PERFORMANCE ANALYSIS OF A FOUR-STROKE COMPRESSED AIR ENGINE

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The purpose of this paper is to investigate working performance for a four-stroke compressed air engine via numerical studies. A mathematical model is developed to study the influence of several operative parameters on working performance. The mathematical model consists of thermodynamic model, each stroke model and dynamic model. In addition, a working principle and an experimental system of the compressed air engine are set up. The aims are: to introduce the novel four-stroke engine and to quantify the influence of rotational speed, supply pressure and supply temperature on working characteristics. The simulation and analysis show several meaningful results. The compressed air engine has higher cylinder pressure and work efficiency in lower speed stage, and the increase of the supply pressure can effectively improve indicated work and work efficiency. However, supply temperature has little effect on the performance of the compressed air engine. Therefore, the study of this work will provide a certain guidance function for further study on optimizing design of the compressed air engine.

Key words: compressed air engine, four-stroke, working performance, mathematical model

Introduction

Over the recent decades, reducing CO_2 emission is a crucial issue worldwide. Exhaust gas from internal combustion (IC) engines contributes largely to CO_2 emissions, and it has become increasingly important to find environmentally friendly energies to replace conventional fossil fuels [1]. Compressed air, as an energy medium, has some distinct benefits for its zero CO_2 emission and convenience in storage, transportation, and conversion [2, 3]. Compressed air has found vast applications in fields such as electricity generation, vehicle engines and energy storage technologies [4-6]. Among them the compressed air engine (CAE) has a direct and common connection with human society and life and so, it attracts substantial attention [7, 8].

Compared with other kind of fuels, compressed air has the following advantages. Its resources are vast and it can be generated through several ways such as solar energy, wind energy, and tidal energy. A CAE has both the advantages of the non-burning fuel and the zero pollution. The cost of a CAE is much less than a fuel cell and an IC engine, though they have higher efficiencies than CAE. The IC engines can be simply modified to CAE if its structure gets a slight change. The type of the CAE in this study is a four-stroke piston-type CAE, and the working process is basically the same as the conventional IC engine. Compressed air ex-

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pands in the engine cylinder, it can convert the reciprocal motion of piston into one-way rotary motion of the output shaft, and discharges in the form of pure air at low temperature.

AirPod, a green energy car, was invented by a French company of air-powered vehicles, in the 1990's, it was the successful application of a CAE [9]. The existing literatures showed that a great deal of investigations on kinds of CAE had been conducted by Chinese research scholars in the past 10 years [10-14]. Liu et al. [10] reported that compressed air have similar energy density as Ni-H battery, the circulation efficiency of compressed air was 25-32.3% in practice and the characteristics of the CAE was suitable for driving a vehicle. Yu et al. [11] performed the analysis of the energy efficiency and the output power of the CAE, and an improved NSGA-II was introduced to optimize the energy efficiency of the engine with the given output power. Yu et al. [12] also studied two kinds of CAE: single cylinder piston-type CAE (SCAE) and double crank link CAE (DCAE), the average output power and efficiency characteristics of two kinds of CAE were obtained by simulation and experiment, and the DCAE could improve the CAE performance under high rotational speeds. In Yu et al. [13], the mathematical model was set-up through analysis of the working process of a twostroke CAE, and experiments were carried out to verify the engine performance. The mathematical model was transformed to a dimensionless expression. The dimensionless speed and efficiency characteristics of the CAE were obtained in his paper. Liu et al. [14] proposed a CAE consisting of one small and one large cylinder to conduct two-stage expansion in series, by fully using the high pressure air and increasing the power output and efficiency of the CAE.



Figure 1. Structure and thermodynamic analysis diagram of four-stroke CAE; *1 – intake valve 2 – exhaust valve 3 – high-frequency electromagnetic valve*

4 - air nozzle, 5 - cylinder 6 - piston

7 - crank-link mechanism

But few studies established complete working process models of the four-stroke CAE, as well as methods to analyze the performance under critical working parameters.

