STUDY ON EXERGY ANALYSIS OF A COMPRESSED AIR ENGINE

by

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In order to reduce exergy loss and optimize exergy efficiency of a compressed air engine (CAE), a theoretical exergy analysis model of the CAE is proposed and a working principle of the CAE based on a conventional IC engine is described. In addition, exergy balance equations of the working process at different stages are setup. The effects of rotational speed, supply pressure and ambient temperature are revealed in the simulation analysis, which have important influences on the exergy efficiency of the CAE. All these analyses of this paper will provide a theoretical basis for further study on optimizing design of the CAE.

Key words: *exergy loss, exergy efficiency, compressed air engine, simulation analysis, exergy analysis model, exergy balance equation*

Introduction

Energy is a vital material foundation of transportation vehicles development, however, in the past few decades, energy crisis have become very crucial issues worldwide [1-5]. The depletion of conventional energy is necessitating the search of environmentally friendly resources such as non-conventional and renewable energy sources [6, 7]. In the field of exergy utilization, lots of research focuses on how to improve the utilization efficiency for the purpose of saving energy [8-10]. Compressed air, as the second by importance energy medium in after electricity, is considered to drive a compressed air engine (CAE) because it is clean and inexhaustible [11]. Nowadays, in the field of the CAE, the relevant technologies have been researched by many domestic and foreign scholars [12-15], and there are many related literatures studying the CAE in the past several decades. These literatures focus on two main aspects: one is the feasibility analysis of the CAE and the other is the working process analysis of the CAE.

On one hand, the feasibility analysis includes principle feasibility analysis and thermal efficiency analysis, and many scholars are engaged in this field [16-19]. Papson and Creutzig [16, 17] pointed that compressed air vehicles offered environmental and economic benefits over conventional vehicles, and analyzed the thermal efficiency of a compressed air car powered by a pneumatic engine and considered the merits of compressed air versus chemical storage of potential energy. Pneumatic-combustion hybrid vehicles were proposed in their paper, and could eventually compete with hybrid electric vehicles. Chen [18] analyzed two types of air fueled engines for zero emission road transportation and indicated that the efficiency of compressed air powered engine was higher than that of liquid air powered engine. Yu [19] 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.

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On the other hand, the working process of different types of CAE is studied by lots of scholars [20-22]. Xu [20] established a basic model of working process of the CAE, and experiments on a prototype modified from an internal combustion engine were carried out to verify the CAE feasibility and the basic model's validity. A CAE mathematical model of working process was built by Chen *et al*. [21]. Single cylinder piston-type CAE and double crank link CAE were investigated, the average output power and efficiency characteristics of two kinds of CAE were obtained by simulation and experiment [22].

However, as most of literatures on CAE only considered feasibility and working process, and the research on feasibility analysis only considered the thermal efficiency, the studied may be more reasonable if the exergy analysis is also considered in the research of the CAE. In addition, exergy analysis is useful for evaluating the compressed air exergy efficiency of the CAE especially for selecting the suitable work parameters. Based on the above considerations, we have established a theoretical exergy analysis model of the CAE and exergy balance equations of the working process at different stages, the influence of working parameters on the CAE are studied and analized via simulation. All the work can provide some helps for reducing exergy losses and optimizing the CAE exergy efficiency.

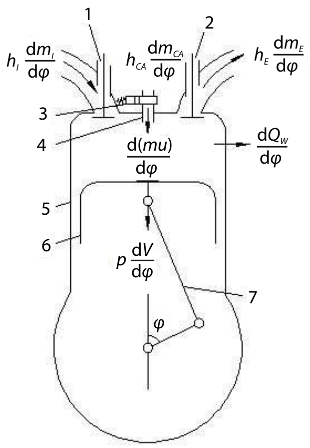

Figure 1. Structure and thermodynamic analysis diagram of the CAE;
1 – intake valve, 2 – exhaust valve, 3 – high-frequency electromagnetic valve, 4 – air nozzle, 5 – cylinder, 6 – piston 7 – crank-link mechanism

The principles of the CAE

In this study, a four-stroke IC engine supplied by SGMW, a Chinese automobile company, is used. By modifying the engine design, the four-stroke IC engine is modified to the four-stroke CAE, the structure and thermodynamic analysis diagram of the CAE is shown in fig. 1. A work cycle includes intake stroke, compression stroke, inflatable expansion stroke and exhaust stroke. In the intake stroke, the atmosphere flows into the cylinder through the intake valves because of the pressure difference. When the piston is near the bottom dead center (BDC), the intake valves close. In the compression stroke, the piston moves up near the top dead center (TDC). Then in the inflatable expansion stroke, the high-frequency electromagnetic valve and the air nozzle begin to work, the compressed air enters the cylinder through the air nozzle, driving the piston downward. After a specific crank angle, the high-frequency electromagnetic valve is forced to power off, and the air nozzle is cut off, the compressed air continues to push the piston down and output work. When the piston moves back to the bottom dead center (BDC), the exhaust valves open, and residual air is discharged into the exhaust air duct.

Exergy analysis model of the CAE

Exergy balance equation of the thermodynamic system

The model based on the crank angle was built at first. To simplify the theoretical analysis, the following assumptions are made:
- the compressed air is ideal, which means specific heat and specific enthalpy are only related to the temperature,
- the changes of kinetic and gravitational energy are negligible,
- there is no leak during the working process,

– the process of gas flowing into/out of the cylinder is a quasi-steady one, and
– the throttling in the nozzle and friction are neglected.

