COMPARATIVE THERMODYNAMIC ANALYSIS OF DUAL CYCLE UNDER ALTERNATIVE CONDITIONS

by

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In this paper, finite-time thermodynamic analysis of an air-standard internal-combustion dual cycle is performed. Maximum power, maximum power density, and maximum efficient power, which are three alternative performance criteria, are derived. The effects of the design parameters such as volume ratio and extreme temperature ratio of the cycle have been investigated under maximum power, maximum power density, and maximum efficient power conditions. The analyzed results of air-standard internal-combustion dual cycle showed the design parameters at maximum power conditions and maximum efficient power conditions have a significant advantage compared to maximum power density criterion.

Key words: *finite-time, thermodynamic, heat engine, dual cycle, performance*

Introduction

In order to provide more rational limits to the performance of real processes, thermodynamics is expanded to finite-time thermodynamics to interested in processes which have distinctive time or rate dependencies. Generally, finite-time thermodynamics is the method of modelling and optimization of real finite-time processes and finite-size devices that owe their thermodynamic deficiency to heat transfer, mass transfer, and fluid flow irreversibilities [1]. In the fundamental analysis of modern Diesel engines, the dual cycle is commonly employed as it includes the heat addition processes both at constant volume and constant pressure [2]. Power and thermal efficiency chosen for the optimization criteria, and design parameters at maximum power and at maximum thermal efficiency were investigated in the air standard Diesel and dual cycle optimization studies [3-9]. Parlak [5] carried out an optimization based on maximum power and maximum thermal efficiency criteria for irreversible dual and Diesel cycles. Parlak *et al.* [10] presented a study on optimal performance analysis on maximum power (MP) and maximum efficiency criterion including internal irreversibility for steady-state operation for the air standard dual cycle. Bhattacharyya

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[11] proposed a simplified irreversible model for air standard Diesel cycle. Zhao *et al*. [12] established an irreversible dual heat engine model which includes the Otto and Diesel cycles and they investigated the influence of the multi irreversibilities mainly resulting from the adiabatic processes, finite time processes and heat leak loss through the cylinder wall on the performance of the cycle. Blank *et al.* [13] analysed and optimized the power potential of an endoreversible Diesel cycle with combustion. Hou [14] analyzed the effects of heat transfer on the net work output and the indicated thermal efficiency of an air standard dual cycle. Chen *et al.* [15] analyzed and optimized the finite-time thermodynamic performance of an air-standard dual cycle, with heat transfer and friction-like term losses.

The proper optimization criteria to be chosen for the optimum design of the heat engines may differ depending on their purposes and working conditions. If the heat engine design was done not to obtain maximum work or power, but to have maximum benefit from energy, then the design objective is to get maximum efficiency. For example, fuel consumption is main concern for heat engines so the maximum thermal efficiency criterion is very important. Despite the fact that for engines of race car, maximum power output criterion is significant, for engines of passenger car, both fuel consumption and crank moment gain may equally important, in such a case both the power and thermal efficiency criteria have to considered in the design. Yilmaz [16] proposed a new performance criterion, called efficient power, is defined as the multiplication of power by efficiency of the cycle. This criterion was successfully applied to the Otto cycle and Brayton cycle [17, 18]. There are a lot more studies on finite-time thermodynamic analysis for the dual cycle in the literature [19-28].

In this study, performance optimization of a dual cycle is carried out based on efficient power criterion to consider the power output and the cycle efficiency together. Performance analyses are performed according to maximum power and maximum power density, also.

Cycle analysis

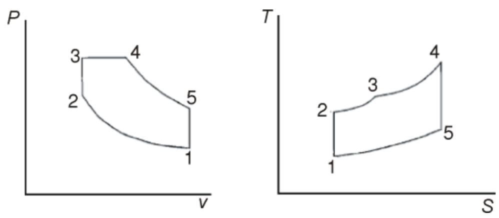

Figure 1. Air standard dual cycle

An ideal air-standard dual cycle is shown in fig. 1. The compression process ignition is isentropic 1-2, the combustion is modeled by a reversible constant volume process 2-3, and a constant pressure process 3-4, the expansion process is isentropic 4-5, and the heat rejection is a reversible constant volume process 5-1.