Several studies provided references for the performance analysis of the four-stroke CAE. The working process mathematical model of the two working modes of hybrid four-stroke compressed-air and fuel engine were respectively established [15]. The adjustable expansion ratio was considered in the research of the CAE [16]. However, no experiments or in-depth discussion was reported for this special study. Therefore, the theoretical model of the fourstroke CAE is established in this paper for performance analysis and the design of the CAE.

Mathematical model of the CAE

As shown in fig. 1, intake valves and exhaust valves are controlled by the valve system. At the beginning of the intake stroke, the intake valves open immediately, and the atmosphere flows into the cylinder through the intake valves because of the pressure difference. When the piston is near the BDC, the intake valves close. In the compression stroke, the piston moves up near the TDC. In the inflation and expansion stroke, the high-frequency electromagnetic valve and the air nozzle begin to work, then the compressed air-flows into the cylinder through the air nozzle, and pushes the piston downwards. After a specific crank angle (CA), the high-frequency electromagnetic valve and the air nozzle close while the compressed air expands to push the piston down and output work. When the piston moves back to the BDC, the exhaust valves open so that residual air discharges under the impetus of the piston. After the piston moves back to the TDC, the four-stroke CAE completes a complete work cycle.

The CAE cylinder can be seen to be a thermodynamic system, and the following assumptions are made [17]. First, the compressed air is ideal, which means specific heat and specific enthalpy are only related to the temperature. Second, the changes of kinetic and gravitational energy are negligible. Third, the process of gas flowing into/out of the cylinder is a quasi-steady one. Finally, there is no leak or friction during the working process.

Thermodynamic model

The energy equation can be expressed as

$$\frac{\mathrm{d}U}{\mathrm{d}\varphi} = \frac{\mathrm{d}Q_{\mathrm{w}}}{\mathrm{d}\varphi} + h_{\mathrm{I}}\frac{\mathrm{d}m_{\mathrm{I}}}{\mathrm{d}\varphi} + h_{\mathrm{CA}}\frac{\mathrm{d}m_{\mathrm{CA}}}{\mathrm{d}\varphi} + h_{\mathrm{E}}\frac{\mathrm{d}m_{\mathrm{E}}}{\mathrm{d}\varphi} + \frac{\mathrm{d}W}{\mathrm{d}\varphi}$$
(1)

where U is the internal energy of the air in the cylinder, Q_w – the heat absorbed by the air from the cylinder walls, h_j (j = I, E, CA) – the specific enthalpies of intake air, exhaust air and injection compressed air, respectively, m_j (j = I, E, CA) – the mass of intake air, exhaust air and injection compressed air, respectively, W – the mechanical work on the piston, and φ – the CA.

The *U* can be written:

$$dU = d(mu) = udm + mdu$$
⁽²⁾

where *m* is the mass of the air in the cylinder and u – the specific heat.

For ideal air, *u* can be seen as a function of air temperature, that is u = u(T), and *u* can be written in a fully differential form:

$$\frac{\mathrm{d}u}{\mathrm{d}\varphi} = \frac{\partial u}{\partial T} \frac{\mathrm{d}T}{\mathrm{d}\varphi} = c_v \frac{\mathrm{d}T}{\mathrm{d}\varphi} \tag{3}$$

where c_v is the constant volume specific heat and T – the temperature of the air in cylinder.

The heat transfer in the process can be expressed:

$$\frac{\mathrm{d}Q_{\mathrm{w}}}{\mathrm{d}\varphi} = \frac{1}{\omega} \sum_{i=1}^{3} a_g A_i (T_{wi} - T) \tag{4}$$

where ω is the angular speed of the crank shaft, a_g – the heat transfer coefficient, A_i – the total heat transfer area, and T_{wi} (i = 1, 2, 3) – the temperatures of the cylinder head, the piston and the cylinder liner, respectively.

The coefficient of the heat transfer between the air and the cylinder walls is given:

$$a_g = 0.1129 D^{-0.2} p^{0.8} \left(\frac{Sn}{30}\right)^{0.8} T^{-0.594}$$
(5)

where D is the diameter of the cylinder, p – the pressure of the air in the cylinder, S – the stroke of the piston, and n – the rotational speed of the CAE.

