ECOLOGICAL FUNCTION OF AN ENDOREVERSIBLE OTTO ENGINE CYCLE

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Abstract - In this paper, a performance analysis and optimization based on the ecological criterion has been performed for an air-standard endoreversible internal combustion engine Otto cycle coupled to constant temperature heat reservoirs. The cycle consists of two constant thermal-capacity heating branches, a constant thermal-capacity cooling branch and two adiabatic branches. The analytical formulae for thermal efficiency and ecological function of the Otto endoreversible thermodynamic cycle with heat resistance loss are derived. The results include the performance characteristics of endoreversible steady flow Otto cycle. The results can provide some theoretical guidance for the design of practical Otto engines.

Index terms - Finite-time thermodynamics, Efficiency; Entropy-generation rate, Ecological function.

I. INTRODUCTION

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 [I-7]. Alternatively, Angulo-Brown et al. [8] proposed an ecological criterion $E = P - T_L\sigma$, a for finite-time Carnot heat engines, where T_L is the temperature of cold heat reservoir, P is the power output and σ is the entropy generation rate. They derived a general property of non-endoreversible thermal cycles with this ecological criterion. Yan [9] showed that it might be more reasonable to use $E = P - T_\circ\sigma$ if the coldreservoir temperature T_L is not equal to the environment temperature $T_\circ$ from the state of view of exergy analysis.

II. THEORETICAL ANALYSIS

An endoreversible steady flow thermodynamic cycle coupled to two constant-temperature heat reservoirs T_H and T_L is shown in figure 1. The compression process is isentropic $1 \to 2$. The heat addition process is heating branch $2 \to 3$ with constant thermal capacity C_v . The expansion process is isentropic $3 \to 4$. The heat rejection process is $4 \to 1$ with constant thermal capacity C_v .

According to the properties of working fluids and the theory of heat exchangers, the rate of heat transfer (Q_H) supplied by the heat source, and the rate of heat transfer (Q_L) released to the heat sink are, respectively:

$$Q_H = \dot{m}C_{in}\left(T_3 - T_2\right) = \dot{m}C_{in}E_H\left(T_H - T_2\right) \qquad (1)$$

$$Q_L = \dot{m}C_{out}\left(T_4 - T_1\right) = \dot{m}C_{out}E_L\left(T_4 - T_L\right) \qquad (2)$$

where $\dot{m}$ is mass flow rate; E_H and E_L are the effectivenesses of the hot- and cold-side heat exchangers.

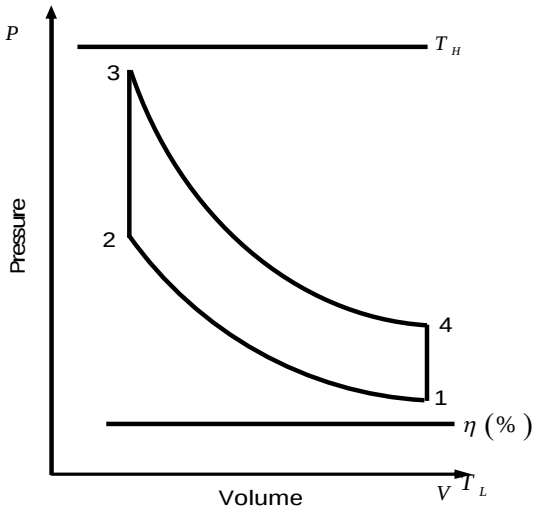

Figure 1. $P-V$ **diagram for the air standard Otto cycle**

The entropy change of the working fluid equals to zero after a cycle:

$$\Delta S = C_v \ln\left(\frac{T_3}{T_2}\right) + C_v \ln\left(\frac{T_4}{T_1}\right) = 0 \qquad (3)$$

Therefore, one has:

$$T_4 = \frac{T_1 T_3}{T_2} \qquad (4)$$

Combining Equations (1) and (2) with (4) gives:

$$T_1 = \frac{E_L T_L}{1-\left(1-E_L\right)a} \qquad (5)$$

$$T_3 = E_H T_H + \left(1-E_H\right)T_2 \qquad (6)$$

$$T_4 = \frac{aE_L T_L}{1-\left(1-E_L\right)a} \qquad (7)$$

where:

$$a = \frac{E_H T_H + (1 - E_H) T_2}{T_2} \quad (8)$$

The ecological function E of the cycle is:

$$E = P - T_\circ \sigma =$$

$$\dot{m} C_v \left[E_H (T_H - T_2) \left(1 + \frac{T_\circ}{T_H} \right) - \frac{E_L T_L (a-1)}{1 - (1 - E_L) a} \right] \quad (9)$$

The efficiency η of the cycle is:

$$\eta = \frac{P}{Q_H} \times 100 = \left\{ 1 - \frac{E_L T_L (a-1)}{E_H (T_H - T_2) \left[1 - (1 - E_L) a \right]} \right\} \times 100 \quad (10)$$

III. NUMERICAL EXAMPLES AND DISCUSSION

To illustrate the preceding analysis, a numerical example is provided. They reflect the performance characteristics of a real irreversible Otto cycle engine. In the calculations, it is set that $T_L = 310K$, $T_\circ = 300K$, $\tau = T_H / T_L = 4.5 \, and \, 5$, $\dot{m} = 1.66 kg/s$, $E_H = 0.9$, $E_L = 0.9$ and $C_v = 0.7166 \frac{kJ}{kg.s}$ [10-13]. The temperature at state 2, is a variable ranging from T_L up to T_H.

