Analyses of Irreversible Radiative Heat Engines Under Maximum Efficient Power Conditions

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Abstract:

In this paper, the efficient power, defined as the product of power output and efficiency of the engine, is taken as the objective for performance analysis and optimization of an internally and externally irreversible radiative Carnot heat engine model in the viewpoint of Finite Time Thermodynamics (FTT) or Entropy Generation Minimization (EGM). The criterion considers not only the power output but also the cycle efficiency. The obtained results are compared with those obtained by using maximum power (MP) and maximum power density (MPD) criterion and the advantages and disadvantages of maximum efficient power design are analyzed. The result showed that the engine design at maximum efficient power (MEP) conditions have an advantage of smaller size and are more efficient than the engines designed at maximum power and maximum power density conditions.

Key-Words:- Efficient Power, Finite Time Thermodynamics, Performance Analyses, Internally And Externally Irreversible Radiative Heat Engine.

1. Introduction

The performance of heat engine has been the subject of many studies using what appear to be different approaches, while in fact, all these methods are similar and can be classified to fall under the Power Maximization (PM) technique. Bejan[1] reviewed the available procedures and suggested a new approach called 'Entropy Generation Minimization' (EGM). The method, a combination of thermodynamics, heat transfers and fluid flow essentially unifies what is known in engineering as 'Finite Time Thermodynamics' (FTT).Since finite time thermodynamics (FTT) or entropy generation minimization was advanced, much work has been carried out for the performance analysis and optimization of finite time processes and finite size devices[2-13]. In these studies, the power output, thermal efficiency, entropy generation and the ecological benefits are chosen for the optimization criteria. However, the performance analyses based on the above optimization criteria do not take the effects of engine sizes related to the investment cost into account. In order to include the effects of engine size in the performance analysis, Sahin et al[14,15] introduced the maximum power density (MPD) as a new optimization criterion. In their study, they maximized the power density (the ratio of power to the maximum specific volume in the cycle) and found design parameters at MPD conditions, which led to smaller and more efficient Joule-Brayton heat engines than those engines working at maximum power (MP) conditions. In the literature[16-21], researchers have extended MPD techniques to the various heat engines having thermal reservoirs of infinite and finite heat capacity. The proper optimization criterion for the heat engines will depend on their purposes. If the heat engine was designed not to obtained maximum power, but to have maximum benefit from energy, then the design objective is to get maximum efficiency. A new performance criterion function, called efficient power, which considers both power output and efficiency was defined by Yilmaz[22].

This analysis is an extension of the work done by the researchers[13, 17]. In this paper, maximum efficient power (MEP) analysis has been carried out for an internally and externally irreversible radiative Carnot heat engine model. In this context, the optimal performance and design parameters under MEP conditions are investigated. The obtained results are comparatively discussed with respect to the results obtained using the maximum power (MP) and maximum power density (MPD) performance criterion. Solar-driven mercury power plant heat engines and radiating solar-powered direct energy conversion devices can be considered as practical radiative heat engines. Such engines have promising future space applications.

2. Theoretical Model

The considered irreversible Carnot like radiative heat engine model which includes finite time heat transfer and internal irreversibilities and its T-s diagram are shown in Figure 1. The heat rate Q_H from the hot reservoir at temperature T_H to the heat engine and the heat rate Q_L from the heat engine to the cold reservoir at temperature T_L are respectively,

$$Q_H = h_H A_H (T_H^4 - T_X^4) \quad (1)$$

$$Q_L = h_L A_L (T_Y^4 - T_{XL}^4) \quad (2)$$

where T_X and T_Y are the warm and cold working fluid temperatures respectively; h is the heat transfer coefficient and A is the heat exchanger surface area.

