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Methods used for evaluation of actual power generating thermal cycles and comparing them

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ABSTRACT

In this study, thermodynamic optimization criteria used for assessing thermal engines are investigated and compared. The Purpose of this is to determine the most advantageous criteria. An irreversible Carnot cycle is analyzed by using five different methods and results are compared. According to calculations, the ecological function criterion (ECF) is defined as the most convenient optimization method. Although, its work output is less than the maximum work criteria and maximum available work (MAW), it has advantageous in terms of entropy generation and first law efficiency. In addition, ecological coefficient of performance (ECOP) and exergetic performance criteria (EPC) values provide minimum entropy generation and maximum efficiency at their maximum, however, their work output is very small. ECF obtains its maximum values at $x = 0.488$ (377.175 kW) for endoreversible cycle and at $x = 0.477$ (329.812 kW) for irreversible cycle. For these reasons, ECF is suggested as the best optimization criteria.

Introduction

Analysis of the irreversible thermodynamic systems has been gained importance especially after the petrol crisis happened in 1970s. This new thermodynamic branch was called as Finite-Time-Thermodynamics (FTT). First studies at this area are about the endoreversible power cycle that is external irreversible and internal reversible cycles. This engine is called as the Curzon-Ahlborn-Novikov (CAN) engine [1,2]. This engine provides us more realistic results than Carnot cycle that operates totally reversible. In addition to these studies, maximum work extracted from an irreversible system was investigated by the several authors [3–5]. Angulo-Brown proposed a criterion called as ecological function (ECF) [6]. Yan suggested to use T_o (heat sink temperature) instead of T_L (heat sink temperature) [7]. Several papers can be found in literature about ecological optimization [8–39]. Another thermo-ecological criterion called as ecological coefficient of performance (ECOP) was presented and applied various thermodynamic cycles [40–49]. Similar performance coefficient in order to determine relationship between exergy and exergy destruction for a cycle presented so called exergetic performance criteria (EPC) [50–54]. Another effort are to obtain a method for application of exergy concept in FTT. A number of study were published by the several authors [55–66]. A new criteria for assessing actual thermal cycles was submitted by Açıkkalp and Yamık [67]. This method is called as max available work (MAW) and it used for determining limits of real cycles.

In this paper, all of these methods are applied to an irreversible Carnot cycle and compared. There are no study comparing these methods and determining the most advantageous one in the open literature. Methods mentioned above are applied to an irreversible Carnot like thermal engine and results are compared. Finally, the most advantageous method is suggested in the conclusion section.

System description and thermodynamic analysis

Carnot cycle presents thermodynamic upper bonds for a thermal cycle. This cycle is totally reversible and contains two isentropic and two adiabatic processes. There is no internal or external irreversibility in the cycle, in addition, it is a theoretical cycle. However, there is no reversible cycle in reality. All cycles includes irreversibilities based on heat transfer at the finite temperature difference, friction, fast expansion and compressing, mixing etc. In considered system, cycle is totally irreversible and it is illustrated in Fig. 1. Analysis is performed for infinite heat source and heat sink. Thermodynamic parameters are listed as following:

Added heat to the system (kW):

$$\dot{Q}_H = k_H(T_H - T_{FH}) \tag{1}$$

where T_H and T_{FH} are the heat source temperature and hot working fluid temperature respectively (K) and k_H is the heat conductance

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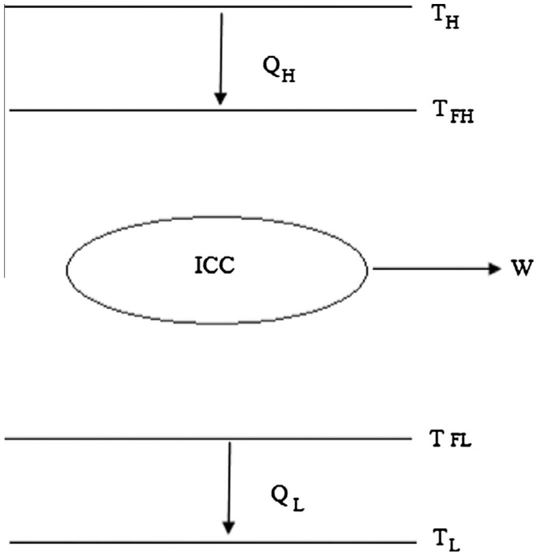

Fig. 1. Schematic of irreversible Carnot cycle.