In this section, the exergy balance equation of thermodynamic system of the CAE is established by using the method of exergy analysis based on the Second law of thermodynamics [23], and it can be expressed as:

$$\frac{\mathrm{d}E_{CA}}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_I}{\mathrm{d}\varphi}=\frac{\mathrm{d}E_O}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_W}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_H}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_A}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_L}{\mathrm{d}\varphi} \tag{1}$$

where E_{CA} is the exergy of the compressed air flowing into the cylinder, E_I – the exergy of the air flowing into the cylinder during the intake stroke, E_O – the exergy of the air flowing out of the cylinder during the exhaust stroke, E_W – the exergy of the piston work, E_H – the exergy of the system caused by heat transfer between the air and the cylinder walls, E_A – the increment of exergy of the system, E_L – the exergy loss caused by irreversibility, and φ – the crank angle.

According to the exergy balance equation, the calculating formula of the variance of exergy can be expressed as follows.

(1) The change of exergy of the compressed air flowing into the cylinder is given:

$$\frac{\mathrm{d}E_{CA}}{\mathrm{d}\varphi}=\frac{\mathrm{d}m_{CA}}{\mathrm{d}\varphi}\mathrm{R}T_0\ln\left(\frac{p_{CA}}{p_0}\right) \tag{2}$$

where m_{CA} is the mass of the injection compressed air, R – the gas constant of air, T_0 – the temperature of the air under environmental conditions, p_{CA} – the supply pressure of the compressed air, and p_0 – the pressure of the air under environmental conditions.

(2) The change of exergy flowing into the cylinder during the intake stroke is given:

$$\frac{\mathrm{d}E_I}{\mathrm{d}\varphi}=\left[h_I-h_0-T_0(s_I-s_0)\right]\frac{\mathrm{d}m_I}{\mathrm{d}\varphi} \tag{3}$$

where h_I is the specific enthalpy of the air during the intake stroke, h_0 – the specific enthalpy of the air under environmental conditions, s_I – the specific entropy of the air at the intake valve, s_0 – the specific entropy of the air under environmental conditions, and m_I – the mass of the intake air.

(3) The change of exergy flowing out of the cylinder during the exhaust stroke is given:

$$\frac{\mathrm{d}E_O}{\mathrm{d}\varphi}=\left[h_E-h_0-T_0(s_E-s_0)\right]\frac{\mathrm{d}m_E}{\mathrm{d}\varphi} \tag{4}$$

where h_E is the specific enthalpy of the air during the exhaust stroke, s_E – the specific entropy of the air at the exhaust valve, and m_E – the mass of the exhaust air.

(4) The change of exergy of the piston work is given:

$$\frac{\mathrm{d}E_W}{\mathrm{d}\varphi}=(p-p_0)\frac{\mathrm{d}V}{\mathrm{d}\varphi} \tag{5}$$

where p is the pressure of the air in the cylinder and V – the cylinder volume.

(5) The change of exergy of the system caused by heat transfer between the air and the cylinder walls is given:

$$\frac{\mathrm{d}E_H}{\mathrm{d}\varphi}=\frac{\mathrm{d}Q_w}{\mathrm{d}\varphi}(1-\frac{T_0}{T}) \tag{6}$$

where Q_w is the heat absorbed by the air from the cylinder walls. The temperature T of the air in the cylinder is:

$$\frac{\mathrm{d}T}{\mathrm{d}\varphi}=\frac{1}{mc_v}\left(\frac{\mathrm{d}Q_w}{\mathrm{d}\varphi}-p\frac{\mathrm{d}V}{\mathrm{d}\varphi}+h_I\frac{\mathrm{d}m_I}{\mathrm{d}\varphi}+h_{CA}\frac{\mathrm{d}m_{CA}}{\mathrm{d}\varphi}-h_E\frac{\mathrm{d}m_E}{\mathrm{d}\varphi}-u\frac{\mathrm{d}m}{\mathrm{d}\varphi}\right) \tag{7}$$

where c_v is the constant specific heat capacity, h_{CA} – the specific enthalpy of the injection compressed air, u – the specific internal energy, and m – the mass of the air in the cylinder is:

The heat transfer in the process can be expressed:

$$\frac{\mathrm{d}Q_w}{\mathrm{d}\varphi}=\frac{1}{\omega}\sum_{i=1}^{3}a_g\,A_i(T_{wi}-T) \tag{8}$$

where ω is the angular speed of the crank shaft, a_g – the coefficient of the heat transfer between the air and the cylinder walls, A_i – the total area of the heat transfer, and T_{wi} (i = 1, 2, 3) are 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:

$$a_g=0.1129D^{-0.2}p^{0.8}(Sn/30)^{0.8}T^{-0.594} \tag{9}$$

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

The increment of exergy of the system is given:

$$\frac{\mathrm{d}E_A}{\mathrm{d}\varphi}=\left[u-u_0-T_0(s-s_0)+p_0(v-v_0)\right]\frac{\mathrm{d}m}{\mathrm{d}\varphi}+m\left[\frac{\mathrm{d}u}{\mathrm{d}\varphi}-T_0\frac{\mathrm{d}s}{\mathrm{d}\varphi}+p_0\frac{\mathrm{d}V}{\mathrm{d}\varphi}\right] \tag{10}$$

where u_0 is the specific internal energy of the air under environmental conditions, s – the specific entropy of the air, v – the specific volume of the air, and v_0 – the specific volume of the air under environmental conditions.