The power (W) produced by the engine according to the first law is:

$$\dot{W} = Q_H - Q_L \quad (3)$$

Formally, the second law for an irreversible cycle requires that,

$$\oint \frac{dQ}{T} = \frac{Q_H}{T_X} - \frac{Q_L}{T_Y} \prec 0 \quad (4)$$

One can rewrite the inequality in Eq.(4) as

$$\frac{Q_H}{T_X} - R\frac{Q_L}{T_Y} = 0 \qquad \text{with } 0<R<1 \quad (5)$$

where the irreversibility parameter R is defined as

$$R = \frac{s_3 - s_{2s}}{s_{4s} - s_1} \quad (6)$$

On substituting Eq (1) and Eq (2) in Eq (5), we have

$$\left(\frac{T_X}{T_H}\right)^4 = \frac{\psi\gamma + R\tau^4}{R\psi^4 + \psi\gamma} \quad (7)$$

where, $\gamma = \frac{h_H A_H}{h_L A_L}$, $\psi = \frac{T_Y}{T_X}$ and $\tau = \frac{T_L}{T_H}$

Assuming an ideal gas, the maximum volume in the cycle V_4 can be written as

$$V_4 = \frac{mR_g T_Y}{p_{min}} \quad (8)$$

where m is the mass of the working fluid and R_g is the ideal gas constant. In the analysis, the minimum pressure (pmin) in the cycle is taken to be constant[8].

2.1 Maximum efficient power (MEP) analysis

The efficient power (W_{ep}), which is defined as the product of power output and efficiency of the cycle, can be written as

$$W_{ep} = \eta * W \quad (9)$$

The thermal efficiency can be written as,

$$\eta = 1 - \frac{\Psi}{R} \tag{10}$$

By using Eq. (1), Eq. (7) and Eq. (10), the expression for dimensionless efficient power(P_{ep}) can be written as

$$P_{ep} = \frac{W}{(h_H A_H T_H^4)} = \left[1 - \left(\frac{T_X}{T_H}\right)^4\right]\left[1 - \frac{\Psi}{R}\right]^2 \tag{11}$$

The dimension less efficient power can be maximized by taking:

$$\frac{dP_{ep}}{d\psi} = 0 \tag{12}$$

For a given values of and R, the solution of Eq (12) can be solved numerically for $(\Psi')_{mep}$ in terms of τ. The maximum efficient power (P_{mep}) can then be found in terms of τ by substituting (Ψ')mep in Equation (11). The thermal efficiency of an irreversible radiative heat engine at maximum efficient power becomes

$$\eta_{mep} = 1 - \frac{(\Psi)_{mep}}{R} \tag{13}$$

2.2 Maximum power density (MPD) analysis

The power density (W_d), defined as the ratio of power to the maximum volume in the cycle, can be written as

$$W_d = W / V_{max} \tag{14}$$

Dimensionless power density can be obtained by using Eq. (1), Eq. (3) and Eq. (5) in Eq.(14).

$$P_d = \frac{W_d}{(h_H A_H T_H^3)\left(\frac{P_{min}}{mR_g}\right)} = \left[1 - \left(\frac{T_X}{T_H}\right)^4\right]\left[1 - \frac{\psi}{R}\right]\frac{1}{\psi\left(\frac{T_X}{T_H}\right)} \tag{15}$$

Power density can be maximized by taking

$$\frac{dP_d}{d\Psi} = 0 \tag{16}$$

For a given values of γ and R, the solution of Eq. (16) can be solved numerically for $(\Psi)_{mpd}$ in terms of . The maximum power density (P_{mpd}) can then be found in terms of by substituting $(\Psi)_{mpd}$ in equation (15).

The efficiency of an irreversible radiative heat engine at MPD will become

$$\eta_{mpd} = 1 - \frac{(\Psi')_{mpd}}{R} \tag{17}$$

2.3 Maximum power (MP) analysis

Writing the expression for dimensionless power output (P) by using Eq. (1) and Eq (7)

$$P = \frac{W}{(h_H A_H T_H^4)} = \left[1 - \left(\frac{T_X}{T_H}\right)^4\right]\left[1 - \frac{\Psi}{R}\right] \tag{18}$$

Power can be maximized by taking

$$\frac{dP}{d\psi} = 0 \tag{19}$$

For a given values of γ and R, the solution of Eq (19) can be solved numerically for $(\Psi')_{mp}$ in terms of τ. The maximum power (P_{mp}) can then be found in terms of by substituting (Ψ')mp in Equation (19). The thermal efficiency of an irreversible radiative heat engine at maximum power becomes

$$\eta_{mp} = 1 - \frac{(\Psi')_{mp}}{R} \tag{20}$$

3. Results and Discussion

To see the advantages and disadvantages of maximum efficient power design, detailed numerical analyses are provided and are compared with those for the maximum power and maximum power density objective. During the variation of any one parameter, all other parameters are assumed to be constant as given below:
$R=0.8, \tau=0.2, =0.2$
The variations of the thermal efficiencies at maximum efficient power((η_{mep}), maximum power density (η_{mpd}) and maximum power conditions (η_{mp}) with respect to and R are shown in Fig. 2 and Fig. 3 respectively. The following conclusions can be drawn:

