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 analyzed via simulation. All the work can provide some helps for reducing exergy losses and optimizing the CAE exergy efficiency.

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:

\[ \frac{dE_{CA}}{d\phi} + \frac{dE_I}{d\phi} + \frac{dE_O}{d\phi} + \frac{dE_H}{d\phi} + \frac{dE_A}{d\phi} + \frac{dE_L}{d\phi} = \frac{dE_{ALEE}}{d\phi} \]  

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 \( \phi \) – 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:

\[ \frac{dE_{CA}}{d\phi} = \frac{dm_{CA}}{d\phi} R T_0 \ln \left( \frac{P_{CA}}{P_0} \right) \]  

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:

\[ \frac{dE_I}{d\phi} = \left( h_I - h_0 - T_0 (s_I - s_0) \right) \frac{dm_I}{d\phi} \]  

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:

\[ \frac{dE_O}{d\phi} = \left( h_E - h_0 - T_0 (s_E - s_0) \right) \frac{dm_E}{d\phi} \]  

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:

\[ \frac{dE_W}{d\phi} = (p - p_0) \frac{dV}{d\phi} \]  

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:

\[ \frac{dE_H}{d\phi} = \frac{dQ_\phi}{d\phi} \left( 1 - \frac{T_b}{T} \right) \]  

where \( Q_\phi \) is the heat absorbed by the air from the cylinder walls. The temperature \( T \) of the air in the cylinder is:
\[
\frac{dT}{d\phi} = \frac{1}{mc_v} \left( \frac{dQ_w}{d\phi} - p \frac{dV}{d\phi} + h_i \frac{dm}{d\phi} + h_{CAE} \frac{dm_{CAE}}{d\phi} - h_e \frac{dm}{d\phi} - u \frac{dm}{d\phi} \right) \tag{7}
\]

where \(c_v\) is the constant specific heat capacity, \(h_{CAE}\) – 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:

\[
\frac{dQ_w}{d\phi} = \frac{1}{\omega} \sum_{i=1}^{n} a_i(T_{wi} - T) \tag{8}
\]

where \(\omega\) is the angular speed of the crank shaft, \(a_i\) – 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:

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

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:

\[
\frac{dE_i}{d\phi} = [u - u_0 - T_0(s - s_0) + p_0(v - v_0)] \frac{dm}{d\phi} + m \left[ \frac{du}{d\phi} - T_0 \frac{ds}{d\phi} + p_0 \frac{dV}{d\phi} \right] \tag{10}
\]

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:

\[
\frac{dE_i}{d\phi} = [u - u_0 - T_0(s - s_0) + p_0(v - v_0)] \frac{dm}{d\phi} +
\]

\[+mc_v \left( 1 - \frac{T_0}{T} \right) \frac{dT}{d\phi} + \frac{mTR}{V} \frac{dV}{d\phi} \tag{12}
\]

**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:

\[
\frac{dE_{ix}}{d\phi} + \frac{dE_{iu}}{d\phi} + \frac{dE_i}{d\phi} + \frac{dE_{i}}{d\phi} = 0 \tag{13}
\]

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

$$\frac{dE_{\text{ex}}}{d\phi} = \frac{dE_{\text{w}}}{d\phi} + \frac{dE_{\text{h}}}{d\phi} + \frac{dE_{\text{i}}}{d\phi} + \frac{dE_{\text{l}}}{d\phi}$$

(15)

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

$$\frac{dE_{\text{L}}}{d\phi} = \frac{dm_{\text{CAE}}}{d\phi} RT_0 \ln \left( \frac{p_{\text{CAE}}}{p_0} \right) - \frac{dQ_{\text{ex}}}{d\phi} \left( 1 - \frac{T_0}{T} \right) - \left( p - \frac{mT_0R}{V} \right) \frac{dV}{d\phi} -$$

$$- \left[ u - u_0 - T_0(s - s_0) + p_0(v - v_0) \right] \frac{dm}{d\phi} + mc_r \left( 1 - \frac{T_0}{T} \right) \frac{dT}{d\phi} + \left( p_0 - \frac{mT_0R}{V} \right) \frac{dV}{d\phi}$$

(16)

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:

$$\frac{dE_{\text{ex}}}{d\phi} + \frac{dE_{\text{h}}}{d\phi} + \frac{dE_{\text{i}}}{d\phi} + \frac{dE_{\text{l}}}{d\phi} = 0$$

(17)

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

$$\frac{dE_{\text{L}}}{d\phi} = - (mc_r \frac{dT}{d\phi} + \frac{dQ_{\text{ex}}}{d\phi} \left( 1 - \frac{T_0}{T} \right) - \left( p - \frac{mT_0R}{V} \right) \frac{dV}{d\phi})$$

