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 (MP), maximum power density (MPD), maximum efficient power (MEP) 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 MP, MPD and MEP conditions. The analyzed results of air-standard internal-combustion Dual cycle showed the design parameters at maximum power (MP) conditions and maximum efficient power (MEP) conditions have a significant advantage compared to maximum power density (MPD) criterion.

Key words: *Finite-time, thermodynamic, Heat engine, Dual cycle, Performance*

1. 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 and Sahin [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 [11] proposed a simplified irreversible model for air standard Diesel cycle. Zhao and Chen [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 and Wu [13] analysed and optimized the power potential of an endoreversible Diesel cycle with combustion. S.S. 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. Also performance analyses are performed according to maximum power and maximum power density.

2. Cycle Analysis

An ideal air-standard Dual cycle is shown in Figure 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.

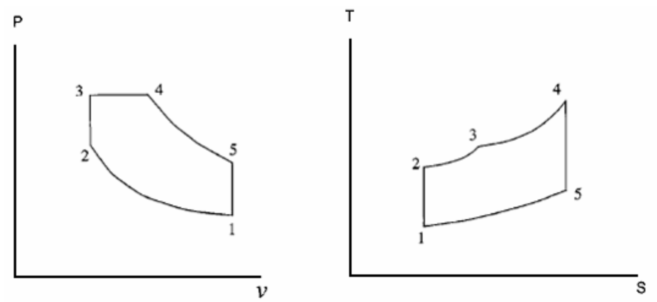

Figure 1. Air Standard Dual cycle

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

$$\dot{W}_{net} = \dot{m}c_v\left[(T_3 - T_2) + k(T_4 - T_3) - (T_5 - T_1)\right] \quad (1)$$

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

$$\dot{W}_d = \frac{\dot{W}}{v_{\min}} = \frac{\dot{m}c_v\left[(T_3 - T_2) + k(T_4 - T_3) - (T_5 - T_1)\right]}{v_2} \quad (2)$$

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

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

where v_1 is the specific cylinder volume, v_2 is the specific combustion chamber volume. Using equation (3) and adiabatic relations equations (1) and (2) rewritten as [17]

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

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

$$\varepsilon = \frac{v_1}{v_2} \quad (5)$$

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

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

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

For γ=constant and $\beta = \frac{\alpha\theta}{\gamma}$

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

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

For β=constant and $\gamma = \frac{\alpha\theta}{\beta}$

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

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

as a special case of the Dual cycle by taking γ=1 as follows:

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

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

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

Thermal efficiency of a Dual cycle can be found as

$$\eta_{DC} = 1 - \frac{\theta(\gamma^k\beta - 1)}{\beta\left[1 + k(\gamma - 1)\right] - 1} \tag{15}$$

For γ=constant and $\beta = \frac{\alpha\theta}{\gamma}$

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

For β=constant and $\gamma = \frac{\alpha\theta}{\beta}$

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

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 maximum power, we differentiated equations (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 maximum power and maximum power density. 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=constant and $\beta = \frac{\alpha\theta}{\gamma}$

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

For β=constant and $\gamma = \frac{\alpha\theta}{\beta}$

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

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

3. Discussion and conclusions

The variations of the normalized power ($\dot{W} / \dot{W}_{max}$), power density ($\dot{W}_d / \dot{W}_{d\,max}$) and efficient power ($\dot{W}_\eta / \dot{W}_{\eta\,max}$) with respect to the thermal efficiency are shown in figures 2a, 2b and 2c respectively in variation of the cycle temperature ratio, α. As one can see from figure 2 that 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.

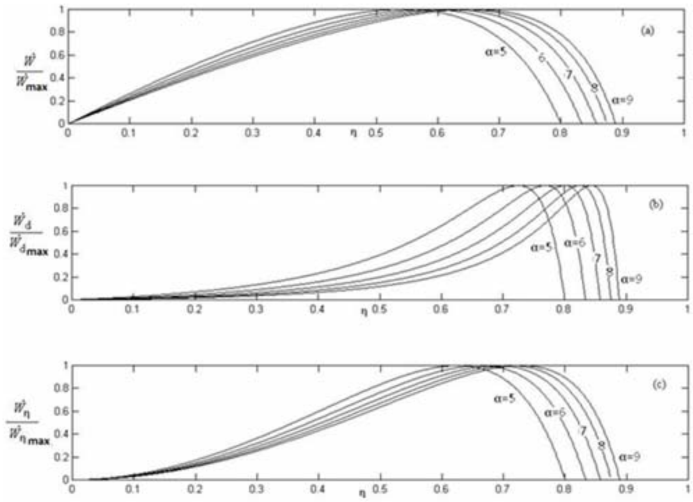

Figure 2. Variations of the normalized power (a), the normalized power density (b) and the normalized efficient power (c) with respect to thermal efficiency.