1. For a given value of and R, the efficiency at maximum efficient power is always greater than that at maximum power density and maximum power conditions. Hence $\eta_{mep} > \eta_{mpd} > \eta_{mp}$.

2. As the value of increases, the value of all the efficiencies decreases and they become zero at =R.

3. It can be seen from Fig. 2 that R has strong effect on η_{mep}, η_{mpd} and η_{mp} for a given value of. When R is increased, which implies the decreasing laws mechanism, all the efficiencies are increased for a given value of less than R.

4. For the radiative type heat engine working under MEP conditions, the analyses shows that the practical range for R should be from 0.6 to 0.9 and $\tau \leq= 0.2$ for any given value of heat transfer area ratio (γ).

The variations of dimensionless powers at maximum efficient power (P_{mep}), maximum power density (P_{mpd}) and at maximum power conditions (P_{mp}) with respect to and R can be seen from Fig. 4 and Fig. 5 respectively. The following comments can be made:

1. For a given value of and R, the P_{mep} is always less than P_{mpd} and P_{mp}. That is if the design parameters are selected at MEP conditions instead of MPD conditions, the thermal efficiency increases as much as $\Delta\eta_{mep} - _{mpd}$ and the power output decreases by $\Delta P = P_{mpd} — P_{mep}$.

2. As τ increases, η_{mep}, η_{mpd} and η_{mp} and P_{mep}, P_{mpd} and Pmp decreases and get closer to each other respectively, and they become zero when τ=R. In order to obtain positive performance in terms of thermal efficiency and power for all MEP, MPD and MP conditions, it is necessary that should be less than R. This case can be seen by evaluating Eqs. (11), (13), (15), (17), (18) and (20).

The size of a heat engine can be characterized by the maximum volume in the cycle, i.e. V_4. The variations of the ratio of the maximum volume at MPD to the one at MP (V_{mpd}^*/V_{mp}^*) and the variations of the ratio of the maximum volume at MEP to the one at MP (V_{mep}^*/V_{mp}^*) with τ are shown in Fig. 6. As can be seen from the figure that the maximum volume at MEP conditions is always smaller than at MPD conditions for all practical values of τ. The maximum volume in the cycle is related to engine size and for a smaller engine this value is desired to be small. The smaller engine size advantage of the MEP conditions becomes more important at higher values of R and lower values of τ. Both volumes get closer to each other as increases.

4. Conclusion

Conventional heat engine developments have been increasingly affected by environmental challenges. A radiative heat engine would possibly meet the demands of maintaining air quality standards and diminishing energy resources. Our theoretical analysis for the practical design of an internally & externally irreversible radiative heat engine shows that power density conditions, must be less than or equal, to 0.2 and should be less than 1.0, for any given value of R between 0.6 and 0.9. The radiative heat engines designed at maximum efficient power conditions are smaller and more efficient than those designed at maximum power density and maximum power conditions. It may be pointed out that the external combustion engines, for the same reasons of enhancing the efficiency and smaller size of the engine, can also be designed by employing efficient power as the objective for optimization.

Nomenclature

A_H = Heat-exchanger area at the high temperature source side (m^2).

A_L = Heat-exchanger area at the low temperature source side (m^2).

h_H = Heat-transfer coefficient at the high temperature source side ($Wm^{-2}K^{-1}$).

h_L = Heat-transfer coefficient at the low temperature source side ($Wm^{-2}K^{-1}$).

m = Mass of the gas (kg).

P_{mp} = Dimensionless maximum power

P_{mpd} = Dimensionless maximum power density.

P_{mep} = Dimensionless maximum efficient power.

$p_{min.}$ = Minimum pressure (Nm^{-2}).

R = Irreversibility parameter.

R_g = Gas constant ($Jkg^{-1}K^{-1}$).

s = Specific entropy ($Jkg^{-1}K^{-1}$).

