer by 14%, increasing the output pressure from 1.7 MPa to 2.2 MPa may improve the efficiency of the transformer by 3%, and decreasing the area ratio of the pistons from 5 to 3 may improve the efficiency of the transformer by 10%.

Therefore, when the designed HP transformer works at its normal condition according to the practice (the input air pressure, output oil pressure and area ratio are regulated within the ranges of 0.625–0.75 MPa, 1.7–2.2 MPa and 3–5 respectively), to improve its output power, the input air pressure, output oil pressure and area ratio should be increased. The efficiency of the HP transformer could also be improved by reducing the input air pressure and the area ratio or by increasing the output oil pressure.

This study can be used as a foundation for the design and performance optimization of compressed air-driven hydraulic HP transformers.

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