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Effect of heat transfer law on the finite-time exergoeconomic performance of a generalized irreversible carnot heat engine

Yi Zhang[1], Lingeng Chen[2,3,4], Guozhong Chai[1]

[1] College of Mechanical Engineering, Zhejiang University of Technology, Hangzhou, 310014, China.
[2] Institute of Thermal Science and Power Engineering, Naval University of Engineering, Wuhan 430033, China.
[3] Military Key Laboratory for Naval Ship Power Engineering, Naval University of Engineering, Wuhan 430033, China.
[4] College of Power Engineering, Naval University of Engineering, Wuhan 430033, China.

Abstract

The analytical expression for profit rate of a generalized irreversible Carnot heat engine cycle based on a generalized radiative heat transfer law $q \propto \Delta(T^n)$ is derived by applying the finite time exergoeconomic method, taking into account several additional irreversibilities, such as heat resistance, heat leakage and other undesirable irreversible factors. The compromise optimization between economics (profit rate) and the efficiency was obtained by searching the efficiency at maximum profit rate, which is termed as the finite time exergoeconomic performance bound.

Keywords: Finite-time thermodynamics; Generalized irreversible Carnot heat engine; Exergoeconomic performance; Generalized thermodynamic optimization; Heat transfer law.

1. Introduction

Recently, the intensive consumption of energy and the exhaustion of resources lead to the rising costs for energy. Hence, from the economic perspective, improvement of engine performance is urgently required. Finite-time thermodynamics [1-8] is a powerful tool often used to optimize thermodynamic parameters including power, efficiency, entropy generation, effectiveness, cooling load, heating load, loss of exergy, etc.

Nowadays, systems like heat engines are analyzed and designed based on the consideration of both thermodynamic parameters and cost accounting requirements after the research of Salamon and Nitzan [9, 10], which was to maximize the profit of an endoreversible heat engine by a combination of a thermodynamic analysis with an engineer economic analysis. In order to distinguish this method from the endoreversible analysis optimizing pure thermodynamic objectives, Chen *et al.* [11-17] analyzed the profit rate of thermal systems by attributing costs to input and output exergy and termed this method as finite-time exergoeconomic analysis and its performance bound at maximum profit as finite-time exergoeconomic performance bound. Other researches seeking for best economic performance of thermal systems were carried out on endoreversible engines, refrigerators and heat pumps by Ibrahim *et al*. [18], De Vos [19, 20] and Bejan [21], with the only irreversibility restricted to the heat transfer between the working fluid and the heat reservoirs. De Vos [19, 20] applied the Newton (linear) heat transfer law to derive the relation between the optimal efficiency and economic returns when carrying out thermoeconomics analysis for heat engine. Chen *et al*. [22] investigated the endoreversible thermoeconomic performance of heat engine with the heat transfer between the working fluid and the heat reservoirs obeying linear phenomenological law. Sahin *et al.* [23-26] proposed an optimization criterion considering thermodynamic parameters per unit total cost.

In many pioneer works concerning finite-time exergoeconomic optimization for heat engines, the basic thermodynamic model is endoreversible. However, a real heat engine will operate in an irreversible power cycle which incorporates several internal and external irreversibilities, such as heat resistance, bypass heat leakage, friction, turbulence and other undesirable irreversibility factors. Considering external and internal irreversibilities, Chen *et al.* [16-27] established a generalized irreversible Carnot heat engine model. As heat transfer is not necessarily Newtonian or linear phenomenological, a further step made in this paper is to establish a fundamental optimal relationship between profit and efficiency of the generalized irreversible Carnot heat engine based on generalized radiative heat transfer law $q \propto \Delta(T^n)$. The result obtained by searching the optimum efficiency at maximum profit involved three common heat transfer laws: Newton's law ($n = 1$), the linear phenomenological law ($n = -1$), and the radiative heat transfer law ($n = 4$). The relative studies can be seen in Refs. [28-35].

