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Exergy Analysis of Ideal Thermodynamic Cycle for the Four Stroke Free Piston Engine (FPE)

Ningxia Yin*[+1], Siqin Chang[+], Zhaoping Xu[+] and Jiming Lin[+]

Abstract – A novel thermodynamic cycle of four-stroke free piston engine (FPE) is proposed in this presentation. Combining with lengthened expansion and exhaust stroke, the shortened intake stroke and compression stroke are supplemented with supercharger and intercooler. The thermodynamic cycle simulation of free piston engine is extended to perform the exergy analysis. In order to demonstrate the advantage of FPE, the results of FPE are compared with the conventional Otto cycle engine. Exergetic terms such as exergy transfer with work, exergy transfer with heat, irreversibility, fuel chemical exergy and total exergy of the cycle, are computed based on principles of the second law. Exergy analysis shows that compression ratio and expansion ratio have considerably affected the second law efficiency. With the increasing of compression ratio, supercharge ratio and expansion ratio, the second-law efficiency is remarkably increased. Furthermore, under the same compression end pressure, the larger supercharge ratio is more favorable than the larger compression ratio, because it can not only increase the exergy efficiency, but also improve the output power.

Keywords – Exergy analysis, free piston engine, four stroke, ideal cycle, second law of thermodynamics.

1. INTRODUCTION

The increasing focus on the environmental impacts of hydrocarbon fuel based on power generation has led to increased research efforts into FPE, which has been canceled the limit of the connecting rod. The potential advantages of FPE consist of variable compression ratio and expansion ratio, possible multi-fuel operation, small friction *etc.* [1]-[4]. In order to make the analysis of FPE much more manageable, ideal cycles are used to describe the major processes that occur in the internal combustion engines. In ideal air standard cycle, the air is treated as ideal gas; the fuel is completely mixed with air at beginning of the compression process, while blow-by is neglected. According to the first-law, the efficiency of FPE is higher than that of the Otto engine, but the results of first-law analysis are based on the fact that energy is conserved in every device and process, and it does not explicitly penalize the system for internal irreversibility of the thermodynamic process. Exergy analysis is a significant tool for evaluating the novel engine concepts [5], [6]. Compared with the first law, the second law of thermodynamics provides different perspectives, and provides the property exergy. Exergy is a measure of the work potential of energy from a given thermodynamic state [7], [8]. Following these differences and concerning the various trade-offs of engine operation and design, more informed decisions may be obtained. Furthermore, a more comprehensive evaluation of novel and unique engine concept can be made. For the second law analysis of the conventional engine combustion, there have been more detailed discussions [9]-[13].

This study described in this paper provides data on the effect of compression ratio, expansion ratio, supercharge ratio, and excess air coefficient on the performance of a spark ignition engine operating on natural gas. For this study and those data provision, an analytical model is established. These data help in the better understanding of the interaction between engine performance and such parameters, which will also provide engine designers with assistance while designing for four stroke free piston natural gas engine.

2. PHYSICO-MATHEMATICAL MODEL OF FPE

2.1 Physical Model of FPE

The single piston, four-stroke free piston engine is illustrated in Figure 1. The main parts of the engine are composed of a compressor, an intercooler, a combustion cylinder and a linear electric machine. After compressed by the compressor, the air is cooled in the intercooler, and then sucked into the cylinder. The piston movement, the energy conversion and transfer can be controlled by adjusting the magnitude and direction of the electromagnetic force. The physical and thermodynamic models of the free piston are respectively established.

2.2 Thermodynamic Model of the Free Piston

A novel thermodynamic cycle for a four-stroke free piston engine has been established. The P-v diagrams of Otto cycle and FPE cycle are shown in Figure 2. The main differences between the two cycles in Figure 2a and 2b are at the expansion process and the charge air system. Conventional Otto cycle expansion stroke is equal to compression stroke and it does not have supercharging system. The process between 1 and 2 is isentropic compression by the piston; process 2-3 is isochoric heating process; process 3-4 is isentropic