The change of the specific entropy of the air can be expressed:

$$s-s_0=c_p\ln\frac{T}{T_0}-R\ln\frac{p}{p_0} \tag{11}$$

here c_p is the constant specific heat pressure.

So the increment of exergy of the system can be written:

$$\begin{aligned}\frac{\mathrm{d}E_A}{\mathrm{d}\varphi}&=\left[u-u_0-T_0(s-s_0)+p_0(v-v_0)\right]\frac{\mathrm{d}m}{\mathrm{d}\varphi}+\\&+mc_v\left(1-\frac{T_0}{T}\right)\frac{\mathrm{d}T}{\mathrm{d}\varphi}+\left(p_0-\frac{mT_0\mathrm{R}}{V}\right)\frac{\mathrm{d}V}{\mathrm{d}\varphi}\end{aligned} \tag{12}$$

Exergy balance equation of each working stage of the CAE

(1) *Compression stage*

During the compression stage, the intake valves and the exhaust valves are closed, the working process of the CAE can be regarded as a typical closed thermodynamic process. There is piston work and heat transfer throughout this process, but no air flowing in and out of the cylinder, so the exergy balance equation can be expressed:

$$\frac{\mathrm{d}E_W}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_H}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_A}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_L}{\mathrm{d}\varphi}=0 \tag{13}$$

The change of the exergy loss caused by irreversibility can be written:

$$\frac{\mathrm{d}E_L}{\mathrm{d}\varphi} = -(mc_v \frac{\mathrm{d}T}{\mathrm{d}\varphi} + \frac{\mathrm{d}Q_w}{\mathrm{d}\varphi})(1 - \frac{T_0}{T}) - (p - \frac{mT_0R}{V})\frac{\mathrm{d}V}{\mathrm{d}\varphi} \tag{14}$$

(2) *Inflating stage*

During the inflating stage, the intake valves and the exhaust valves are closed, but the high-frequency electromagnetic valve is opened and the compressed air is charged into the cylinder through the air nozzle, the working process of the CAE can be regarded as an open thermodynamic process. There is the flow of the compressed air, piston work and heat transfer throughout this process, but no ordinary air flowing in and out of the cylinder, so the exergy balance equation can be expressed:

$$\frac{\mathrm{d}E_{CA}}{\mathrm{d}\varphi} = \frac{\mathrm{d}E_W}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_H}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_A}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_L}{\mathrm{d}\varphi} \tag{15}$$

The change of the exergy loss caused by irreversibility can be written:

$$\begin{aligned} \frac{\mathrm{d}E_L}{\mathrm{d}\varphi} &= \frac{\mathrm{d}m_{CA}}{\mathrm{d}\varphi} RT_0 \ln\left(\frac{p_{CA}}{p_0}\right) - \frac{\mathrm{d}Q_w}{\mathrm{d}\varphi}\left(1 - \frac{T_0}{T}\right) - \left(p - \frac{mT_0R}{V}\right)\frac{\mathrm{d}V}{\mathrm{d}\varphi} - \\ &-\left[u - u_0 - T_0(s - s_0) + p_0(v - v_0)\right]\frac{\mathrm{d}m}{\mathrm{d}\varphi} + mc_v\left(1 - \frac{T_0}{T}\right)\frac{dT}{d\varphi} + \left(p_0 - \frac{mT_0R}{V}\right)\frac{\mathrm{d}V}{\mathrm{d}\varphi} \end{aligned} \tag{16}$$

(3) *Expansion stage*

The expansion stage is the same as the compression stage, the intake valves and the exhaust valves are closed, the working process of the CAE can be seen as a closed thermodynamic process. The exergy balance equation can be expressed:

$$\frac{\mathrm{d}E_W}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_H}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_A}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_L}{\mathrm{d}\varphi} = 0 \tag{17}$$

The change of the exergy loss caused by irreversibility can be written:

$$\frac{\mathrm{d}E_L}{\mathrm{d}\varphi} = -(mc_v \frac{\mathrm{d}T}{\mathrm{d}\varphi} + \frac{\mathrm{d}Q_w}{\mathrm{d}\varphi})(1 - \frac{T_0}{T}) - (p - \frac{mT_0R}{V})\frac{\mathrm{d}V}{\mathrm{d}\varphi} \tag{18}$$

(4) *Exhaust stage*

During the exhaust stage, the intake valves are closed and the exhaust valves are opened. There is flow of the compressed air, piston work and heat transfer throughout this process, and the exhaust air takes away some exergy, so the exergy balance equation can be written:

$$\frac{\mathrm{d}E_O}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_W}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_H}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_A}{\mathrm{d}\varphi} + \frac{\mathrm{d}E_L}{\mathrm{d}\varphi} = 0 \tag{19}$$

and $\mathrm{d}E_L/\mathrm{d}\varphi$ can be written:

$$\begin{aligned} \frac{\mathrm{d}E_L}{\mathrm{d}\varphi} &= -\left[h - h_0 - 2T_0\left(c_p \ln\frac{T}{T_0} - \mathrm{R}\ln\frac{p}{p_0}\right) + u - u_0 + p_0(v - v_0)\right]\frac{\mathrm{d}m}{\mathrm{d}\varphi} \\ &- mc_v\left(1 - \frac{T_0}{T}\right)\frac{\mathrm{d}T}{\mathrm{d}\varphi} - \frac{\mathrm{d}Q_w}{\mathrm{d}\varphi}\left(1 - \frac{T_0}{T}\right) - \left(p - \frac{mT_0\mathrm{R}}{V}\right)\frac{\mathrm{d}V}{\mathrm{d}\varphi} \end{aligned} \tag{20}$$