The mechanical work by the compressed air is described by:

$$\frac{\mathrm{d}W}{\mathrm{d}\varphi} = -p\frac{\mathrm{d}V}{\mathrm{d}\varphi} \tag{6}$$

where V is the cylinder volume.

The cylinder volume *V* can be written:

$$V = \frac{\pi D^2}{4} \left\{ \frac{S}{\varepsilon - 1} + \frac{S}{2} \left[\left(1 + \frac{1}{\lambda} \right) - \cos \varphi - \frac{1}{\lambda} \sqrt{1 - \lambda^2 \sin^2 \varphi} \right] \right\}$$
(7)

where ε is the compression ratio and λ – the ratio of crank radius to connecting rod.

The change rate of the cylinder volume can be expressed:

$$\frac{\mathrm{d}V}{\mathrm{d}\varphi} = \frac{\pi D^2 S}{8} \left[\sin\varphi + \frac{\lambda}{2} \frac{\sin(2\varphi)}{\sqrt{1 - \lambda^2 \sin^2 \varphi}} \right] \tag{8}$$

Substituting eqs. (2)-(6) into eq. (1) yields the following differential equation:

$$\frac{\mathrm{d}T}{\mathrm{d}\varphi} = \frac{1}{mc_{\nu}} \left(\frac{\mathrm{d}Q_{\mathrm{w}}}{\mathrm{d}\varphi} - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} + h_{\mathrm{I}} \frac{\mathrm{d}m_{\mathrm{I}}}{\mathrm{d}\varphi} + h_{\mathrm{CA}} \frac{\mathrm{d}m_{\mathrm{CA}}}{\mathrm{d}\varphi} + h_{\mathrm{E}} \frac{\mathrm{d}m_{\mathrm{E}}}{\mathrm{d}\varphi} - u \frac{\mathrm{d}m}{\mathrm{d}\varphi} \right)$$
(9)

The mass air-flow of the CAE can be expressed:

$$\frac{\mathrm{d}m_j}{\mathrm{d}\varphi} = \frac{1}{\omega} \mu F \sqrt{\frac{p_1}{v_1}} \psi \tag{10}$$

where μ is the coefficient of discharge, F – the effective sectional area, p_1 – the upstream pressure, v_1 – the upstream air specific volume, and ψ – the flow function.

When $p_r/p_1 > [2/(k+1)]^{[k/(k-1)]}$, the air-flow state is sub-sonic flow state, and the flow function ψ can be written:

$$\psi = \sqrt{\frac{2k}{k-1}} \left[\left(\frac{p_r}{p_1}\right)^2 - \left(\frac{p_r}{p_1}\right)^{\frac{k+1}{k}} \right]$$
(11)

where k is the adiabatic exponent of the air and p_r the downstream pressure.

When $p_r/p_1 \leq [2/(k+1)]^{[k/(k-1)]}$, the air-flow state is sonic flow state, and the flow function ψ can be written:

$$\psi = \left(\frac{2}{k+1}\right)^{\frac{1}{k-1}} \sqrt{\frac{2k}{k+1}}$$
(12)

The ideal gas equation of state can be derived:

$$pV = mRT \tag{13}$$

where R is the gas constant of air.

Compression stroke

During the compression stroke, the intake valves and exhaust valves are closed, because it is assumed that gas has no leak, the mass air-flow of the CAE can be considered to be zero:

$$\frac{\mathrm{d}m_{\mathrm{I}}}{\mathrm{d}\varphi} = 0, \quad \frac{\mathrm{d}m_{\mathrm{CA}}}{\mathrm{d}\varphi} = 0, \quad \frac{\mathrm{d}m_{\mathrm{E}}}{\mathrm{d}\varphi} = 0 \tag{14}$$

The energy conservation equation can be expressed:

$$\frac{\mathrm{d}T}{\mathrm{d}\varphi} = \frac{1}{mc_{\nu}} \left(\frac{\mathrm{d}Q_{\mathrm{w}}}{\mathrm{d}\varphi} - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} \right) \tag{15}$$

Simultaneously, the ideal gas equation of state can be rewritten:

$$\frac{\mathrm{d}p}{\mathrm{d}\varphi} = p \left(\frac{1}{T} \frac{\mathrm{d}T}{\mathrm{d}\varphi} - \frac{1}{V} \frac{\mathrm{d}V}{\mathrm{d}\varphi} \right) \tag{16}$$

Inflation and expansion stroke

Inflation and expansion stroke can be divided into two stages, namely the inflating stage and the expansion stage. During the inflating stage, the intake valves and exhaust valves are closed, and compressed air is charged into the cylinder. In this stage, the change of the gas mass in the cylinder is the mass change of the compressed air injecting into the cylinder.