Figure 2 shows the ecological function versus the thermal efficiency for Otto cycle. One can see that the curves of E versus η are parabolic-type ones. The ecological function has a maximum $(E_{\max(\eta)})$ and the corresponding efficiency is η_E. The figure also shows the influence of heat reservoir temperature ratio on ecological function versus efficiency characteristic. As it can be clearly seen from the figure, the ecological function of the Otto cycle is dependent on the heat reservoir temperature ratio. It can be seen that with an increase of heat reservoir temperature ratio, the maximum ecological function increases. The corresponding thermal efficiency η_E, at maximum ecological function increase with increasing heat reservoir temperature ratio.

Figure 3 shows the $E - T_2$ characteristic of an endoreversible Otto cycle. It can be seen from figure 3 that there exist a maximum ecological function $(E_{\max(T_2)})$ and the corresponding temperature is T_{2E}. In other words, it can be seen that increasing temperature at state 2 makes increasing the ecological function at first and then decreases the ecological function. It can be clearly seen from the figure that the ecological function of the Otto cycle is dependent on T_2. Figure 3 also shows that if temperature at state 2 is less than certain value, the ecological function decreases with increasing heat reservoir temperature ratio, while if temperature at state 2 exceeds certain value, the ecological function increases with increasing heat reservoir temperature ratio.

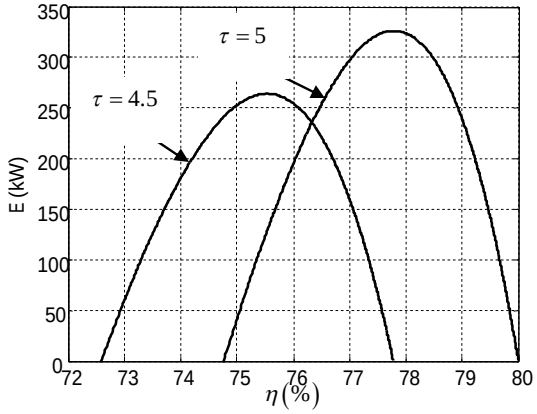

Figure 2: Ecological function versus thermal efficiency

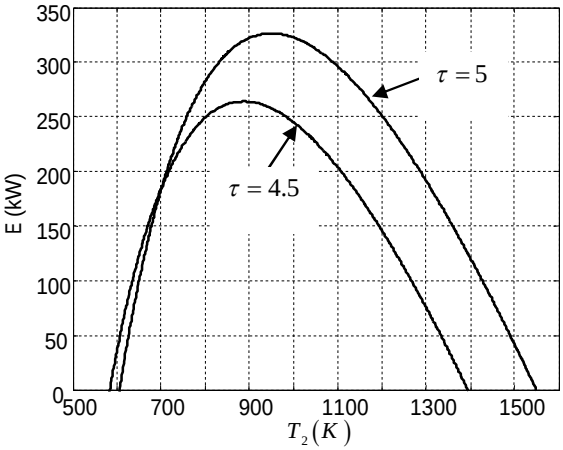

Figure 3: Ecological function versus temperature at state 2

Figure 4 shows the $\eta - T_2$ characteristic of an endoreversible Otto cycle. It can be clearly seen from the figure that the thermal efficiency of the Otto cycle is dependent on T_2. It can be concluded from figure 4 that, throughout the temperature at state 2, the thermal efficiency increases with the increasing heat reservoir temperature ratio.

CONCLUSION

The optimal performance for a class of endoreversible Otto cycle, consisting of two heating branches, two cooling branches and two adiabatic branches was analyzed using finite-time thermodynamics.A numerical example is given to show the effects of the heat reservoir temperature ratio on the optimal performance of the Otto cycle.The ecological function versus the thermal efficiency and ecological function versus the temperature at state 2, as well as the thermal efficiency versus the temperature at state 2 for Otto cycle are illustrated by numerical examples. The results obtained in this paper can provide some guidance for the performance evaluations and improvement of real heat engines.

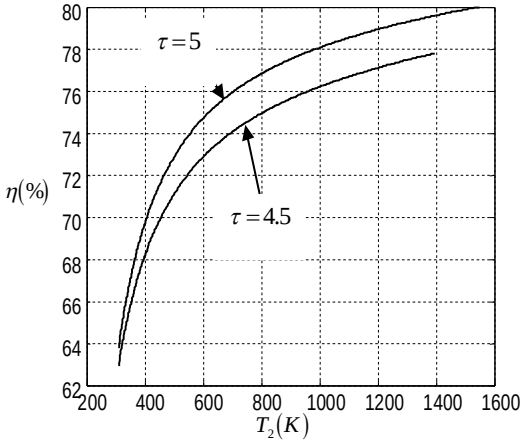

Figure 4: Thermal efficiency versus temperature at state 2

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