Theoretical study of combustion efficiency in an Otto engine

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Abstract: Multi-irreversibilities, mainly resulting from the adiabatic processes, finite-time processes and heat transfer loss, are considered in the cycle model of an Otto heat engine. The relations between the power output and the compression ratio, between the thermal efficiency and the compression ratio, and the optimal relation between power output and the efficiency of the cycles are derived. The performance characteristic curves of the cycle are presented. Moreover, the effects of combustion efficiency on the cycle performance are analyzed. The results show that the effect of the combustion efficiency on the cycle performance is significant. The results obtained may provide a theoretical basis for both the optimal design and operation of real Otto heat engines. [Journal of American Science 2010;6(2):113-116]. (ISSN: 1545-1003).

Key words: combustion efficiency; Otto cycle; internal irreversibility; performance

1. Introduction

A study of gas cycles as the models of internal combustion engines is useful for illustrating some of the important parameters influencing engine performance. In the last two decades, by using finite time thermodynamics theory, many optimization studies based on various performance criteria have been carried out for endoreversible and irreversible heat engine models (Chen et al., 2008; Ge et al., 2008a; Ebrahimi, 2009a). Mozurkewich and Berry (1982) used mathematical techniques, developed in optimal-control theory, to reveal the optimal motions of the pistons in Otto cycle engines. Leff (1987) showed that some model engines (e.g., Otto, Diesel, Joule-Brayton, and Atkinson), operating reversibly without any loss at maximum work output per cycle, have efficiencies equal to, or well approximated by, the Novikov–Chambadal–Curzon–Ahlborn (NCCA) efficiency. Wu and Blank (1993) also optimized the endoreversible Otto cycle with respect to both net power output and mean effective pressure. Orlov and Berry (1993) deduced the power and efficiency upper limits for internal-combustion engines. Bera and Bandyopadhyay (1998) studied the effect of combustion on the thermoeconomic performances of Otto and Joule–Brayton engines. Gonzalez et al. (2000) derived the maximum irreversible work and efficiency of the Otto cycle by considering the irreversible adiabatic processes with the compression and expansion efficiencies. Fischer and Hoffman (2004) concluded that a quantitative simulation of an Otto-engine's behavior can be accurately achieved by a simple Novikov model with heat leaks. Chen et al. (2003, 2004) determined the characteristics of power and efficiency for Otto and Dual cycles with heat transfer and friction losses. Ozsoysal (2006) gave the valid ranges of the heat transfer loss parameters of the Otto and diesel cycles with consideration of the heat loss as a percentage of the fuel's energy. Hou (2007) compared the performances of air standard Atkinson and Otto cycles with heat transfer loss considerations. Ge et al. (2008a; 2008b; 2009) analyzed the performance of an air standard Otto, Diesel and dual cycles. In the irreversible cycle model, the non-linear relation between the specific heat of the working fluid and its temperature, the friction loss computed according to the mean velocity of the piston, the internal irreversibility described by using the compression and expansion efficiencies, and the heat transfer loss are considered.

As can be seen in the relevant literature, the investigation of the effect of combustion efficiency on performance of Otto cycle does not appear to have been published. Therefore, the objective of this study is to examine the effect of combustion efficiency on performance of air standard Otto cycle.

2. An air standard Otto cycle model

An air-standard Otto cycle model is shown in Fig. 1. Process $1 \rightarrow 2s$ is a reversible adiabatic compression, while process $1 \rightarrow 2$ is an irreversible adiabatic process that takes into account the internal irreversibility in the real compression process. The heat addition is an isochoric process $2 \rightarrow 3$. Process $3 \rightarrow 4s$ is a reversible adiabatic expansion, while $3 \rightarrow 4$ is an irreversible adiabatic process that takes into account the internal irreversibility in the real expansion process. The heat rejection is an isochoric process $4 \rightarrow 1$. The total reversible power output per second is

$$P_{otto} = Q_{23} - Q_{41} = \dot{m}_t c_v \left(T_3 - T_2\right) - \dot{m}_t c_v \left(T_4 - T_1\right) = \frac{R_{air}\dot{m}_t}{\gamma - 1}\left(T_1 - T_2 + T_3 - T_4\right) \quad (1)$$

where $\dot{m}_t$ is the mass flow rate of the air–fuel mixture, R_{air} is the gas constant, c_v is the specific heat at constant volume for the working fluid, T is the absolute temperature and γ is the specific heat ratio, $\gamma = c_p / c_v$.