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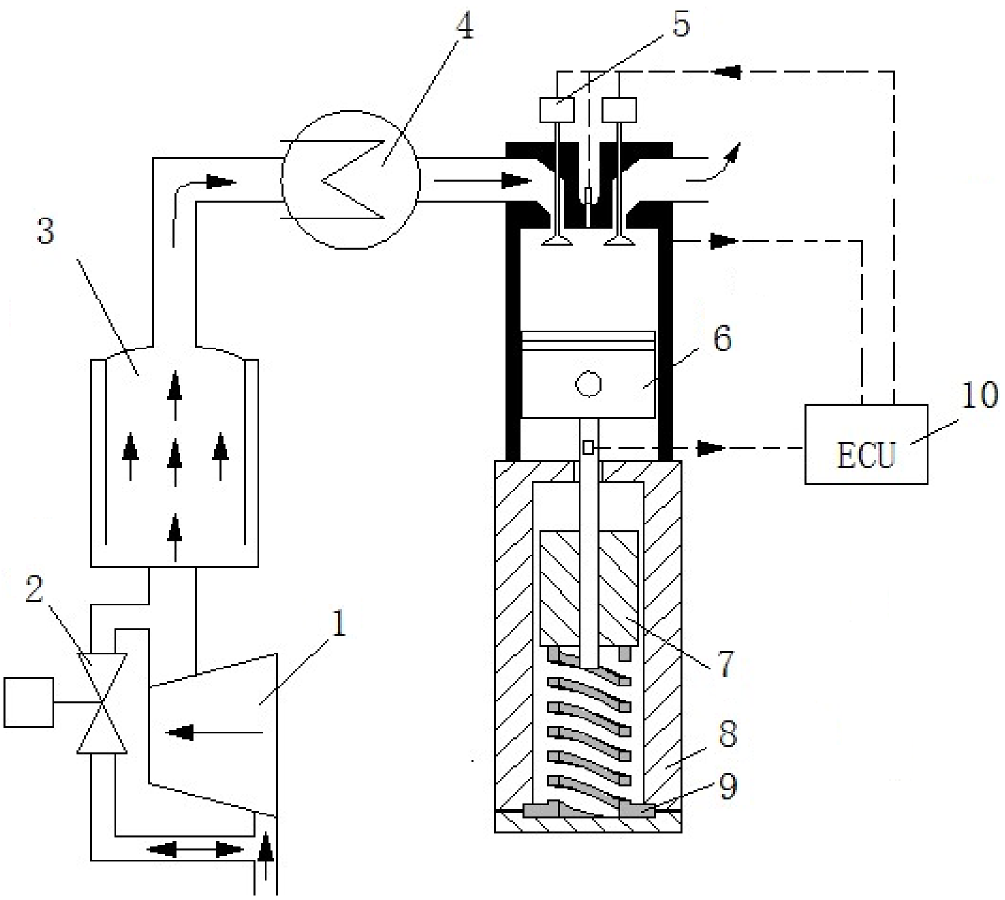
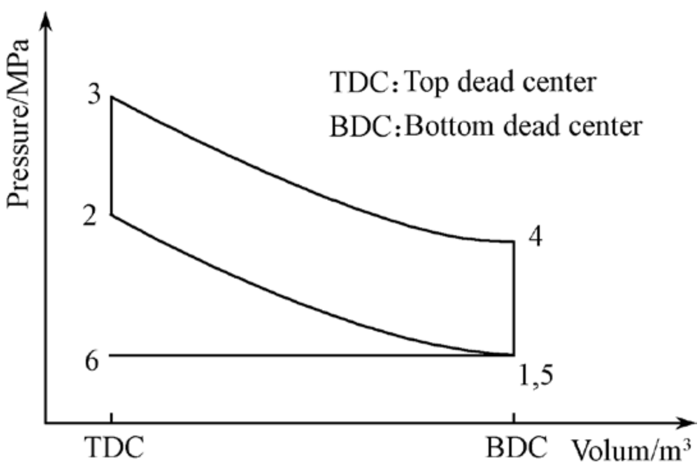
expansion process; process 4-5 is isochoric cooling process; process 5-6 is isobaric cooling process with the exhaust valve open; the process 6-1 (in Figure 2a) or the process 7-1 (in Figure 2b) is isobaric process. While in Free piston engine cycle, process 6'-7' in Figure 1b is one independent compressed process outside the cylinder. Then compressed and heated air enters into intercooler (processes 7'-7) and passes through the cylinder in free piston engine cycle (Figure 2b). Compared with the conventional four-stroke engine, the remarkable characteristic of the four-stroke free piston engine is the variability of intake stroke length, compression ratio, and expansion ratio and motion law of the piston. The shorten intake stroke and compression stroke supplemented with turbocharger and intercooler, and the prolonged expansion stroke and exhaust stroke realized fully expansion.