(5) *Intake stage*

During the intake stage, the intake valves are opened and the exhaust valves are closed, and the exergy balance equation can be expressed:

$$\frac{\mathrm{d}E_I}{d\varphi}=\frac{\mathrm{d}E_W}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_H}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_A}{\mathrm{d}\varphi}+\frac{\mathrm{d}E_L}{\mathrm{d}\varphi} \tag{21}$$

and $\mathrm{d}E_L/\mathrm{d}\varphi$ can be written:

$$\frac{\mathrm{d}E_L}{\mathrm{d}\varphi}=-\left(mc_v\frac{\mathrm{d}T}{\mathrm{d}\varphi}+\frac{\mathrm{d}Q_w}{\mathrm{d}\varphi}\right)\left(1-\frac{T_0}{T}\right)-\left(p-\frac{mT_0\mathrm{R}}{V}\right)\frac{\mathrm{d}V}{\mathrm{d}\varphi} \tag{22}$$

Exergy efficiency

Exergy efficiency can be defined as the ratio of the yield exergy to the dissipated exergy. In the CAE, the exergy efficiency η_e can be expressed as the ratio of the exergy in to the exergy out:

$$\eta_e=\frac{E_O+E_W+E_H}{E_{CA}+E_I}=1-\frac{E_A+E_L}{E_{CA}+E_I} \tag{23}$$

Exergy analysis of the CAE during the working process

Based on the exergy analysis model of the CAE, the corresponding calculation procedure is prepared. This subsection is to analyze the exergy of the CAE and to get the influence laws of different working parameters on the exergy. Some parameters of the CAE are given in tab. 1. If ambient temperature T_0 is set to 290 K, supply pressure p_{CA} is set to 2 MPa and rotational speed n is set to 1000 rpm. Figure 2 illustrate the crank angle-exergy diagram of the CAE.

As seen in this figure, the increment of exergy of the system E_A increases rapidly during the compression stage. As the compressed air is charged into the cylinder, E_A reaches the peak value, and then begins to decrease. The exergy of the compressed air flowing into the cylinder E_{CA} tends to increase linearly with inflating the compressed air, and the growth is fast, this change lasts until the end of the expansion stage, and then E_{CA} continues to increase and keeps the maximum until entering the exhaust stage. At the be-

Table 1. The parameters of the CAE

Parameters	Values
Diameter of the cylinder, [mm]	$D = 69.5$
Stroke of the piston, [mm]	$S = 79.5$
Ratio of crank radius to connecting rod	$\lambda = 0.32$
Compression ratio	$\varepsilon = 9.8$
Radius of the crank, [mm]	$r = 39$
Ambient pressure, [MPa]	0.101
Diameter of the intake valve, [mm]	25
Diameter of the exhaust valve, [mm]	20

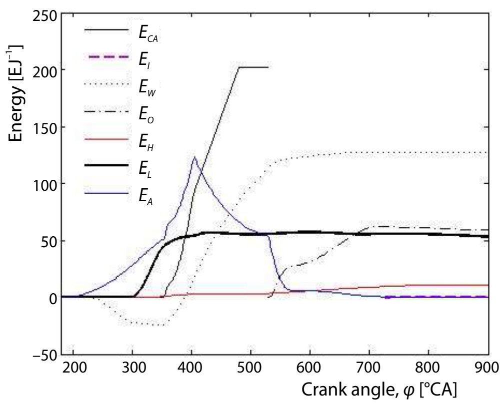

Figure 2. Crank angle-exergy diagram
(*for color image see journal web site*)

ginning of the compression stage, the piston does negative work, the exergy of the piston work E_W is negative and goes up in the negative direction. After entering the inflatable expansion stage, E_W gradually increases to a positive value, and after entering the exhaust stage and intake stage, the fluctuation of E_W is very small, basically keep a fixed value. At the beginning of exhaust stage, the air pressure in the cylinder is higher than the ambient pressure p_0, causing the rapid increase of E_O during the supercritical flow. At the beginning of compression stage, the exergy of the system caused by heat transfer between the air and the cylinder walls E_H is small, basically fluctuating around zero. With the progress of the working process, E_H is slightly greater than zero, but its value is still very small, this means that E_H has little effect on the exergy of the whole system. The exergy of the air flowing into the cylinder during the intake stroke E_I only exists at the intake stage, and its effect on the exergy of the system is extremely small, even negligible. At the compression stage, the exergy loss caused by irreversibility E_L is basically zero and it almost stays the same. After slowly entering the inflatable expansion stage, E_L increases gradually, and its value fluctuates little at other stages.