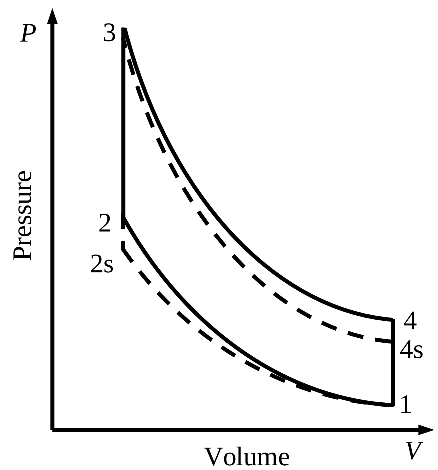

Figure 1. $P-V$ diagram for the air standard Otto cycle

The compression ratio, r_c , is defined as:

$$r_c = V_1 / V_2 \tag{2}$$

where V is the volume of the gas in the cylinder.

For the processes $1 \rightarrow 2s$ and $3 \rightarrow 4s$, we have

$$T_{2s} = T_1 r_c^{\gamma - 1} \tag{3}$$

and

$$T_{4s} = T_3 r_c^{1-\gamma} \tag{4}$$

For the two reversible adiabatic processes $1 \rightarrow 2s$ and $3 \rightarrow 4s$, the compression and expansion efficiencies can be defined as (Ge et al., 2008a):

$$\eta_c = (T_{2s} - T_1)/(T_2 - T_1) \tag{5}$$

and

$$\eta_e = (T_4 - T_3)/(T_{4s} - T_3) \tag{6}$$

When the total energy of the fuel is utilized, the maximum cycle temperature reaches undesirably high levels with regard to structural integrity. Hence, engine designers intend to restrict the maximum cycle temperature. The total energy of the fuel per second input into the engine can be given by:

$$Q_{fuel} = \eta_c \dot{m}_f Q_{LHV} \tag{7}$$

The heat loss through the cylinder wall is given in the following linear expression (Chen et al., 2008)

$$Q_{ht} = \dot{m}_t B (T_2 + T_3) \tag{8}$$

where B is constant.

Since the total energy of the delivered fuel Q_{fuel} is assumed to be the sum of the heat added to the working fluid Q_{in} and the heat leakage Q_{ht} .

$$Q_{in} = Q_{fuel} - Q_{ht} = \eta_c \dot{m}_f Q_{LHV} - \dot{m}_t B (T_2 + T_3) \tag{9}$$

The relation between $\dot{m}_f$ and $\dot{m}_t$ is defined as (Heywood, 1988):

$$\dot{m}_t = \dot{m}_f \left(1 + \frac{1}{(m_a/m_f)_s \phi} \right) \tag{10}$$

where ϕ is the equivalence ratio, m_a/m_f is the air–fuel ratio and the subscript s denotes stoichiometric conditions.

The thermal efficiency of the Otto cycle engine is expressed by

$$\eta_{th} = P_{otto} / Q_{in} \tag{11}$$

Where

$$Q_{in} = \frac{R_{air} \dot{m}_t}{\gamma - 1} (T_3 - T_2) \tag{12}$$

Notice that both power and efficiency are convex functions of the compression ratio.

When r_c , η_c , η_e and T_1 are given, T_{2s} can be obtained from Eq. (3), then, substituting T_{2s} into Eq. (5) yields T_2 . T_3 can be deduced by substituting Eq. (9) into Eq. (12). T_{4s} can be found from Eq. (4), and T_4 can be deduced by substituting T_{4s} into Eq. (6). Substituting T_1 , T_2 , T_3 and T_4 into Eqs. (1) and (11), respectively, the power output and thermal efficiency of the Otto cycle engine can be obtained. Therefore, the relations between the power output, the thermal efficiency and the compression ratio can be derived.