T = Temperature (K).

T_H = Temperature of heat source (K).

T_L = Temperature of heat sink (K).

T_X = Warm working fluid temperature (K).

T_Y = Cool working fluid temperature (K).

W = Power output (W).

W_d = Power density (Wm^{-3}).

W_{ep} = Efficient Power (W).

= Thermal efficiency.

η_{mep} = Efficiency at maximum efficient power.

$_{mp}$ = Efficiency at maximum power.

$_{mpd}$ = Efficiency at maximum power density.

= Heat transfer area ratio.

= Ratio of T_L to T_H.

Ψ = Ratio of T_Y to T_X.

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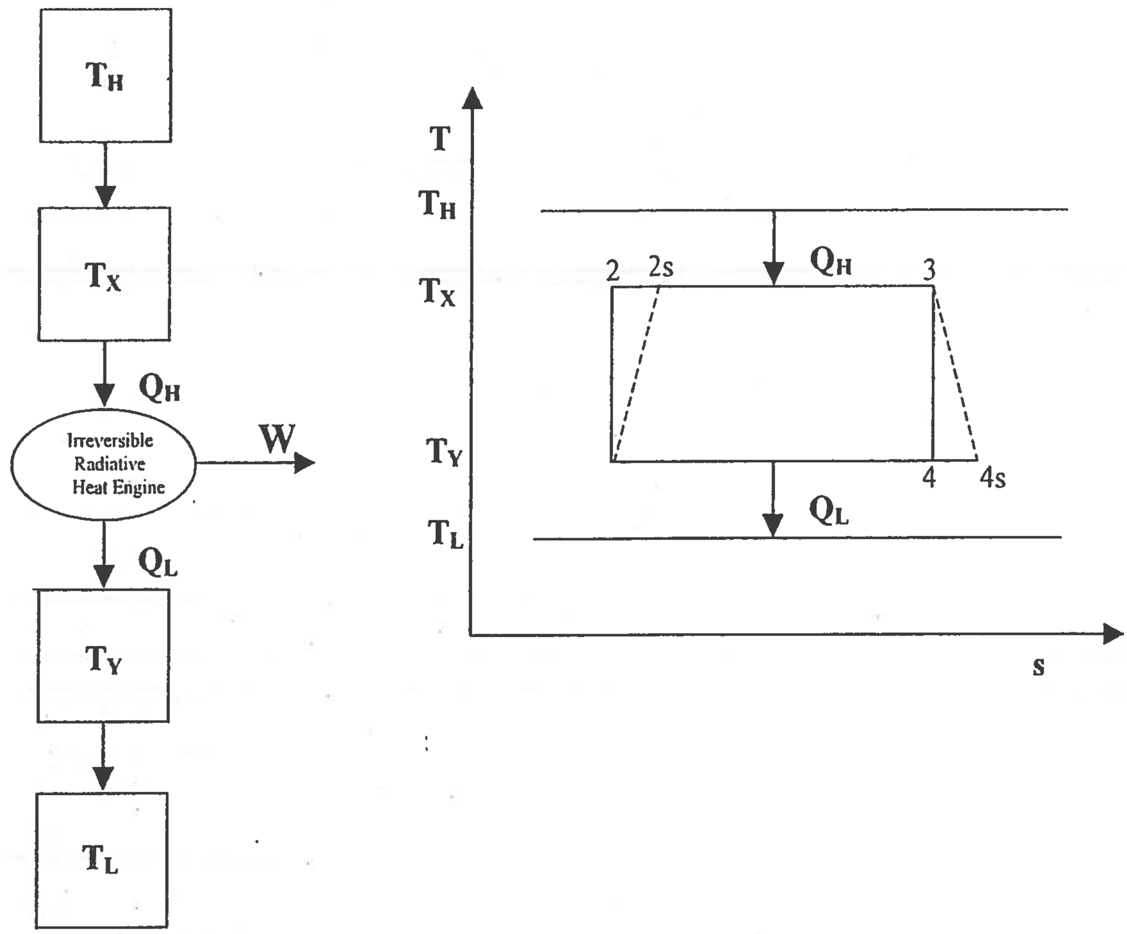