The mass conservation equation can be expressed:

$$\frac{\mathrm{d}m}{\mathrm{d}\varphi} = \frac{\mathrm{d}m_{\mathrm{CA}}}{\mathrm{d}\varphi} \tag{17}$$

The energy conservation equation can be expressed:

$$\frac{\mathrm{d}T}{\mathrm{d}\varphi} = \frac{1}{mc_v} \left(\frac{\mathrm{d}Q_w}{\mathrm{d}\varphi} - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} + h_{\mathrm{CA}} \frac{\mathrm{d}m_{\mathrm{CA}}}{\mathrm{d}\varphi} - u \frac{\mathrm{d}m}{\mathrm{d}\varphi} \right)$$
(18)

The ideal gas equation of state can be rewritten:

$$\frac{\mathrm{d}p}{\mathrm{d}\varphi} = \frac{1}{V} \left[\mathbf{R} \left(\frac{\mathrm{d}m}{\mathrm{d}\varphi} T + \frac{\mathrm{d}T}{\mathrm{d}\varphi} m \right) - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} \right]$$
(19)

During the expansion stage, the intake valves, the exhaust valves and the air nozzle are all closed. Similar to the compression stage, the gas mass in the cylinder remains unchanged.

The mass conservation equation can be expressed:

$$\frac{\mathrm{d}m}{\mathrm{d}\varphi} = 0 \tag{20}$$

The energy conservation equation can be expressed:

$$\frac{\mathrm{d}T}{\mathrm{d}\varphi} = \frac{1}{mc_{\nu}} \left(\frac{\mathrm{d}Q_{\mathrm{w}}}{\mathrm{d}\varphi} - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} \right)$$
(21)

The ideal gas equation of state can be rewritten:

$$\frac{\mathrm{d}p}{\mathrm{d}\varphi} = p \left(\frac{1}{T} \frac{\mathrm{d}T}{\mathrm{d}\varphi} - \frac{1}{V} \frac{\mathrm{d}V}{\mathrm{d}\varphi} \right)$$
(22)

Exhaust stroke

During the exhaust stroke, the intake valves are closed while the exhaust valves are open, and the change of the gas mass in the cylinder is the mass change of the residual air flowing out of the cylinder.

The mass conservation equation can be expressed:

$$\frac{\mathrm{d}m}{\mathrm{d}\varphi} = \frac{\mathrm{d}m_{\mathrm{E}}}{\mathrm{d}\varphi} \tag{23}$$

The energy conservation equation can be expressed:

$$\frac{\mathrm{d}T}{\mathrm{d}\varphi} = \frac{1}{mc_{\nu}} \left(\frac{\mathrm{d}Q_{\mathrm{w}}}{\mathrm{d}\varphi} - p\frac{\mathrm{d}V}{\mathrm{d}\varphi} - h_{\mathrm{E}}\frac{\mathrm{d}m_{\mathrm{E}}}{\mathrm{d}\varphi} - u\frac{\mathrm{d}m}{\mathrm{d}\varphi} \right)$$
(24)

The ideal gas equation of state can be rewritten:

$$\frac{\mathrm{d}p}{\mathrm{d}\varphi} = \frac{1}{V} \left[\mathbf{R} \left(\frac{\mathrm{d}m}{\mathrm{d}\varphi} T + \frac{\mathrm{d}T}{\mathrm{d}\varphi} m \right) - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} \right]$$
(25)

Intake stroke

During the intake stroke, the intake valves are open while the exhaust valves are closed, and the change of the gas mass in the cylinder is the mass change of the common air flowing into the cylinder.