3. Numerical examples and discussions

As it can be concluded from Eqs. (1) and (18), the efficiency and the net power output of the Otto cycle are dependent on the combustion efficiency. In order to illustrate the effect of this parameter, the relations between the power output and the compression ratio, between the thermal efficiency and the compression ratio, and the optimal relation between power output and the efficiency of the cycles presented in Figs. 2–4. According to references (Chen et al. 2006; Ozsoysal, 2006; Ge et al., 2009; Ebrahimi, 2009b), the following parameters are used: $\eta_e = 0.97$, $\eta_c = 0.97$, $\dot{m}_f = 0.001 kg/s$, $\gamma = 1.4$, $B = 0.728 kJ/kg\,K$, $Q_{hv} = 45000 kJ/kg$, $T_1 = 300 K$, $\eta_c = 80 \rightarrow 100\%$, $r_c = 1 \rightarrow 100$, $(m_a/m_f)_s = 14.5$ and $\phi = 1$.

Figures 2–4 show the effects of the combustion efficiency on the power output and the thermal efficiency of the cycle with heat resistance and internal irreversibility. From these figures, it can be found that the combustion efficiency plays an important role on the power output and the thermal efficiency. They reflect the performance characteristics of an Otto cycle engine.

The variations of the power output with respect to the compression ratio and the combustion efficiency are indicated in Figure 2. One can see that the power output versus the compression ratio characteristic is parabolic like curve. In other words, there is a maximum power output in the range of compression ratio. With increasing combustion efficiency, the maximum power output, the working range of the cycle and the compression ratio at the maximum power output increase. Therefore, it can be resulted that the effect of combustion efficiency on the power output of the cycle is related to compression ratio. It should be noted that the increase of the value of maximum power output with increasing combustion efficiency is due to the increase in the ratio of the heat added to the heat rejected. In this case, when combustion efficiency increases by about 20%, the maximum power output, the compression ratio at the maximum power output point and, the working range of the cycle increase by about 32%, 26.6% and 42.8% , respectively.

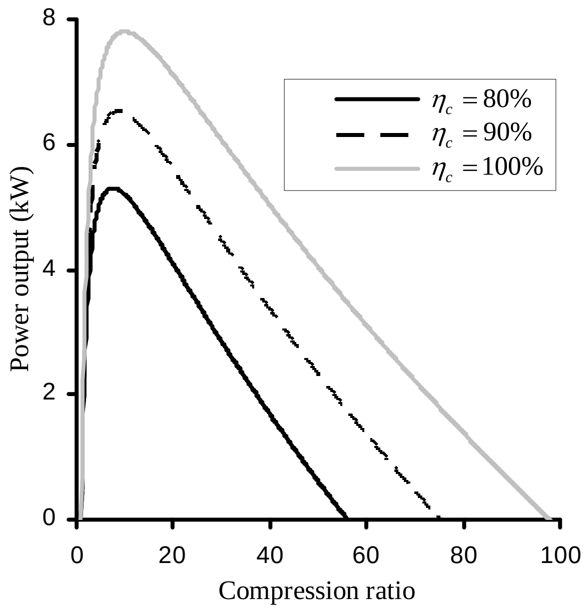

Figure 2. Effect of combustion efficiency on the variation of the power output with compression ratio

Figure 3 shows the effect of combustion efficiency on thermal efficiency with respect to the compression ratio. It can be seen that the thermal efficiency versus the compression ratio characteristic is parabolic like curve. In other word, the thermal efficiency increase with increasing compression ratio, reach their maximum values and then decrease with further increase in compression ratio. With increasing combustion efficiency, the maximum thermal efficiency and the compression ratio at the maximum thermal efficiency increase. Therefore, it can be resulted that the effect of combustion efficiency on the thermal efficiency of the cycle is related to compression ratio. It should be noted that the increase of the value of maximum thermal efficiency with increasing combustion efficiency is due to the increase in the ratio of the heat added to the heat rejected. Numerical calculation shows that when combustion efficiency increases by about 20%, the maximum thermal efficiency and the compression ratio at the maximum thermal efficiency increase 38% and 7.3%, respectively.