Figure 3 shows the exergy of the system and proportion, and the exergy efficiency η_e can be calculated, η_e= 66.8%. It is clear that the ratio of E_O to E_{CA} is 25.9%, that means reducing the exergy loss of exhaust can be beneficial in improving exergy efficiency η_e. In addition, E_W has the highest proportion. And compared with E_H , E_L, and E_A have a higher proportion.

Then, the influence of relevant working parameters on the exergy of the system is discussed. The rotational speed n, the supply pressure p_{CA}, and the ambient temperature T_0 are included. According to the above analysis, the exergy losses and exergy efficiency under different working conditions can be studied further.

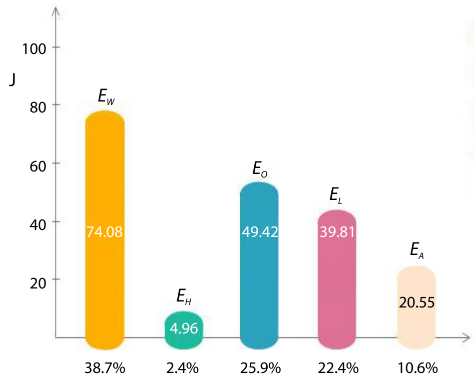

Figure 3. Exergy of the system and proportion of the CAE

Influence of rotational speed on exergy change

In this simulation, the rotational speed n is commonly used as an important control parameter, its value affects the performance of the CAE. This is because the higher the rotational speed n, the smaller the air inflow and the smaller the output torque. In this analysis, when the supply pressure p_{CA} is changed, the value of the ambient temperature is fixed as T_0 = 290 K and the value of the supply pressure is fixed as p_{CA} = 2 MPa. Different kinds of exergy are shown in figs. 4-9 through the numerical simulation for three different values of n = 1000 rpm, n = 1500 rpm, and n = 2500 rpm.

It can be seen that the changed tendencies of exergy are roughly the same under the different rotational speeds. E_{CA}, E_W, E_H, and E_A all decrease with increasing n, however, E_O and E_L increase. This indicates that increasing the rotational speed n can result in an increase in the exergy loss of the CAE and a reduction in the power performance. Simultaneously, it also proves that the CAE is suitable for running at low rotational speed.

Exergy efficiency η_e varies with the rotational speed n as shown in fig. 10, the case when n is less then 1000 rpm is not considered in our paper, but with the increased n, the exergy efficiency η_e is basically a linear downward trend above 1000 rpm. Therefore, the higher the rotational speed n, the smaller the exergy of the compressed air and the larger E_O and E_L, so that leads to the lower η_e. In addition, the proportions of the exergy at different rotational speeds n are shown in fig. 11.