The combustion heat input is Q_{23} + Q_{34}. The net cyclic work output can be written in the form:

$$\dot{W}_{\text{net}} = \dot{m}c_{\text{v}}[(T_3 - T_2) + k(T_4 - T_3) - (T_5 - T_1)] \tag{1}$$

where c_{v} is the constant-volume specific heat, $\dot{m}$ – the mass flow rate, and k – the ratio of specific heat. The power density defined as the power per minimum specific volume in the cycle then takes the form [17]:

$$\dot{W}_{\text{d}} = \frac{\dot{W}}{v_{\text{min.}}} = \frac{\dot{m}c_{\text{v}}[(T_3 - T_2) + k(T_4 - T_3) - (T_5 - T_1)]}{v_2} \tag{2}$$

In order to write eqs. (1) and (2) can be written in more suitable form, let us define volume ratio as:

$$\theta = \left(\frac{v_2}{v_1}\right)^{k-1} \tag{3}$$

where v_1 is the specific cylinder volume and v_2 – the specific combustion chamber volume. Using eq. (3) and adiabatic relations eqs. (1) and (2) rewritten as [17]:

$$\dot{W}_{\mathrm{DC}} = \dot{m}c_{\mathrm{v}}T_1\left[\frac{1}{\theta}(\beta - 1) + \frac{k\beta}{\theta}(\gamma - 1) - (\gamma^k \beta - 1)\right] \tag{4}$$

Let us define the compression ratio ε, the cut-off ratio γ, the pressure ratio β, the cycle extreme temperature ratio α as follows:

$$\varepsilon = \frac{v_1}{v_2} \tag{5}$$

$$\gamma = \frac{v_4}{v_3} = \frac{T_4}{T_3} \tag{6}$$

$$\beta = \frac{P_3}{P_2} = \frac{T_3}{T_2} \tag{7}$$

$$\alpha = \frac{T_4}{T_1} = \frac{T_{\mathrm{max.}}}{T_{\mathrm{min.}}} \tag{8}$$

For γ = const. and $\beta = \alpha\theta/\gamma$:

$$\dot{W}_{\mathrm{DC}} = \dot{m}c_{\mathrm{v}}T_1\left[\frac{\alpha}{\gamma} - \frac{1}{\theta} + k\left(\alpha - \frac{\alpha}{\gamma}\right) - \gamma^{k-1}\alpha\theta + 1\right] \tag{9}$$

$$\dot{W}_{\mathrm{DC}_{\mathrm{PD}}} = \frac{\dot{m}c_{\mathrm{v}}T_1}{v_1}\theta^{\frac{1}{1-k}}\left[\frac{\alpha}{\gamma} - \frac{1}{\theta} + k\left(\alpha - \frac{\alpha}{\gamma}\right) - \gamma^{k-1}\alpha\theta + 1\right] \tag{10}$$

For β = const. and $\gamma = \alpha\theta/\beta$:

$$\dot{W}_{\mathrm{DC}} = \dot{m}c_{\mathrm{v}}T_1\left[\frac{\beta}{\theta} - \frac{1}{\theta} + k\left(\alpha - \frac{\beta}{\gamma}\right) - \beta\left(\frac{\alpha\theta}{\beta}\right)^{k-1} + 1\right] \tag{11}$$

$$\dot{W}_{\mathrm{DC}_{\mathrm{PD}}} = \frac{\dot{m}c_{\mathrm{v}}T_1}{v_1}\theta^{\frac{1}{1-k}}\left[\frac{\beta}{\theta} - \frac{1}{\theta} + k\left(\alpha - \frac{\beta}{\gamma}\right) - \beta\left(\frac{\alpha\theta}{\beta}\right)^{k-1} + 1\right] \tag{12}$$

as a special case of the dual cycle by taking $\gamma = 1$ as:

$$\dot{W}_{\mathrm{Otto}} = \dot{m}c_{\mathrm{v}}T_1\left(\frac{1}{\theta} - 1\right)(\alpha\theta - 1) \tag{13}$$

as a special case of the dual cycle by taking β = 1 as follows:

$$\dot{W}_{\mathrm{D}} = \dot{m}c_{\mathrm{v}}T_1\left[\frac{k}{\theta}(\alpha\theta-1)-(\alpha\theta)^k+1\right] \tag{14}$$