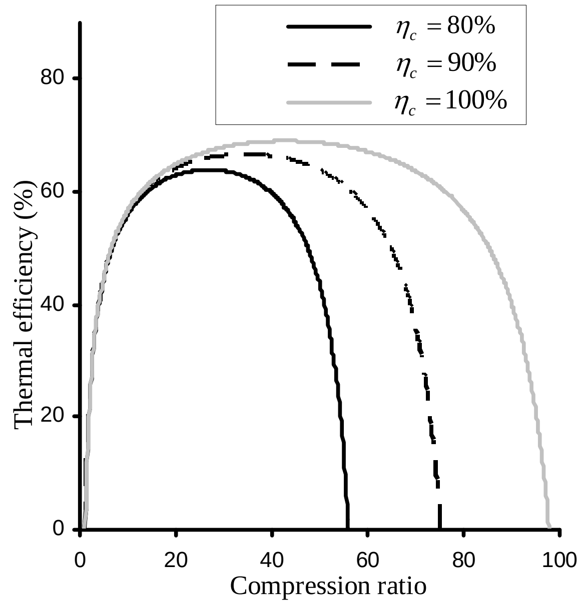

Figure 3. Effect of combustion efficiency on the variation of the thermal efficiency with compression ratio

Figure 4 shows the effects of the combustion efficiency on the power output versus the thermal efficiency characteristic. The power output versus thermal efficiency characteristics exhibit loop shaped. From the figure, it is found that the parameter combustion efficiency has a significant influence on the power output versus thermal efficiency characteristic. They show that the maximum power output point and the maximum efficiency point are very adjacent. When combustion efficiency increases, the efficiency at the maximum power output point, as well as the power output at the maximum efficiency point, will also increase. If combustion efficiency increases by about 20%, the optimal power output corresponding to maximum efficiency and the optimal thermal efficiency corresponding to maximum power output increase by about 30% and 8.4%, respectively.

According to the above analysis, it can be concluded that the effects of the combustion efficiency on the cycle performance are significant, and should be considered carefully in practical-cycle analysis and design.

4-Conclusion

In this paper, the effect of combustion efficiency on the performance of an Otto cycle during the finite time is investigated. The relations between net power output, efficiency, compression ratio, and the combustion efficiency are derived. The maximum power output and the corresponding efficiency and the maximum efficiency and the corresponding power output are also calculated. The detailed effect analyses are shown by one numerical example. The results can provide significant guidance for the performance evaluation and improvement of real Otto engines.

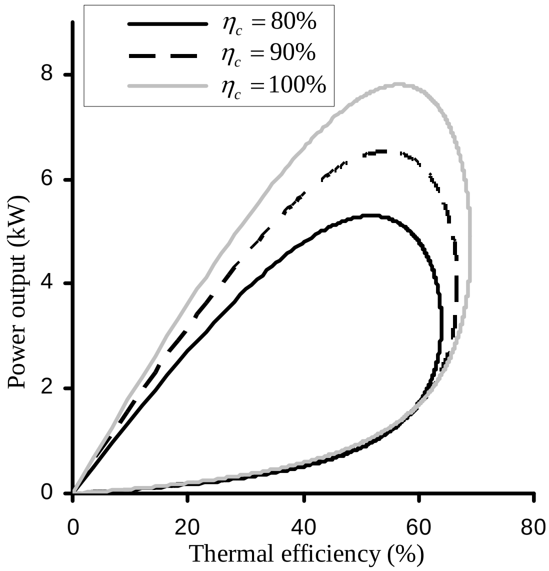

Figure 4. Effect of combustion efficiency on the variation of the power output with thermal efficiency

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