The mass conservation equation can be expressed:

$$\frac{\mathrm{d}m}{\mathrm{d}\varphi} = \frac{\mathrm{d}m_{\mathrm{I}}}{\mathrm{d}\varphi} \tag{26}$$

The energy conservation equation can be expressed:

$$\frac{\mathrm{d}T}{\mathrm{d}\varphi} = \frac{1}{mc_{v}} \left(\frac{\mathrm{d}Q_{w}}{\mathrm{d}\varphi} - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} + h_{\mathrm{I}} \frac{\mathrm{d}m_{\mathrm{I}}}{\mathrm{d}\varphi} - u \frac{\mathrm{d}m}{\mathrm{d}\varphi} \right)$$
(27)

The ideal gas equation of state can be rewritten:

$$\frac{\mathrm{d}p}{\mathrm{d}\varphi} = \frac{1}{V} \left[\mathbf{R} \left(\frac{\mathrm{d}m}{\mathrm{d}\varphi} T + \frac{\mathrm{d}T}{\mathrm{d}\varphi} m \right) - p \frac{\mathrm{d}V}{\mathrm{d}\varphi} \right]$$
(28)

In the numerical calculation, the processes of four strokes are computed using the fourth order Runge-Kutta method, and the theoretical computing results are closer to the actual operation of the CAE [18].

Dynamic model

From the force analysis of the crank-link mechanism, and the output torque of the CAE can be expressed:

$$M = \frac{(p - p_0)A_h - m_d r\omega^2(\cos\varphi + \lambda\cos 2\varphi)}{\cos\beta}$$
(29)

where p_0 is the atmospheric pressure, A_h – the projected area of the piston, m_d – the mass the crank-link mechanism, r – the radius of the crank, and β – the angle between the connecting rod and the axis of the cylinder, $\sin\beta = \lambda \sin\varphi$.

Key performance parameters

The calculations and analyses of relevant performance can be calculated by the following equations.

The indicated work of single cylinder per cycle W_i

$$W_i = \int_{\text{cyc}} p \frac{\mathrm{d}V}{\mathrm{d}\varphi} \mathrm{d}\varphi \tag{30}$$

- The average effective torque of single cylinder $M_{\rm e}$

$$M_{\rm e} = \eta_{\rm m} \frac{1}{4\pi} \int_{\rm cyc} M \,\mathrm{d}\varphi \tag{31}$$

where η_m is the mechanical efficiency.

- The effective power of the CAE $P_{\rm e}$

$$P_{\rm e} = \frac{\frac{\pi}{4} D^2 S \cdot 10^3 nip_{\rm me}}{30\tau}$$
(32)

where p_{me} is the average effective pressure, i – the number of cylinders, and τ – the number of strokes.

- The work efficiency η

$$\eta = \frac{W_i}{W} \eta_m \tag{33}$$

Experimental set-up

The development of the four-stroke CAE required original system experiments and calibrations on the test bench, in order to accomplish some steady tests of the injection pressure and the injection temperature characteristics. These processes can also verify and test the stability and performance of the CAE. Generally, a CAE test bench is composed of an air compressor, compressed air storage tanks, a pressure reducing valve, supply pressure sensors, cylinder pressure sensors, flow sensors, high-frequency electromagnetic valves, air nozzles, thermocouples, a high-speed data acquisition unit and an engine electronic control unit. After completing the experiments and verification, the overall test can be conducted, which mainly focuses on output parameters, such as engine power, torque *etc*. Meanwhile, some other parameters like rotational speed, supply pressure, supply temperature, flow rate, exhaust pressure, and exhaust temperature *etc*. ought to be monitored to adjust the control parameters in real time and protect the CAE from malfunctions. The engine test bench is universally made up of a complete motor, dynamometer, and monitoring system. The experimental prototype test bench and measurement equipment are illustrated in fig. 2.