Thermal efficiency of a dual cycle can be found as:

$$\eta_{\mathrm{DC}} = 1-\frac{\theta(\gamma^k\beta-1)}{\beta\;1+k(\gamma-1)\;-1} \tag{15}$$

For γ = const. and $\beta = \alpha\theta/\gamma$:

$$\eta_{\mathrm{DC}} = 1-\theta\left\{\frac{\gamma^{k-1}\alpha\theta-1}{\dfrac{\alpha\theta}{\gamma}\;1+k(\gamma-1)\;-1}\right\} \tag{16}$$

For β = const. and $\gamma = \alpha\theta/\beta$:

$$\eta_{\mathrm{DC}} = 1-\theta\left\{\frac{\beta\left(\dfrac{\alpha\theta}{\beta}\right)^k-1}{\beta\left[1+k\left(\dfrac{\alpha\theta}{\beta}-1\right)\right]-1}\right\} \tag{17}$$

For γ = 1, thermal efficiency can be written in the form:

$$\eta \;= 1-\theta \tag{18}$$

For β = 1, thermal efficiency can be written in the form:

$$\eta = 1-\theta\left[\frac{(\alpha\theta)^k-1}{k(\alpha\theta-1)}\right] \tag{19}$$

To find MP, we differentiated eqs. (4) with respect to θ, set the resultant derivative equal to zero (*i. e.* $\partial\dot{W}/\partial\theta = 0$). The optimum θ value are calculated numerically for MP and maximum power density (MPD). The thermal efficiencies at MP and MPD are also calculated numerically. The efficient power, which is defined as multiplication of power by efficiency of the cycle as:

$$\dot{W}_{\eta} = \eta\dot{W} \tag{20}$$

For γ = const. and $\beta = \alpha\theta/\gamma$:

$$\dot{W}_{\eta} = \dot{m}c_{\mathrm{v}}T_1\left[\frac{\alpha}{\gamma}-\frac{1}{\theta}+k\left(\alpha-\frac{\alpha}{\gamma}\right)-\gamma^{k-1}\alpha\theta+1\right]\left\{1-\theta\frac{\gamma^{k-1}\alpha\theta-1}{\dfrac{\alpha\theta}{\gamma}\;1+k(\gamma-1)\;-1}\right\} \tag{21}$$

For β = const. and $\gamma = \alpha\theta/\beta$:

$$\dot{W}_\eta = \dot{m}c_\mathrm{v}T_1\left[\frac{\beta}{\theta}-\frac{1}{\theta}+k\left(\alpha-\frac{\beta}{\gamma}\right)-\beta\left(\frac{\alpha\theta}{\beta}\right)^{k-1}+1\right]\left\{1-\theta\frac{\beta\left(\dfrac{\alpha\theta}{\beta}\right)^{k}-1}{\beta\left[1+k\left(\dfrac{\alpha\theta}{\beta}-1\right)\right]-1}\right\} \tag{22}$$

The optimum θ value for maximum efficient power (MEP) and the maximum efficient power are calculated numerically.

Discussion and conclusions

The variations of the normalized power, $(\dot{W}/\dot{W}_{\mathrm{max.}})$, power density $(\dot{W}_\mathrm{d}/\dot{W}_{\mathrm{d\,max.}})$ and efficient power $(\dot{W}_\eta/\dot{W}_{\eta\mathrm{max.}})$ with respect to the thermal efficiency are shown in figs. 2(a), 2(b), and 2(c), respectively, in variation of the cycle temperature ratio, α. As one can see from fig. 2 the thermal efficiency at MPD(η_{MPD}) and the thermal efficiency at MEP(η_{MEP}) are always greater than the thermal efficiency at MP conditions (η_{MP}). It can be concluded from those figures that, when α increases the global performance curves get closer for all performance criteria.