(kW/K) between the hot temperature heat source and working fluid. Rejected heat from the system (kW):

$$\dot{Q}_L = k_L(T_{FL} - T_L) \tag{2}$$

where T_L and T_{FL} are the heat sink temperature and cool working fluid temperature (K) respectively and k_L is the heat conductance (kW/K) between the low temperature heat sink and working fluid. Work output of the system (kW):

$$\dot{W} = \dot{Q}_H - \dot{Q}_L \tag{3}$$

Entropy generation in the system (kW/K):

$$S_{gen} = \left(\frac{\dot{Q}_L}{T_L} - \frac{\dot{Q}_H}{T_H}\right) \tag{4}$$

First law efficiency of the system:

$$\eta = \frac{\dot{W}}{\dot{Q}_H} \tag{5}$$

Criteria to evaluate actual thermal cycles are ECF, ECOP, EPC and MAW. ECF and ECOP are aimed to determine the maximum power output while the exergy destruction is the minimum. EPC and MAW, similarly, try to the optimum point between exergy output and the exergy destruction.

Ecological function criteria (kW):

$$\mathrm{ECF} = \dot{W} - T_o(S_{gen}) \tag{6}$$

where T_o is environment temperature (K). Maximum available work (kW):

$$\mathrm{MAW} = \dot{Q}_H\left(1 - \frac{T_o}{T_H}\right) - T_o(S_{gen}) \tag{7}$$

Ecological coefficient of performance:

$$\mathrm{ECOP} = \frac{\dot{W}}{T_o(S_{gen})} \tag{8}$$

Exergetic performance criteria:

$$\mathrm{EPC} = \frac{\dot{Q}_H\left(1 - \frac{T_o}{T_H}\right)}{T_o(S_{gen})} \tag{9}$$

In this study, a methodology that was submitted by Chen et al. [23,24] is applied. Optimization parameter is chosen as ratio of hot fluid temperature T_{FL} to T_{FH} (x). In addition, parameter of the heat conductance rate $\left(y = \frac{k_{FL}}{k_{FH}}\right)$ and the sum of heat conductance rate $(z = k_{FL} + k_{FH})$ is defined. According to second law of the thermodynamics:

$$\frac{\dot{Q}_L}{T_{FL}} - \frac{\dot{Q}_H}{T_{FH}} \leqslant 0 \tag{10}$$

This inequality can be converted to an equality by describing an internal irreversibility parameter (I):

$$\frac{\dot{Q}_L}{T_{FL}} - I\frac{\dot{Q}_H}{T_{FH}} = 0 \tag{11}$$

According to all Eqs. (1)–(11):

Added heat to the system:

$$\dot{Q}_H = \frac{z}{1+y}\frac{y(T_Hx - T_L)}{(y+I)x} \tag{12}$$

Rejected heat from the system:

$$\dot{Q}_L = I\dot{Q}_H x \tag{13}$$

Work output of the system:

$$\dot{W} = \frac{(T_L - T_Hx)(Ix - 1)yz}{x(1+y)(I+y)} \tag{14}$$

Entropy generation in the system:

$$S_{gen} = \frac{(T_L - T_Hx)(T_L - IT_Hx)yz}{T_LT_Hx(1+y)(I+y)} \tag{15}$$

First law efficiency:

$$\eta = 1 - Ix \tag{16}$$

Ecological function criteria:

$$\mathrm{ECF} = \frac{(T_L - T_Hx)(T_H(IT_ox + T_L(Ix - 1)) - T_LT_o)yz}{T_LT_Hx(1+y)(I+y)} \tag{17}$$

Ecological coefficient of performance:

$$\mathrm{ECOP} = \frac{T_HT_L(Ix - 1)}{T_o(T_L - IT_Hx)} \tag{18}$$

Exergetic performance criteria:

$$\mathrm{EPC} = \frac{T_L(T_o - T_H)}{T_o(T_L - IT_Hx)} \tag{19}$$

Maximum available work:

$$\mathrm{MAW} = \frac{(T_Hx - T_L)(T_L - IT_ox)yz}{T_Lx(1+y)(I+y)} \tag{20}$$

Results and discussion

In this section, thermodynamics methods presented previous sections are searched in detail and compared to each other. Firstly, analyses is performed for classical thermodynamics parameters including the entropy production, work output, optimum (maximum) function value and first law efficiency. Secondly, other criteria are investigated and then, all results are compared to each other. According to calculations, system cannot be operated under the point x that is equal to 0.34, because of thermodynamic limitations. Fixed parameters used in the calculations listed in Table 1.