2. Cycle model and performance analysis

In order to conduct the simulation closer to the performance of an actual heat engine, Chen, *et al.* [16, 27] established a generalized irreversible steady flow Carnot heat engine cycle model as shown in Figure 1, considering heat resistance, heat leakage, and internal irreversibilities. The working fluid in this generalized irreversible engine with constant-temperature heat-reservoirs flows steadily. The system undergoes a cycle which consists of four irreversible processes, two isothermal and two adiabatic. External irreversibilities are caused by the heat resistance existed in the high- and low-temperature heat-exchangers. Heat-transfer between the heat engine and its surrounding heat reservoirs leads to the difference between the working fluid temperature (T_{HC} and T_{LC}) and the heat-reservoir temperature (T_H and T_L). These temperatures are related to one another in the following order:

$$T_H > T_{HC} > T_{LC} > T_L \tag{1}$$

A constant rate of heat leakage (q) from the heat source at the temperature T_H to the heat sink at T_L is assumed for this system, which yields,

$$Q_H = Q_{HC} + q \tag{2}$$

$$Q_L = Q_{LC} + q \tag{3}$$

where Q_{HC} and Q_{LC} are the rates of heat-transfer supplied by the heat source and released to the heat sink by the working fluid, respectively; Q_H and Q_L are the real rates of heat-supply and heat-release, respectively. Assuming the heat-transfer law obeys $q \propto \Delta(T^n)$, the rate of heat leakage can be expressed as

$$q = C_i (T_H^n - T_L^n) \tag{4}$$

where C_i is the heat leakage coefficient.

When analyzing actual heat engines, heat resistance and heat leakage discussed above are not the only irreversibilities. Irreversibilities caused by friction, turbulence, and non-equilibrium activities inside the working fluid are also required to be considered. Thus when compared with an endoreversible Carnot heat engine of the same heat input, the generalized irreversible Carnot engine can deliver less power and release more heat to the heat sink. Hence, the rate of heat flow (Q_{LC}) to the heat sink for the generalized irreversible Carnot engine is larger than that (Q'_{LC}) for the endoreversible Carnot engine with the same input. A constant coefficient (φ) is introduced in the following expression to generally characterize the additional miscellaneous irreversible effects

$$\varphi = Q_{LC} / Q'_{LC} \geq 1 \tag{5}$$

Application of the second law of thermodynamics yields,

$$Q'_{LC} / T_{LC} = Q_{HC} / T_{HC} \tag{6}$$

Combining Eqs. (5) and (6) gives

$$Q_{LC} = \varphi Q_{HC} / x \tag{7}$$

where $x = T_{HC} / T_{LC}$ ($1 \leq x \leq T_H / T_L$) is the temperature ratio of the working fluid.
Application of the first law of thermodynamics gives the expressions of power output and thermal efficiency, respectively

$$P = Q_H - Q_L = Q_{HC} - Q_{LC} \tag{8}$$

$$\eta = P/Q_H = (Q_{HC} - Q_{LC})/(Q_{HC} + q) \tag{9}$$

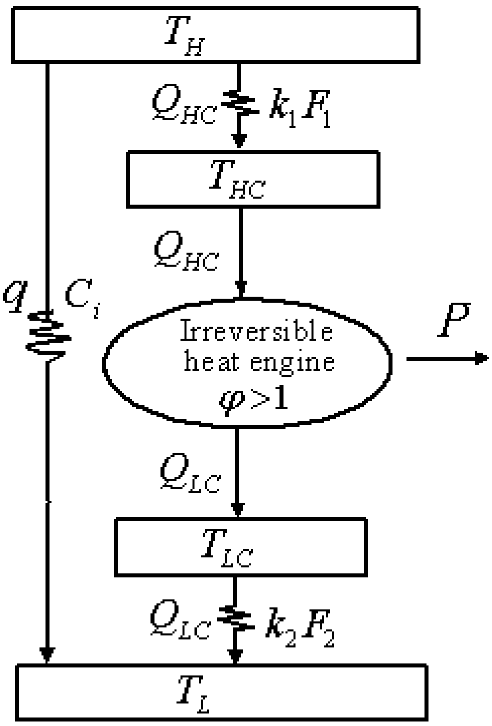

Figure 1. The generalized irreversible Carnot heat engine cycle model

Assuming the rates of the heat flow in the heat-exchangers follow the generalized radiative heat transfer law, $q \propto \Delta(T^n)$, where n is a heat transfer exponent, with $n = 1$ representing the Newton's law, $n = -1$ representing the linear phenomenological law and $n = 4$ representing the radiative heat transfer law. Then