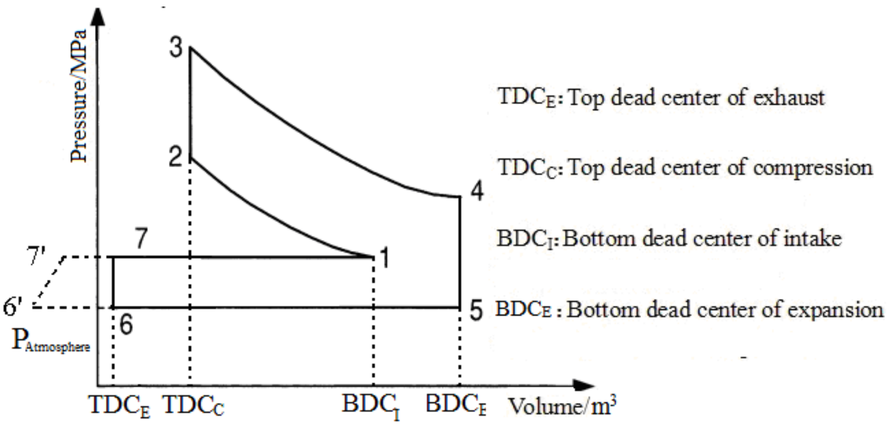


1. compressor, 2. pressure regulating valve, 3. stable pressure box, 4. thermostat, 5. electromagnetic valves, 6. free piston, 7. mover of the linear electric machine, 8. stator of the linear electric machine, 9. spring, 10. electronic control unit.

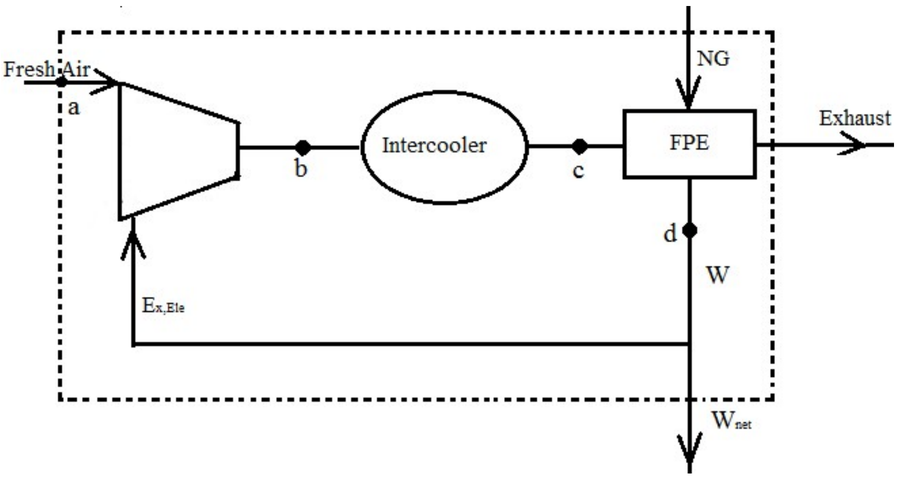
Fig. 1. The proposed system showing the components.



a) Otto cycle.



b) FPE cycle.



c) FPE Exergy calculation model.

Fig. 2. Thermodynamic model.

3. EXERGY ANALYSIS OF THE THERMODYNAMIC PROCESS FOR FPE

Irreversibility values of the mentioned systems were investigated by analytical models which developed from second law of thermodynamics. The exergy balance equation is implemented to FPE. In current study, different parameters affecting cycle performance and network output is considered.

3.1 Exergy Value of the Fuel

In an engine, the input exergy is contained in its chemical availability of fuel. The exergy content of a material represents its potential to do work, and the exergy of the natural gas can be defined as follows [9].

$$E_{x,\,fuel} = 1.06\,LHV \tag{1}$$

Since the overall engine operation includes both closed system and open system portions, two forms of availability are needed.

3.2 Availability of the Subsystems

3.2.1 Compressor Subsystem

The gas compressor is driven by electric motor and the compression, which can be simplified as adiabatic compression. The exergy at the inlet of compressor is 0. So the exergy lost in the compressor is as follows.

$$E_{x,L,Compressor} = m_{air} T_0 \left(c_p \ln \frac{T_{7'}}{T_{6'}} - R_g \ln \pi \right) \tag{2}$$

The work cost in the compressor is defined as follow.

$$\begin{aligned} W_{Compressor} &= h_{7'} - h_{6'} \\ &= m_{air} c_p (T_{7'} - T_{6'}) \end{aligned} \tag{3}$$

$$p_{6'} = p_{atm} \tag{4}$$

$$p_{7'} = p_{6'} \pi_c = p_{atm} \pi_c \tag{5}$$

$$T_{7'} = T_{6'} \left(\frac{P_{7'}}{p_{atm}} \right)^{(k-1)/k} = T_{atm} \pi_c^{\,(k-1)/k} \tag{6}$$

3.2.2 Intercooler Subsystem

The air is cooled to the temperature T_7, which is the state required at the beginning of FPE cycle. The available changing in the intercooler (Figure 2c) can be evaluated as follow.

$$E_{x,L,Intercooler} = E_{x,b} - E_{x,c} = m_{air}\{(h_b - h_0) - T_0(s_b - s_0) - [(h_c - h_0) - T_0(s_c - s_0)]\} = m_{air}\left[c_p(T_{7'} - T_7) - T_0\left(c_p \ln\frac{T_{7'}}{T_7} - R_g \ln\frac{p_{7'}}{p_7}\right)\right] \quad (7)$$

3.2.3 The Cylinder Subsystem

The exergy loss analysis of the process in the cylinder of FPE is the same as that of in the Otto engine. The only difference between them is the states of the points dissimilar. In the ideal cycle, there is no exergy loss in the process of intake and exhaust , and therefore the heat transfer is neglected.