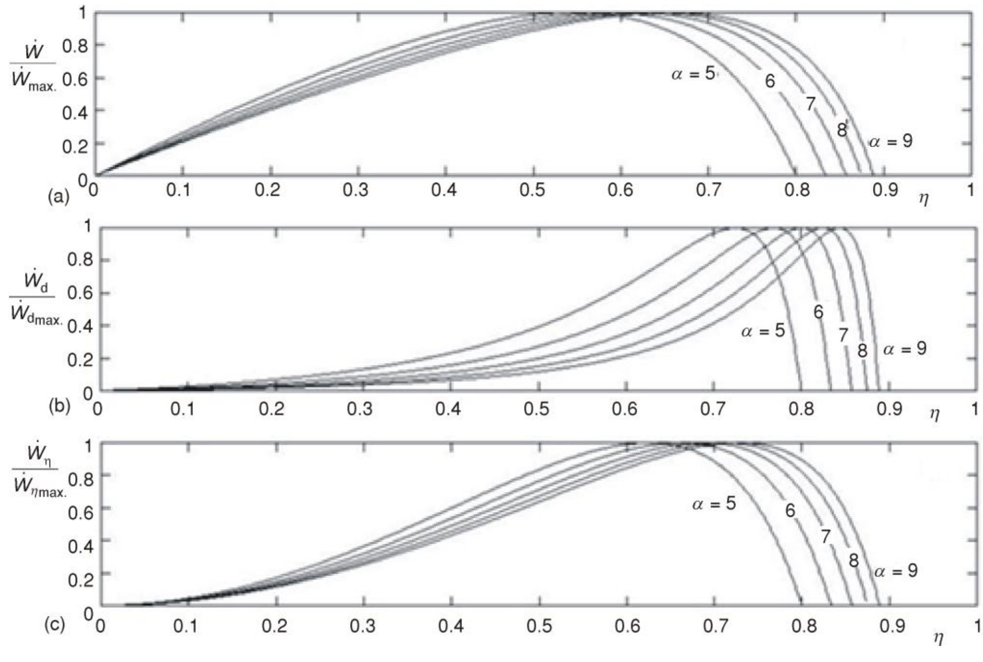

Figure 2. Variations of the normalized power (a), the normalized power density (b), and the normalized efficient power (c) with respect to thermal efficiency

Normalized power, normalized power density, and normalized efficient power are plotted together for α = 5 and α = 9 in figs. 3(a) and 3(b), respectively. It can be observed from these figures that, the η_{MPD} and η_{MEP} are greater than η_{MP} for α = 5 and α = 9.

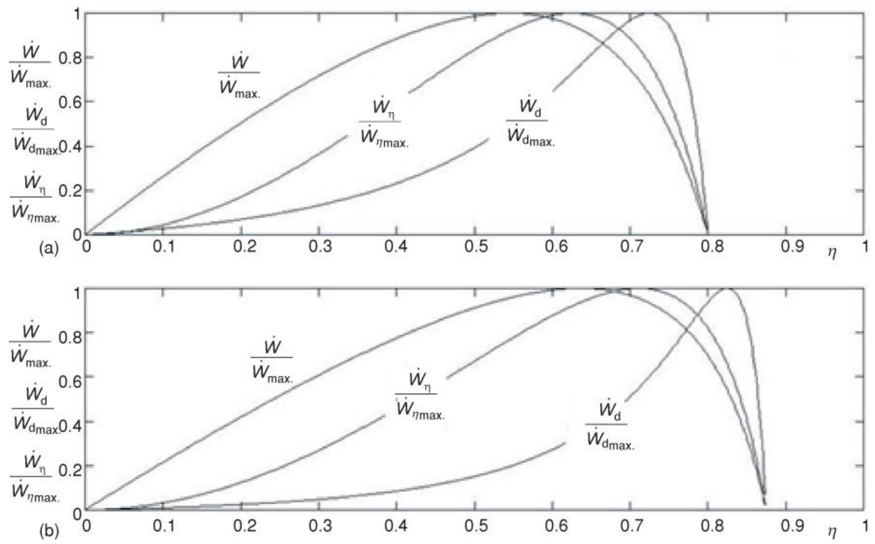

Figure 3. Comparison of the normalized power, the normalized power density, and the normalized efficient power for α = 5 (a) and α = 9 (b)

This finding can be seen more clearly from fig. 4 which shows the comparison of three maximum efficiencies for different cycle temperature ratios, α. As it can be seen from the figure, η_{MP} and η_{MEP} are greater than η_{MPD}.