Figure 2. Experimental prototype test bench and measurement equipment; 1 – air compressor, 2 – compressed air storage tanks, 3 – compressed air supply test bench, 4 – pressure reducing valve, 5 – supply pressure sensor, 6 – flow sensor, 7 – high-frequency electromagnetic valve, 8 – cylinder pressure sensor, 9 – air nozzle, 10 – high-speed data acquisition unit, 11 – ECU, 12 – motor, 13 – dynamometer, 14 – monitoring system

Result and discussion

Working characteristics of the four-stroke CAE can be investigated by cylinder pressure, output torque, average effective torque, effective power, indicated work, work efficiency and so on. Parameters for rotational speed, supply pressure and supply temperature are important to working process simulation. In this paper, the working characteristics and working processes at different initial conditions are investigated by the mathematical model. The working initial angle of the CAE is compression start angle while simulating working process.

Parameters	Values		
Diameter of the cylinder, [mm]	<i>D</i> = 69.5		
Stroke of the piston, [mm]	<i>S</i> = 79.5		
Ratio of crank radius to connecting rod	$\lambda = 0.32$		
Compression ratio	$\varepsilon = 9.8$		
Radius of the crank, [mm]	<i>r</i> = 39		
Ambient pressure, [bar]	1.01		
Ambient temperature, [K]	293		
Diameter of the intake valve, [mm]	25		
Diameter of the exhaust valve, [mm]	20		
Supply pressure, [bar]	$p_i = 20$		
Rotational speed, [rpm]	<i>n</i> = 1000		
Intake sustain angle, [°CA]	50		
Exhaust advance angle, [°CA]	10		

Table 1	The	narameters	of	the	CAE
Table L.	THC	par ameters	UL.	une	CAL

In present work, intake parameters are imposed on the entire computational domain as initial conditions, tab. 1, for numerical simulation. The effect of heat transfer between the outer wall and air is not considered. Thus, wall boundary is in adiabatic condition. The CA is at 355 °CA, corresponding to the intake angle of the compressed air. Figure. 3 illustrates the port timing diagram of the CAE.

As shown in figs. 4 and 5, the indicated work and the variation of cylinder pressure in a working cycle are revealed. According to eq. (30), the total pressure volume (P-V) area represents the value of the indicated work. The cylinder pressure increases rapidly in the compression stage, and the peak cylinder pressure is close to the supply pressure, the pressure drops rapidly in the expansion stage. Figure 6 shows output torque changing with different CA. From this figure, it can be found that the piston moves upward and the piston work is negative in the compression stroke, which results in a negative output torque of the CAE. As the compressed air continuously filled into the cylinder, it continues to push the piston to output the mechanical work on the piston. Thus, the output torque increases. At the end of inflation stage, the output torque reaches the maximum.



Rotational speed

Figure 7 illustrates the indicator diagrams at different rotational speeds. From this figure, it can be found that the lower the rotational speed, the larger the indicated work. This is because with the increased rotational speed, the intake time of the compressed air becomes shorter. As a result, air inflow decreases and energy of the compressed air is reduced, which leads to a decrease in the indicator work. Figure 8 shows the variation of the cylinder pressure under various rotational speeds. It is found that the rotational speed has an obvious effect on cylinder pressure. The higher the rotational speed may result in an evident change of cylinder pressure. While the rotational speed decreases, the appearance of the top pressure has a tendency to move backward, and the pressure at the end of the expansion stage will increase. Consequently, the cylinder pressure will decrease sharply when entering the expansion stage



and a steep slope of pressure will follow up. With the increasing of rotational speed, however, this phenomenon will disappear slowly.

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The simulation shows that the cylinder temperature varies with the rotational speed changing from 1000 rpm to 3000 rpm. However, its variation tendency is different from cylinder pressure, that is, the higher the rotational speed, the higher the cylinder temperature at the inflation and expansion stroke and exhaust stroke. Because of the higher the rotational



Figure 9. Output torque variation at different rotational speeds

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speed, the smaller the mass of the compressed air that flows into the cylinder, this will lead to the lower temperature drop when the air is mixed at the end of the compression stroke. Therefore, the temperature of the mixed air is higher.

The effect of rotational speed to output torque may be analyzed through fig. 9. It is found that, with the increased rotational speed, the output torque of the CAE is smaller. In the exhaust stroke, the piston pushes the gas and the output torque is negative. However, the exhaust time becomes shorter with the increased rotational speed, so the mass of the residual air is larger. The residual air in the cylinder becomes the resistance of the exhaust gas,

thereby increasing the cylinder pressure, which results in an increase in the reverse output torque of the CAE.