The compression and expansion processes can be simplified as isentropic compression process and isentropic expansion process respectively, so there is no transition entropy in these two processes. The exergy balance equation of the cylinder (Figure 2c) is as follow.

$$E_{x,L,Cylinder} = E_{x,fuel} + E_{in} - E_{out} - E_W = E_{x,fuel} + E_1 - E_4 - E_W \quad (8)$$

$$E_1 = m_{air}\left[(h_1 - h_0) - T_0(s_1 - s_0)\right] \quad (9)$$

$$E_W = m_{air}\left[1 + (F/A)\right]c_p(T_3 - T_4) - m_{air}\left[1 + (F/A)\right]c_p(T_2 - T_1) \quad (10)$$

$$T_2 = \varepsilon^{k-1}T_1 \quad (11)$$

$$p_2 = \varepsilon^k p_1 \quad (12)$$

$$T_4 = \left(\frac{1}{\lambda}\right)^{k-1} T_3 \quad (13)$$

$$p_4 = \left(\frac{1}{\lambda}\right)^{k} p_3 \quad (14)$$

The combustion process is analyzed under an assumption of constant volume and adiabatic system. The exergy loss contains $E_{x,LN}$ and $E_{x,LA}$. $E_{x,LN}$ is the exergy loss which is created for the irreversible combustion. It will be produced when $E_{x,LA}$ is the exergy loss produced for the incomplete combustion, or be zero while the fuel can be adequately burned up. In the ideal cycle, the fuel is supposed to be burned up, so is the only exergy loss in the ideal cycle combustion.

$$E_{x,L,Combustion} = m_{air}T_0[1 + (F/A)]\left(c_p \ln\frac{T_3}{T_2} - R_g \ln\frac{p_3}{p_2}\right) \quad (15)$$

The exergy lost in the exhaust procedure $E_{x,L,Exhaust}$ can be calculated as follow.

$$E_{x,L,Exhaust} = (h_4 - h_0) - T_0(s_4 - s_0) = m_{air}(1 + F/A)c_p(T_4 - T_0) - m_{air}(1 + F/A)T_0\left(c_p \ln\frac{T_4}{T_0} - R_g \ln\frac{p_4}{p_0}\right) \quad (16)$$

3.2 Exergy Efficiency

The efficiency is defined to compare different cycle engines and evaluate various improvements effects. From the classical energy method, the exergy can be given the ratio of net exergy extracted for intended use to the fuel exergy input [14], [15].

$$\eta_{ex,Free} = \frac{E_{gain}}{E_{pay}} = \frac{m_f \cdot E_{x,fuel} - E_{x,L,Compressor} - E_{x,L,Intercooler}}{m_f \cdot E_{x,fuel}} \frac{-E_{x,L,Cylinder} - E_{x,L,Exhaust}}{m_f \cdot E_{x,fuel}} \quad (17)$$

4. DISCUSSIONS

4.1 Engine Specification

In order to validate the presented FPE (Figure 2b), the predicted values are compared with the values of Otto cycle engine that described in Figure 2a. The engine specifications are given in Table 1. A set of thermodynamic parameters during the free piston engine work is shown in Table 2.

Table 1. Engine specifications.

Item	Value
Engine type	Four stroke
Number of cylinder	1
Bore/mm	62
Stoichiometric air to fuel ratio	17.2
Maximum stroke length/mm	75

Table 2. Parameter data for the cylinder.

Item	Value
Indicated Power/kW	2
LHV/(J/kg)	50 200 000
Mass of fuel per cycle/kg	0.0001696
Mass of exhaust per cycle/kg	0.0030876
Expansion end temperature/K	1031.3
Expansion end pressure /MPa	0.2536

4.2 Influence of Compression Ratio (CR)

The thermal efficiency is improved with the increase of the CR. The improvement in the exergy efficiency is attributed to the improvement of the combustion process with the increasing of CR. Figure 3 shows the relationship between exergy efficiency and compression ratio changes at optimum spark timing and stoichiometric. Because of the increase in the maximum temperature inside the cylinder, so the exergy efficiency increases can increase as the CR increases.