(18)

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:

$$\frac{dE_{\text{ex}}}{d\phi} + \frac{dE_{\text{w}}}{d\phi} + \frac{dE_{\text{h}}}{d\phi} + \frac{dE_{\text{i}}}{d\phi} + \frac{dE_{\text{l}}}{d\phi} = 0$$

(19)

and \( \frac{dE_{\text{i}}}{d\phi} \) can be written:

$$\frac{dE_{\text{i}}}{d\phi} = - \left[ h - h_0 - 2T_0 \left( c_p \ln \frac{T}{T_0} - R \ln \frac{p}{p_0} \right) + u - u_0 + p_0(v - v_0) \right] \frac{dm}{d\phi}$$

$$- mc_r \left( 1 - \frac{T_0}{T} \right) \frac{dT}{d\phi} - \frac{dQ_{\text{ex}}}{d\phi} \left( 1 - \frac{T_0}{T} \right) - \left( p - \frac{mT_0R}{V} \right) \frac{dV}{d\phi}$$

(20)
During the intake stage, the intake valves are opened and the exhaust valves are closed, and the exergy balance equation can be expressed:

\[
\frac{dE_i}{d\phi} = \frac{dE_H}{d\phi} + \frac{dE_L}{d\phi} + \frac{dE_T}{d\phi} + \frac{dE_I}{d\phi}
\]  

\( (21) \)

and \( \frac{dE_i}{d\phi} \) can be written:

\[
\frac{dE_i}{d\phi} = -\left( mc_v \frac{dT}{d\phi} + \frac{dQ}{d\phi} \right) \left( \frac{1}{T} - \frac{1}{T_0} \right) - \left( \rho - m \frac{T R}{V} \right) \frac{dV}{d\phi}
\]  

\( (22) \)

**Exergy efficiency**

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

\[
\eta = \frac{E_A + E_W + E_H}{E_{CA} + E_I} = 1 - \frac{E_A + E_L}{E_{CA} + E_I}
\]  

\( (23) \)

**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>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of the cylinder, [mm]</td>
<td>D = 69.5</td>
</tr>
<tr>
<td>Stroke of the piston, [mm]</td>
<td>S = 79.5</td>
</tr>
<tr>
<td>Ratio of crank radius to connecting rod</td>
<td>( \lambda = 0.32 )</td>
</tr>
<tr>
<td>Compression ratio</td>
<td>( \varepsilon = 9.8 )</td>
</tr>
<tr>
<td>Radius of the crank, [mm]</td>
<td>( r = 39 )</td>
</tr>
<tr>
<td>Ambient pressure, [MPa]</td>
<td>0.101</td>
</tr>
<tr>
<td>Diameter of the intake valve, [mm]</td>
<td>25</td>
</tr>
<tr>
<td>Diameter of the exhaust valve, [mm]</td>
<td>20</td>
</tr>
</tbody>
</table>

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. After slowly entering the inflatable expansion stage, \( E_i \) increases gradually, and its value fluctuates little at other stages.

Figure 3 shows the exergy of the system and proportion, and the exergy efficiency \( \eta_e \) can be calculated, \( \eta_e = 66.8\% \). It is clear that the ratio of \( E_O \) to \( E_{ci} \) is 25.9\%, that means reducing the exergy loss of exhaust can be beneficial in improving exergy efficiency \( \eta_e \). In addition, \( E_B \) has the highest proportion. And compared with \( E_H \), \( E_i \), 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.

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. \( E_{ci}, E_w, E_{str} \) and \( E_i \) 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 \( \eta_e \) 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 \( \eta_e \) 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 \( E_R \) and \( E_L \), so that leads to the lower \( \eta_e \). 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 \( E_I \) variation at 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 $\eta_e$ 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.
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 $E_W$, $E_{th}$, $E_L$ and $\eta_e$ 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 $E_W$ variation at different ambient temperatures](image1)

![Figure 20. The $E_{th}$ variation at different ambient temperatures](image2)

![Figure 21. The $E_L$ variation at different ambient temperatures](image3)

![Figure 22. The $E_O$ variation at different ambient temperatures](image4)

![Figure 23. The $E_{th}$ variation at different ambient temperatures](image5)

![Figure 24. The $\eta_e$ variation at different ambient temperatures](image6)
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 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 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 $E_s$ and the exergy efficiency $\eta$ increase with decreasing $n$ or increasing $p_{CA}$. Moreover, $\eta$ 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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