Supply pressure

Supply pressure is another factor to affect working characteristics of the CAE. The cylinder pressure variation at different supply pressures is shown in fig. 10. As observed from this figure, the increase of supply pressure results in a sharp increase of the top pressure of the cylinder, and the increase of the supply pressure results in pressure peak moving toward the larger CA. This is due to energy of compressed air increases as supply pressure increases

without other influence factors, which means that the supply pressure has a positive effect on the dynamic performance of the CAE. The output torque variation at different supply pressures is shown in fig. 11. Its variation tendency is the same as cylinder pressure. The larger the supply pressure, the larger the output torque. However, larger supply pressure leads to exhaust pressure is greater, which increases the reverse output torque of the CAE. Under different supply pressure, the change rules of the relevant performance parameters are shown in figs. 12-14. With the same supply pressure condition, the increase of rotational speed is bad for increasing average effective torque and work efficiency, this indicates that the CAE is more suitable for lower rotational speed. Furthermore, it can be seen from figs. 12 and 14 that average effective torque and work efficiency increase with the rising of supply pressure for the same rotational speed. Figure 13 presents the working characteristics of the effective power at different supply pressures. From fig. 13, one can find that effective power increases with the rising of supply pressure for the same rotational speed, and with the increased rotational speed, the change trend of effective power increases first and then decreases for the same supply pressure. On the whole, the rotational speed range of the effective power reaches the maximum is 1500~2000 rpm.









Figure 12. Average effective torque variation at different supply pressures

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Figure 11. Output torque variation at different supply pressures

(for color image see journal web site)



Figure 13. Effective power variation at different supply pressures

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Supply temperature

The effect of supply temperature on working characteristics seems to be nonsignificant different with the range of whole work cycle. Figures 15-17 illustrated the variation of average effective torque, effective power and work efficiency under various supply temperatures. It is found that there is a slight variation of these characteristics parameters. As shown in these figures, with the increasing of supply temperature, their values will become smaller for the same rotational speed. Under the conditions of same supply temperature, average effective torque and work efficiency decrease with the increasing of rotational speed. The relationship between rotational speed and effective power is a parabola going downwards, when the effective power reaches the maximum, the rotational speed is about 1500 rpm. According to the effect analysis of the supply temperature, increasing the supply temperature make little sense to power lift of the CAE, the key is to enhance heat transfer in the working process so as to improve the air temperature, thus improving the working performance of the CAE.



Figure 14. Work efficiency variation at different supply pressures (for color image see journal web site)



Figure 16. Effective power variation at different supply temperatures (for color image see journal web site)



Figure 15. Average effective torque variation at different supply temperatures (for color image see journal web site)



Figure 17. Work efficiency variation at different supply temperatures (for color image see journal web site)

Conclusions

In this paper, a four-stroke compressed air engine is as a new research object is used to investigate the working performance. A mathematical model is developed to study the influence of several key performance parameters on working characteristics, and the experimental system is set up. The method of valid modeling is introduced to simulate real operating conditions, and the performance analysis on the influences of rotational speed, supply pressure and supply temperature are carried out. On the basis of the above analysis, some brief conclusions have been drawn.

- In the work process, the cylinder pressure and temperature rise rapidly during the compression stroke, then decrease gradually during the inflation and expansion stroke, and the air fluctuation is relatively stable during the exhaust stroke and intake stroke.
- The CAE has a higher cylinder pressure in the low speed stage and has the higher work efficiency, which is more suitable for low speed and stable condition.
- Compared with other working parameters, supply pressure has a greater influence on the performance of the CAE, and the increase of the supply pressure can effectively improve the indicated work and work efficiency.
- The supply temperature has little effect on the performance of the CAE, with the increasing of supply temperature, the average effective torque, effective power and work efficiency will decrease slightly.

It is obvious that the output torque, effective power and work efficiency of the CAE grow with the decrease of rotational speed and the increase of supply pressure. Not affecting the other performance, CAE may choose a higher supply pressure.

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