The importance of CR and expansion ratio(ER) for conventional, reciprocating, internal combustion engines has been recognized from the very beginning of engine development. A large number of literatures have been published show that exergy efficiency is a function of CR, to a lesser extent, of ER. It is known that thermodynamic efficiency can be improved by the increment of CR and ER, but this improvement is limited by knock as well. The current work is a detail study that describes the effects of CR and ER on engine performance from the second law perspective.

4.3 Influence of ER

For FPE, not only the ER is alterable, but the expansion process is also longer than the compression process throughout. So it becomes most noticeable performance of FPE. As one of the major alternatives of the Otto engine, through prolonged the expansion process relative to the compression, FPE has been examined to determine its potential for increased efficiency and network in the spark ignited internal combustion engine. Compared with FPE and Otto cycle engine, Figure 4 shows the relationship between expansion ratio and exergy efficiency at the same compression end pressure. In FPE, the length of expansion stroke is greater than that of the compression stroke, and it hence improves cycle efficiency. Moreover, it is getting higher and higher in exergy efficiency along with the increase of ER. In other words, by applying FPE cycle, the CR can be kept to a level that prevents knocking, while keeping the expansion ratio at a high level to ensure high efficiency.

Affecting combustion irreversibility through its effect on gas temperature and pressure The ER plays a significant role in second-law balances. Figure 5 shows that the bulk gas temperatures and pressures during exhaust of cylinder are much lower in FPE. The lower temperatures are a consequence of the lower irreversibility, and it has the advantage of increasing the exergy efficiency.

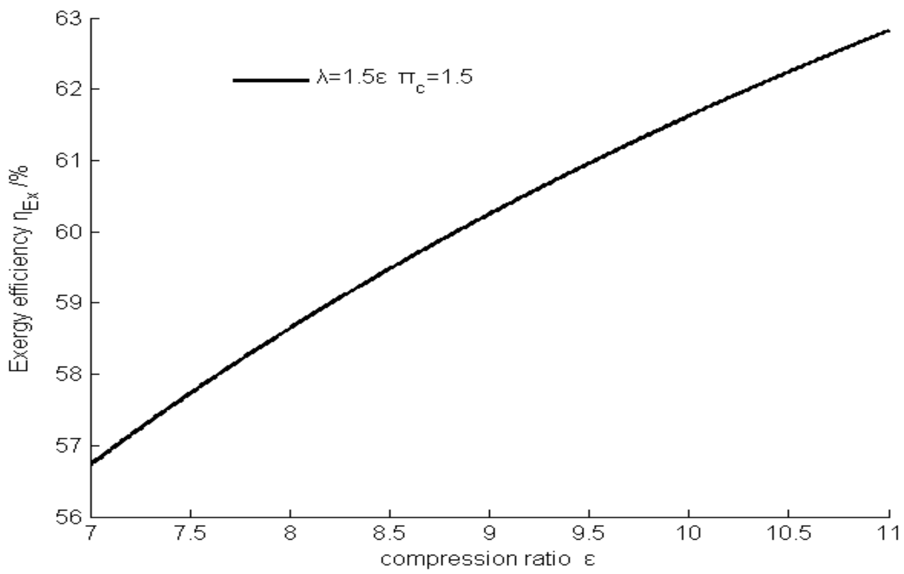


Fig. 3. Effects of compression ratio to exergy efficiency.

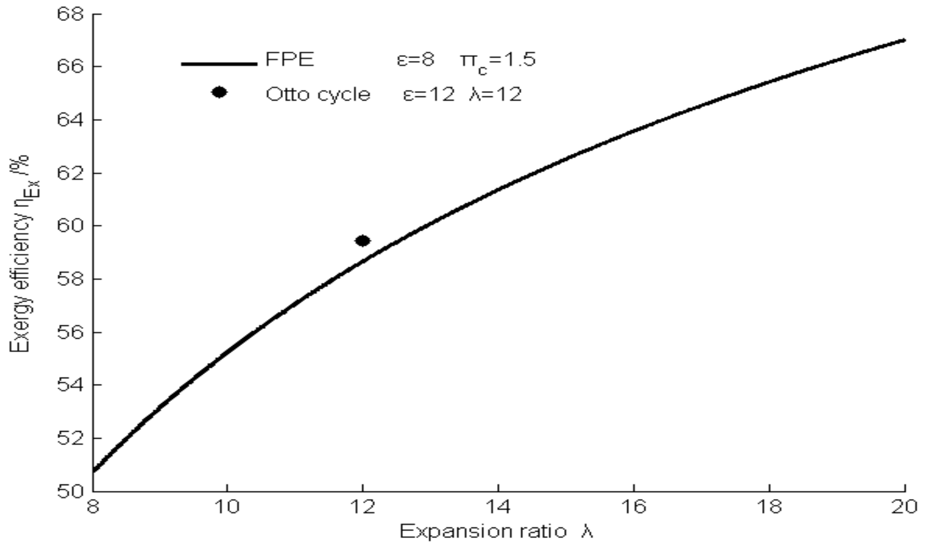


Fig. 4. Effects of expansion ratio to exergy efficiency.