Normalized power, normalized power density and normalized efficient power are plotted together for α=5 and α=9 in figures 3a and 3b 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

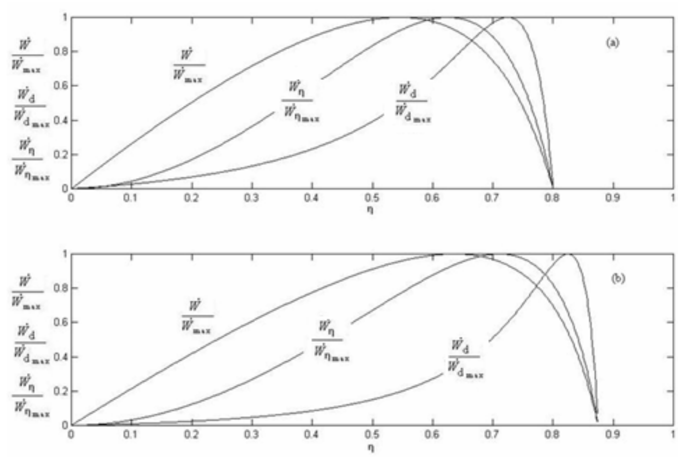

Figure 3. Comparison of the normalized power, the normalized power density and normalized efficient power for α=5 (a) and α =9 (b)

This finding can be seen more clearly from figure 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}.

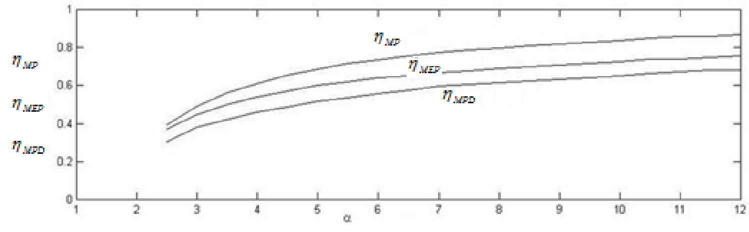

Figure 4. Variations of the thermal efficiencies at MP, MPD and MEP conditions with respect to α

Power outputs at MP, MPD and MEP conditions can be seen with respect to a in Figure 5. Both of the power outputs at MP and MPD condition are higher than the MPD output of the cycle as expected.

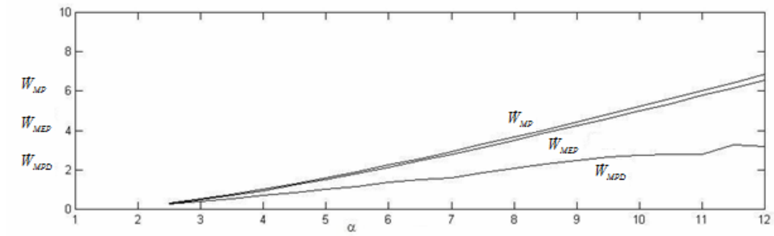

Figure 5. Variations of the power outputs of the cycle at MP, MPD and MEP conditions with respect to α

4. Conclusion

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 α=2.5. Also, increasing temperature ratios would result in an increase in power outputs. Finally, it can easily be said that the maximum efficient power conditions (MEP) is suitable to compromise the power and efficiency of the Dual cycles.

NOMENCLATURE

c_v constant volume specific heat $(J\cdot kg^{-1}\cdot K^{-1})$

k ratio of specific heat

$\dot{m}$ mass flow rate (kg/s)

T temperature (K)

v_1 specific volume of cylinder chamber (m^3/kg)

v_2 specific volume of combustion chamber (m^3/kg)

v_{min} per minimum specific volume in the cycle (m^3/kg)

$\dot{W}$ power generated from the heat engine (W)

$\dot{W}_\eta$ efficient power (W)

α cycle extreme temperature ratio (T_4/T_1)

η thermal efficiency

θ volume ratio

ε compression ratio

γ cut-off ratio

β pressure ratio

Subscripts

max maximum

min minimum

MP maximum power

MPD maximum power density

MEP maximum efficient power

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