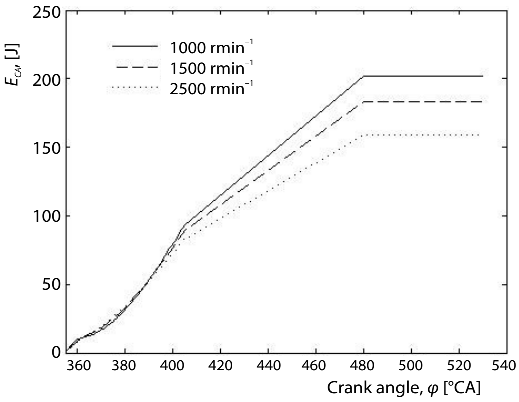

Figure 4. The E_{CA} variation at different rotational speeds

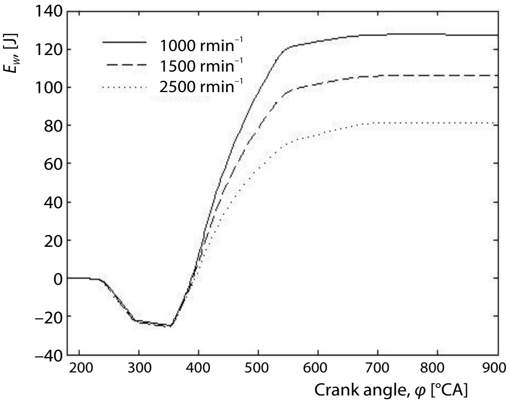

Figure 5. The E_W variation at different rotational speeds

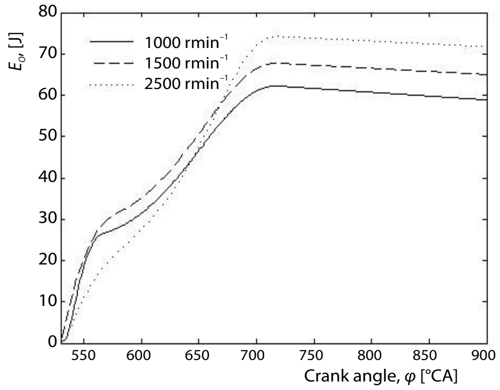

Figure 6. The E_O variation at different rotational speeds

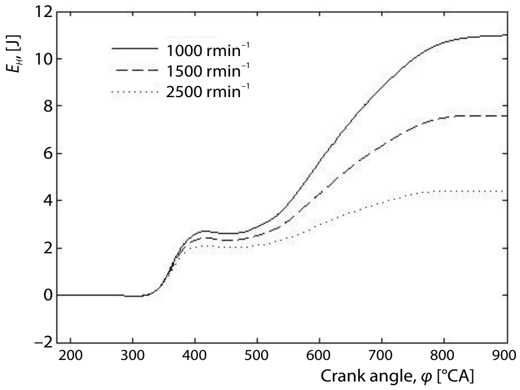

Figure 7. The E_H variation at different rotational speeds

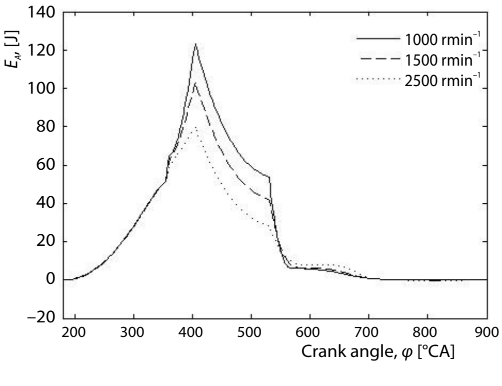

Figure 8. The E_A variation at different rotational speeds

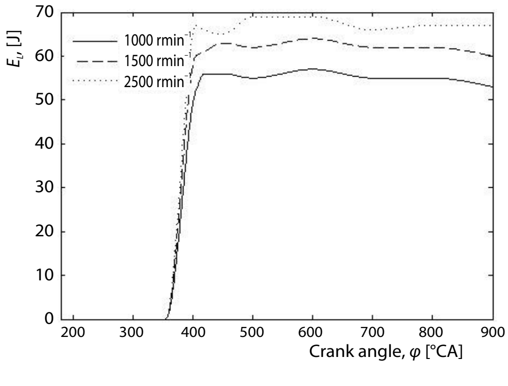

Figure 9. The E_L variation at different rotational speeds

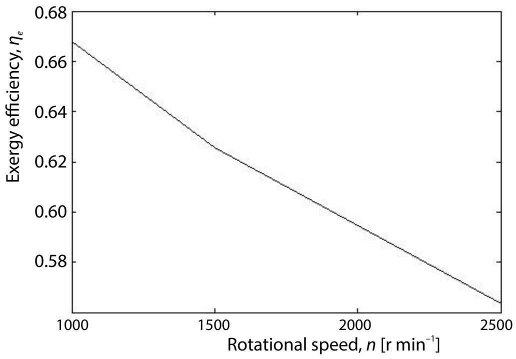

Figure 10. The η_e variation at different rotational speeds

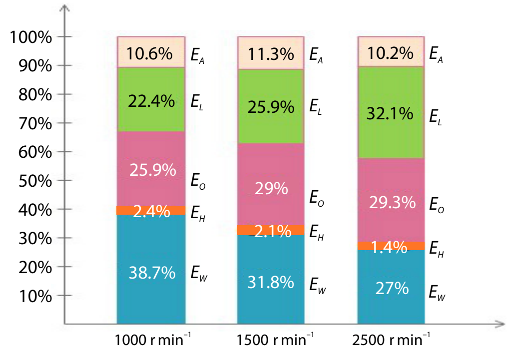

Figure 11. Proportions of the exergy different rotational speeds

Influence of supply pressure on exergy change

The supply pressure is another important parameter that greatly affects the exergy utilization and the exergy losses. On one hand, the larger the supply pressure p_{CA}, the larger the exergy of the compressed air, but the air pressure will increase after the expansion stage, which will cause the larger exhaust pressure, and this is not desirable. On the other hand, the compressed air source pressure of the CAE is determined, if the supply pressure p_{CA} is larger, that means the basic pressure value of the air source is higher, on the condition that air source volume is fixed, the less exergy the CAE can use and the shorter the effective working time. When the supply pressure p_{CA} are 1.5 MPa, 2.0 MPa, 2.5 MPa, and 3.0 MPa, respectively, the relations of the exergy at different crank angles are shown in figs. 12-17.

From the figures, E_{CA}, E_W, E_O and E_A all increase with increasing p_{CA}, and the effect of the increasing E_W is greater than the effect of the increasing E_O. Hence, the exergy efficiency η_e increases with the increased p_{CA}, this analysis result can be observed from fig. 18.

However, this can not be simple to explain that the larger the supply pressure p_{CA}, the better for the CAE. It is necessary to fully consider the problems such as the sealing of components in the CAE, the air leakage in the actual working process and the exhaust recovery, *etc*. Hence, in the actual operation, the supply pressure p_{CA} should be properly selected to achieve the high working efficiency and exergy efficiency.