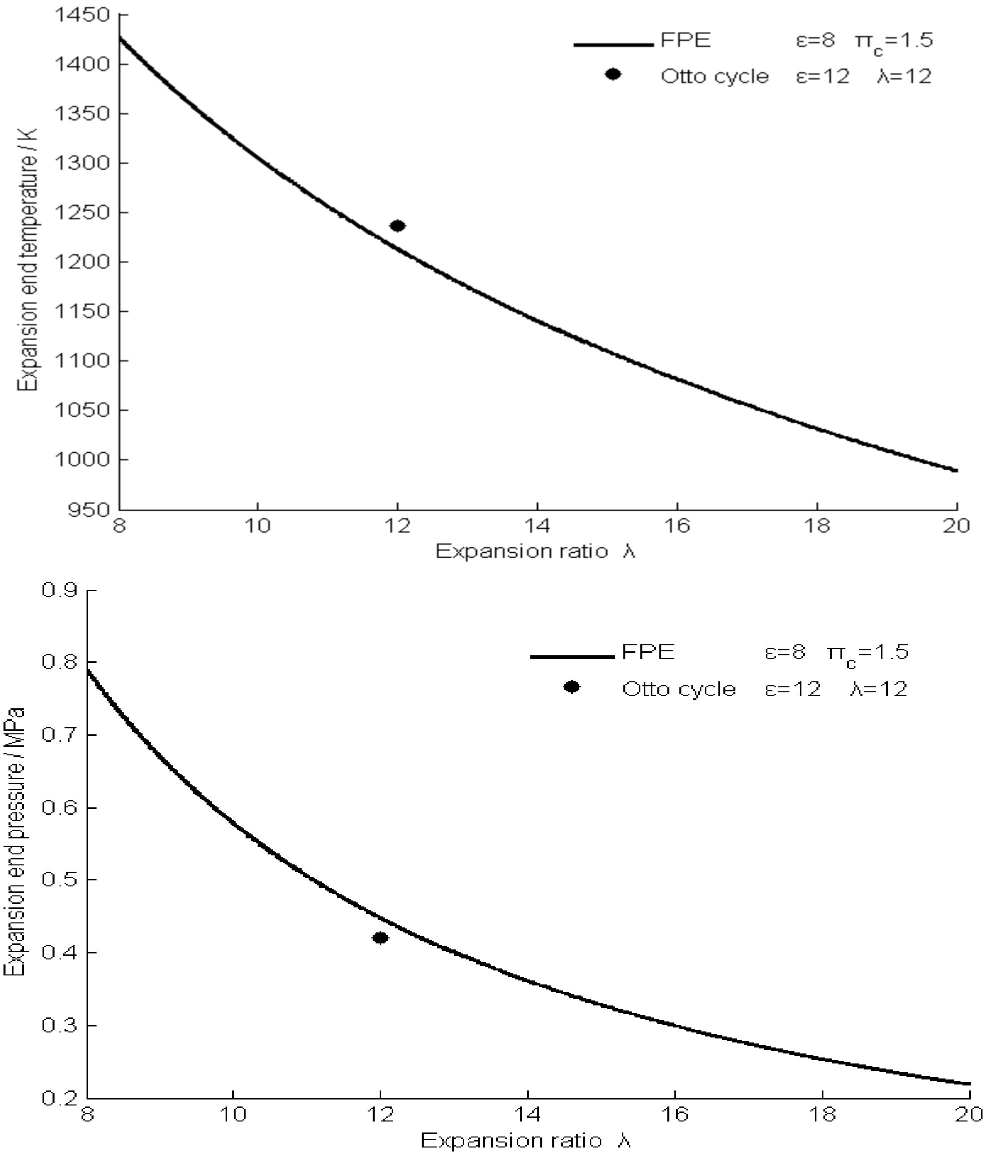


Fig. 5. Effects of expansion ratio to expansion end temperature and pressure.

4.4 Influence of Supercharge Ratio

Supercharging, utilized in order to increase engine power, on the other hand, proves a favorable second-law process which increasing the amount of the fresh gas [14], [15]. Although the combustion exergy loss decreases with the increasing of supercharging ratio, the increases of mechanical exergy loss, so the supercharging ratio hardly influence the exergy efficiency only when the exhaust exergy entered into the turbine can drive the compressor.