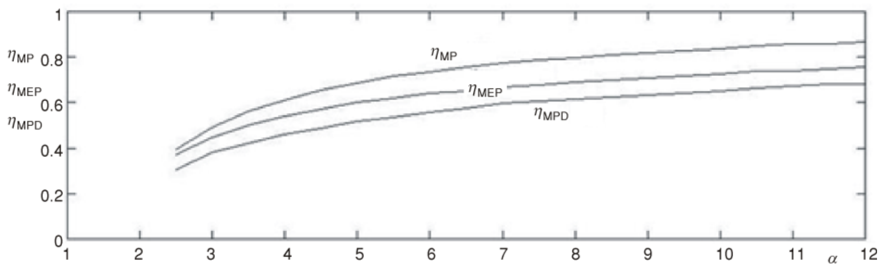

Figure 4. Variations of the thermal efficiencies at MP, MPD, and MEP conditions with respect to α

Power outputs at MP, MPD, and maxiumum efficient power (MEP) conditions can be seen with respect to α in fig. 5. Both of the power outputs at MP and MPD condition are higher than the MPD output of the cycle as expected.

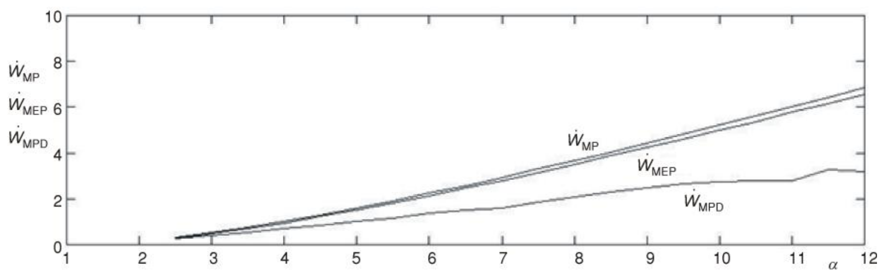

Figure 5. Variations of the power outputs of the cycle at MP, MPD, and MEP conditions with respect to α

Conclusions

The investigation of air-standard dual cycle under reversible heat transfer conditions was presented in this study. The effects of various engine parameters were presented by using an alternative approach to evaluate net power output, power density, and efficiency power from more realistic parameters such as cycle thermal efficiency and temperature ratios.

Numerical results showed that power outputs at MP condition are higher than the power output at MEP and MPD conditions of the cycle. But power outputs at MP condition and MEP condition are very close to each other. The MP and MEP criterion have a significant power advantage compared to MPD criterion after $\alpha = 2.5$. Also, increasing temperature ratios would result in an increase in power outputs. Finally, it can easily be said that the maximum MEP is suitable to compromise the power and efficiency of the dual cycles.

Nomenclature

c_v – constant volume specific heat, [$\text{Jkg}^{-1}\text{K}^{-1}$]
k – ratio of specific heat
$\dot{m}$ – mass flow rate, [kgs^{-1}]
T – temperature, [K]
v_1 – specific volume of cylinder chamber, [m^3kg^{-1}]
v_2 – specific volume of combustion chamber, [m^3kg^{-1}]
$v_{\text{min.}}$ – per minimum specific volume in the cycle, [m^3kg^{-1}]
$\dot{W}$ – power generated from the heat engine, [W]
$\dot{W}_\eta$ – efficient power, [W]

Greek symbols

α – cycle extreme temperature ratio (T_4/T_1)
β – pressure ratio
γ – cut-off ratio
ε – compression ratio
η – thermal efficiency
θ – volume ratio

Subscripts

MP – maximum power
MPD – maximum power density
MEP – maximum efficient pover

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