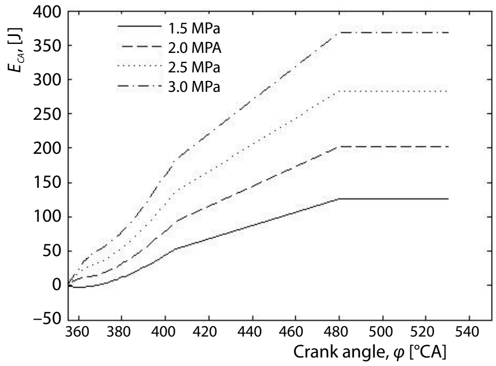

Figure 12. The E_{CA} variation at different supply pressures

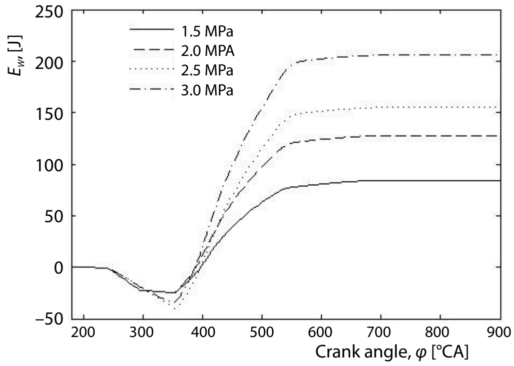

Figure 13. The E_W variation at different supply pressures

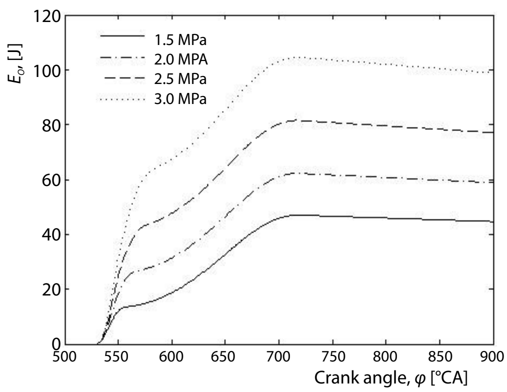

Figure 14. The E_O variation at different supply pressures

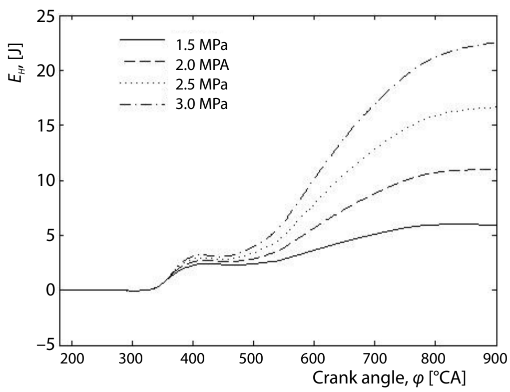

Figure 15. The E_H variation at different supply pressures

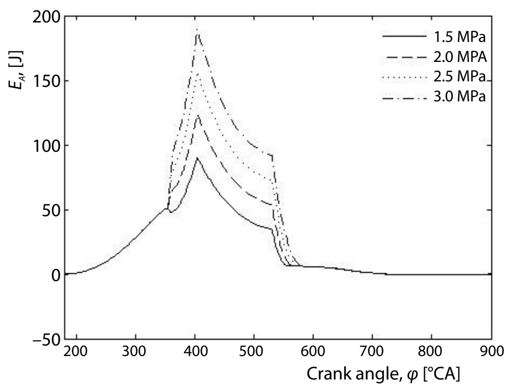

Figure 16. The E_A variation at different supply pressures

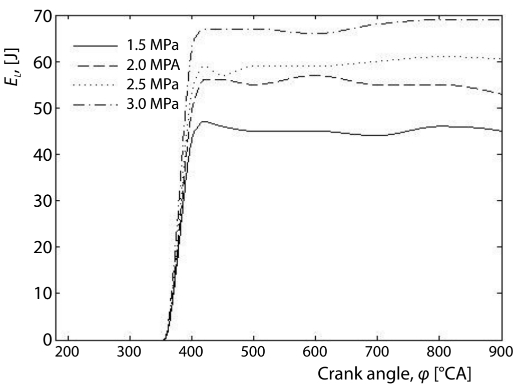

Figure 17. The E_L variation at different supply pressures

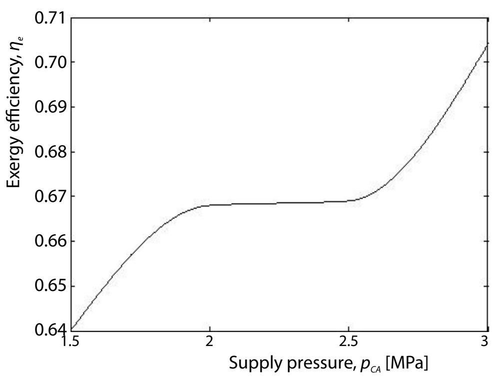

Figure 18. The η_e variation at different supply pressures

Influence of ambient temperature on exergy change

It can be observed that the influence of ambient temperature on the exergy is great from the calculation equations of the exergy change, so it is also necessary to analyze the influence of the ambient temperature T_0. In this simulation, keep other parameters fixed, the ambient temperature T_0 are set to 265 K, 280 K, and 300 K, respectively, then the relations of the exergy at different crank angles and the exergy efficiency are analyzed, the simulation results are shown in figs. 19-24.

As illustrated in these figures, the higher the ambient temperature T_0, the larger the exergy of the compressed air flowing into the cylinder E_{CA}, the more the energy can be used. That means the increase in ambient temperature T_0 can increase available energy of the compressed air, so better thermal conductivity material can be used in the CAE to keep warm to improve the ambient temperature. The E_W, E_H, E_L and η_e all increase with the increased T_0, but E_O decreases. In conclusion, the increase in the ambient temperature T_0 is beneficial to the effect of the exergy change. In the experiment, if conditions permit, the ambient temperature T_0 can be improved by taking effective measures, so as to improve the exergy of the compressed air and the exergy efficiency.