In order to prevent knocking, a suitable cylinder pressure is necessary before knocking. Comparison of the compression outside of cylinder impact on work, the compression end pressure and expansion end pressure keep constant (the pressure is the state of $\pi_c = 1.5$, $\varepsilon = 8$, $\lambda = 18$). The effects of supercharge ratio on exergy efficiency are depicted in Figure 6. In order to keep the compression end pressure constant, the compressor ratio need decrease with the supercharge ratio increasing. And the expansion ratio increases so as to remain the same expansion end pressure. As predicted, while the supercharge ratio increases, the exergy efficiency also increases. So only if the FPE can spark normally, the compression outside of the cylinder is beneficial to the exergy efficiency of FPE.

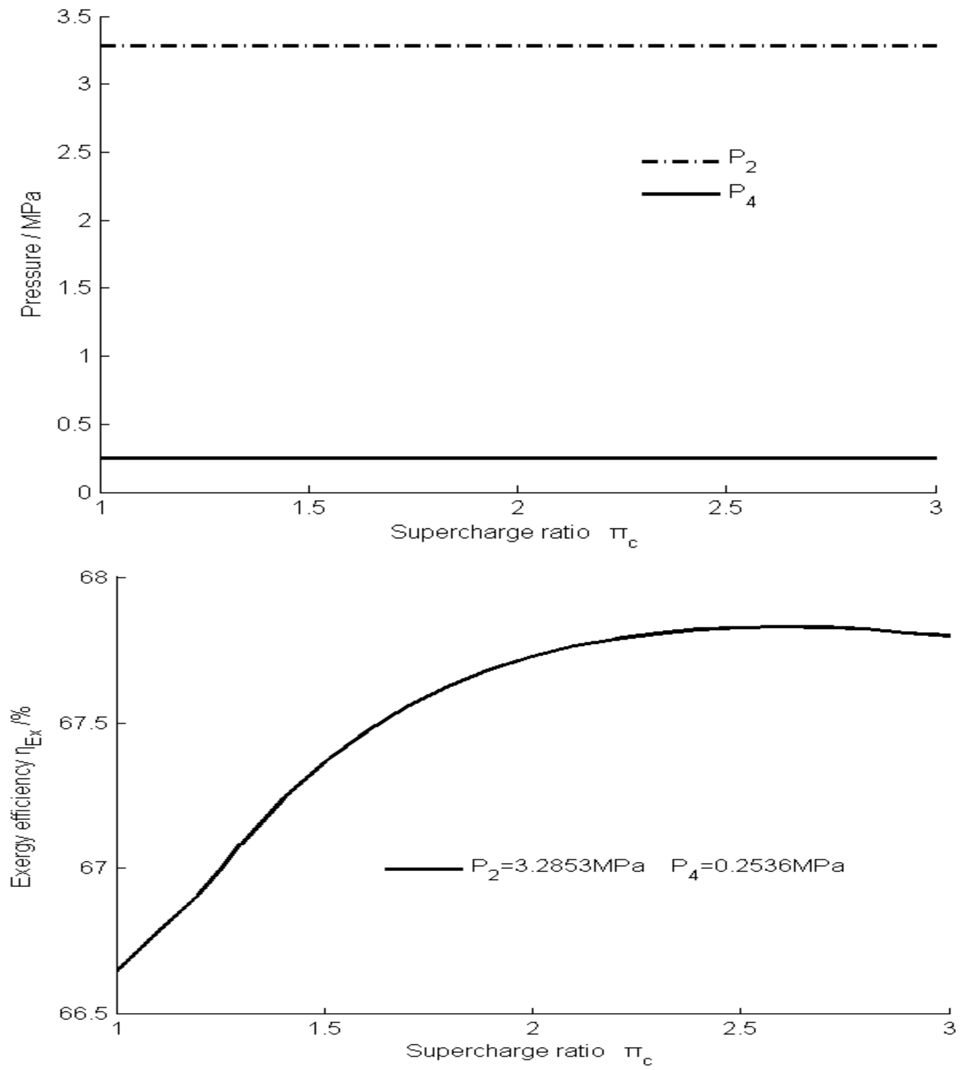


Fig. 6. Effect of supercharging to exergy efficiency.

4.5 The Influence of Air-Fuel Ratio

As can be seen from Figure 7, the composition of the air-fuel ratio influences the rate of the combustion and the amount of heat releases. Rich mixture results in incomplete combustion and part of the fuel chemistry exergy can't be fully released. Excess air flow into the engine and dilute the charge, so lower temperature is achieved at higher relative air-fuel ratio. Therefore only if the mixture is close or at stoichimetric, then the exergy efficiency is relatively higher and the conversion of chemical potential to work is more effective.

The exergy analysis results (the calculated exergy losses of free piston engine and Otto engine are all based on 1kg fuel.) shown in Table 3 indicate that the free piston engine exergy efficiency is higher than the Otto cycle engine.