Figure 1: Irreversible Carnot- like radiative heat engine and its T s diagram

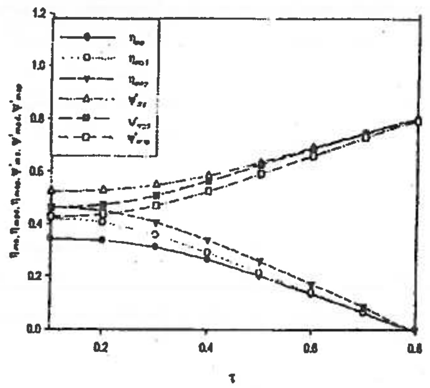

Figure 2: Variations of various efficiencies and optimum working fluid temperature ratios with τ.

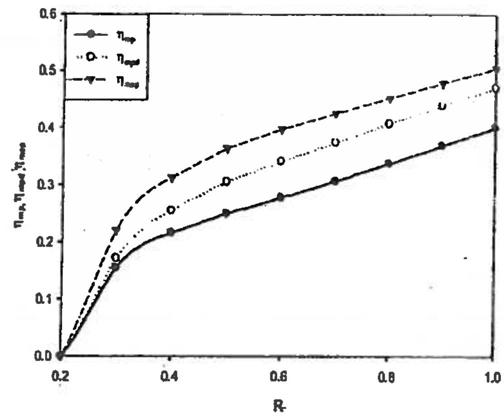

Figure 3: Variations of various efficiencies with R.

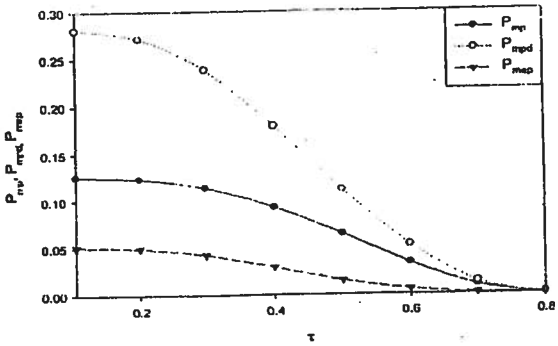

Figure 4: Variations of various dimensionless powers with τ.

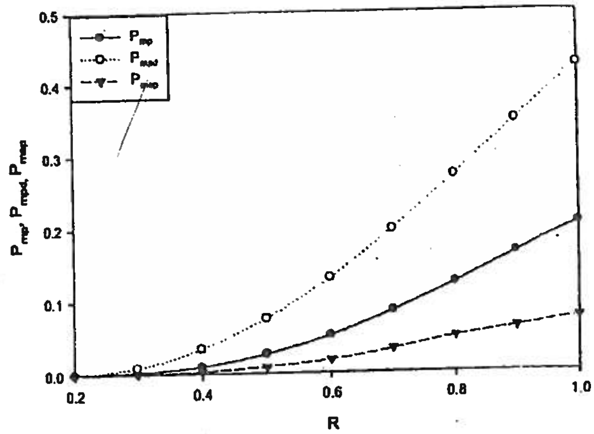

Figure 5: Variations of various dimensionless powers with R.

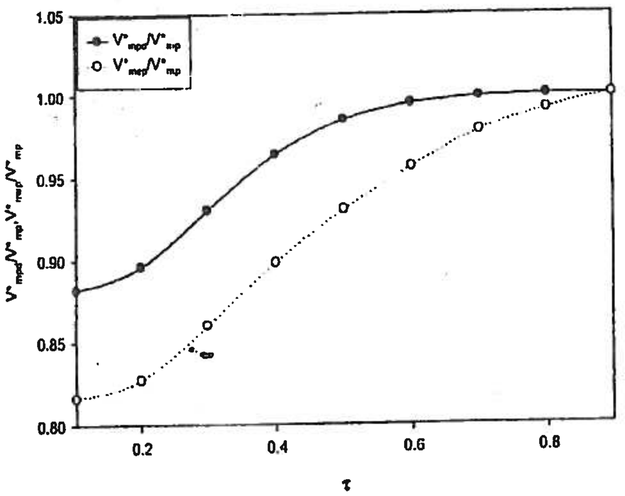

Figure 6: Variations of maximum volume ratios with τ.

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