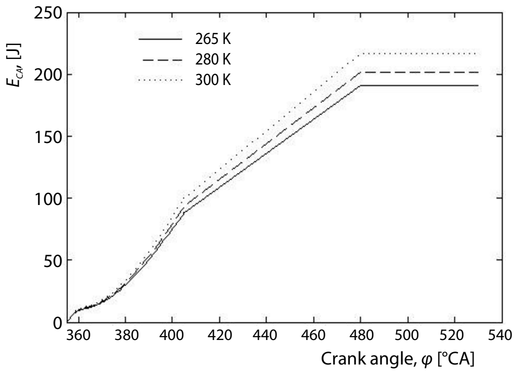

Figure 19. The E_{CA} variation at different ambient temperatures

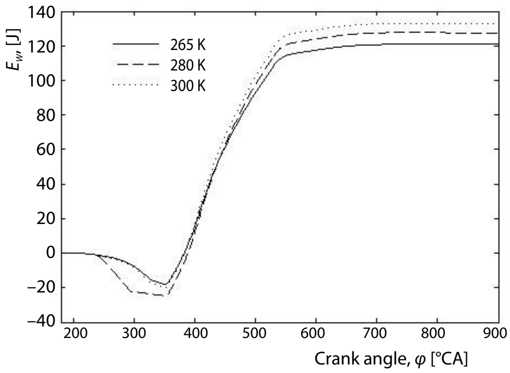

Figure 20. The E_W variation at different ambient temperatures

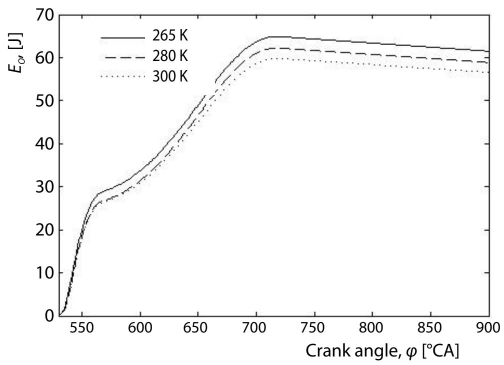

Figure 21. The E_O variation at different ambient temperatures

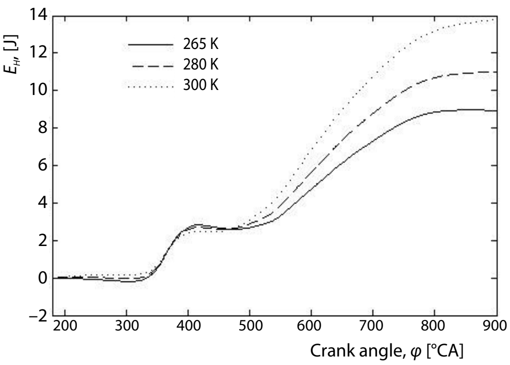

Figure 22. The E_H variation at different ambient temperatures

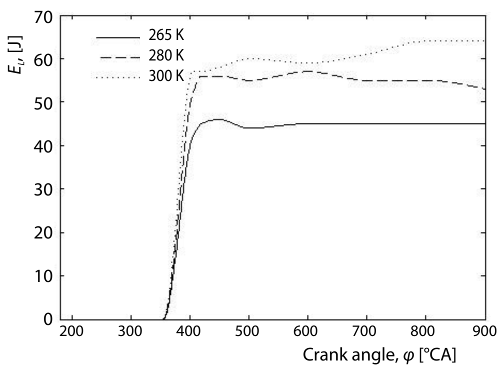

Figure 23. The E_L variation at different ambient temperatures

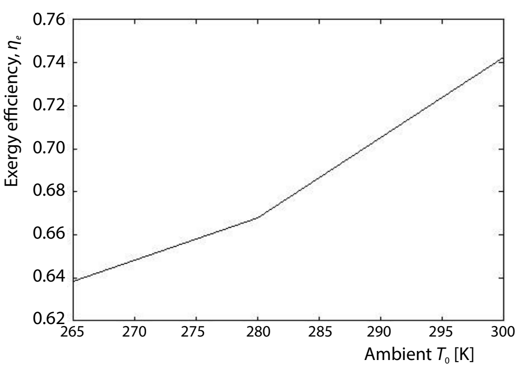

Figure 24. The η_e variation at different ambient temperatures

Conclusions

A theoretical exergy analysis model of the CAE is investigated, and exergy balance equations of the working process at different stages are put forward. Then exergy analyses on the influence of the working parameters are carried out. Some important conclusions can be drawn from the simulation analysis of the CAE. From what has been discussed above, we may safely arrive at the conclusions as follows.

- The exergy of the compressed air flowing into the cylinder E_{CA} and the exergy of the piston work E_W increase with decreasing rotational speed n, but E_{CA} and E_W increase with the increased the exergy of the compressed air flowing into the cylinder p_{CA} and the ambient temperature T_0. The exergy of the air flowing out of the cylinder during the exhaust stroke E_O increases with increasing n.
- The exergy of the system caused by heat transfer between the air and the cylinder walls E_H increases with the increased p_{CA} and T_0, but with the decreased n; the exergy loss caused by irreversibility E_L increases with the increased n, p_{CA}, and T_0.
- The increment of exergy of the system E_A and the exergy efficiency η_e increase with decreasing n or increasing p_{CA}. Moreover, η_e increases with increasing T_0.

Therefore, the working parameters have important influence on the exergy efficiency of the CAE, all these analyses of this paper will provide a theoretical basis for further study on optimizing design of the CAE.

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