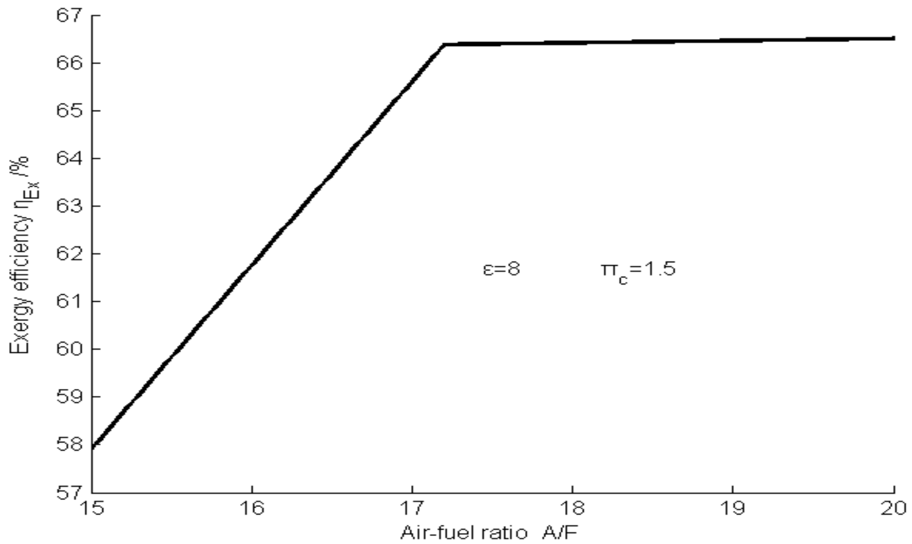


Fig. 7. Effects of air-fuel ratio to exergy efficiency.

Table 3a. Free piston engine cycle exergy analysis and calculation ($\pi_c = 1.5, \varepsilon = 8, \lambda = 18, A/F = 17.2$).

Item	Value
Compressor exergy loss/kJ	153.9
Intercooler exergy loss /kJ	9.2296
Cylinder exergy loss /kJ	755.4236
Exhaust exergy loss/ kJ	1294.8
Cycle exergy efficiency /%	65.4174

Table 3b. Otto cycle exergy analysis and calculation ($\varepsilon = 12, \lambda = 12, A/F = 17.2$ **).**

Item	Value
Compressor exergy loss/ kJ	0
Intercooler exergy loss / kJ	0
Cylinder exergy loss / kJ	739.9059
Exhaust exergy loss/ kJ	1863.7
Cycle exergy efficiency /%	59.4418

5. CONCLUSIONS

In this paper, a novel thermodynamic cycle for a four-stroke free piston engine is analyzed. The shorten intake stroke and compression stroke supplemented with turbocharger and intercooler. The prolonged expansion stroke and exhaust stroke realized fully expansion. With parametrical studying on the effect of main operating parameters such as the compression ratio, expansion ratio, supercharge ratio and air-fuel ratio, The comparative second-law analysis of the previous researchers is fully implemented to FPE, which can serve as a significant guide towards a better understanding of FPE processes.

1) For those parameters can increase the level of maximum pressures and temperatures of the cylinder, compression ratio increasing, stoichiometric air-fuel ratio, etc., they lead to a reduction in the combustion irreversibility.

2) In FPE, the expansion stroke is greater than the compression process, which can decrease the expansion temperature and improve cycle exergy efficiency.

3) CNG has a greater potential to convert initial fuel availability to do useful work, and the compression ratio can be increased by taking advantage of its higher octane number rating.

4) If the compression end temperature and the expansion end pressure are kept constant, the compression ratio can help the engine to burn normally; the expansion ratio help the engine holding the same power capability, then the bigger supercharge ratio is more useful than the bigger compression ratio. Once the

exergy is added, what we care more about is that the output power is further improved. Consequently, the independent compression outside of the cylinder is favorable.

NOMENCLATURE

c_p	specific heat under constant pressure ($J / kg \cdot K$)
E_x	exergy efficiency (J)
LHV	low heating value (J/kg)
m	mass (kg)
T	absolute temperature (K)
R_g	specific gas constant ($J / kg \cdot K$)
W	work (J)
p	pressure (MPa)

Greek symbols

π_c	supercharge ratio
ε	compression ratio
λ	expansion ratio

Subscripts

0	restricted dead state
1	intake end
2	compression end
3	combustion end
4	expansion end
5	isochoric exhaust end
6	isobaric exhaust end
6'	initial conditions
7'	compressor outlet
7	intercooler outlet
a	compressor inlet
b	intercooler inlet
c	cylinder inlet

Abbreviation

A/F	air-fuel ratio
CR	compression ratio
ER	expansion ratio
NG	natural gas

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