$$Q_{HC} = k_1 F_1 (T_H^n - T_{HC}^n) \tag{10}$$

$$Q_{LC} = k_2 F_2 (T_{LC}^n - T_L^n) \tag{11}$$

where k_1 and k_2 are the overall heat-transfer coefficients of high- and low-temperature side heat-exchangers, F_1 and F_2 are the surface areas of high- and low-temperature side heat-exchangers. The total heat transfer surface area of the two heat exchangers is taken as a constant , that is

$$F_1 + F_2 = F_T \tag{12}$$

And a ratio (f) of heat exchanger area is defined as

$$f = F_1 / F_2 \tag{13}$$

Assuming that the prices of the work output and exergy input are ψ_1 and ψ_2 respectively, the profit rate (profit per unit time) of the generalized irreversible Carnot heat engine is [11]

$$\pi = \psi_1 P - \psi_2 A \tag{14}$$

where A is the rate of exergy input of the heat engine which can be expressed as

$$A = Q_H (1 - T_0/T_H) - Q_L (1 - T_0/T_L) = Q_H \varepsilon_1 - Q_L \varepsilon_2 \tag{15}$$

where ε_i is the Carnot coefficient of the reservoir and T_0 is the environmental temperature.
Combining Eqs. (2)-(3) and (7)-(15)gives

$$\eta = B'(x - \varphi)[T_H^n - (xT_L)^n] / \{B' x [T_H^n - (xT_L)^n] + q\} \tag{16}$$

$$\pi = B'\psi_1 [T_H^n - (xT_L)^n][x(1 - \varepsilon_1 \psi_2/\psi_1) - \varphi(1 - \varepsilon_2 \psi_2/\psi_1)] + q\psi_2 (\varepsilon_2 - \varepsilon_1) \tag{17}$$

Where $B' = k_1 f F_T / [(1 + f)(x + x^n \varphi f\, k_1/k_2)]$.
Maximizing η and π with respect to f by setting $d\eta/df = 0$ and $d\pi/df = 0$ using Eqs. (16) and (17) yields the same optimal ratio of heat-exchanger area (f_{opt})

$$f = f_{opt} = [k_2 / (x^{n-1} \varphi k_1)]^{0.5} \tag{18}$$

Substituting Eq. (18) into Eqs. (16) and (17), respectively, yields the optimal efficiency and profit rate in the following forms:

$$\eta = B(x - \varphi)[T_H^n - (xT_L)^n] / \{Bx[T_H^n - (xT_L)^n] + q\} \tag{19}$$

$$\pi = B\psi_1 [T_H^n - (xT_L)^n][x(1 - \varepsilon_1 \psi_2/\psi_1) - \varphi(1 - \varepsilon_2 \psi_2/\psi_1)] + q\psi_2 (\varepsilon_2 - \varepsilon_1) \tag{20}$$

where $B = k_1 F_T / [x^{0.5} + (x^n \varphi k_1/k_2)^{0.5}]^2$.
Maximum profit rate and maximum efficiency with respect to temperature ratio can be derived by taking derivatives of Eq.(19) and Eq.(20) with respect to x. However, in general, the optimal temperature ratio

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x_π at maximum profit rate $\pi_{\max}$ does not equal to the optimal temperature ratio x_η at maximum efficiency $\eta_{\max}$. The optimal temperature ratio x_π at maximum profit rate $\pi_{\max}$ can be derived by taking the derivative of the profit rate with temperature ratio and setting it equal to zero ($d\pi/dx = 0$). By substituting the optimal temperature ratio x_π into Eq. (20), the maximum profit rate can be achieved. Furthermore, the finite-time exergoeconomic bound of the generalized irreversible Carnot heat engine will be obtained by substituting the optimal temperature ratio x_π with respect to maximum profit rate into Eq. (19).

3. Discussions

3.1 Effects of various losses on the performance

If $\varphi = 1$ and $q > 0$, Eq.(19) and Eq.(20) become

$$\eta = B_{en}(x-1)[T_H^n - (xT_L)^n] / \{B_{en}x[T_H^n - (xT_L)^n] + q\} \tag{21}$$

$$\pi = B_{en}\psi_1[T_H^n - (xT_L)^n][x(1-\varepsilon_1\psi_2/\psi_1) - (1-\varepsilon_2\psi_2/\psi_1)] + q\psi_2(\varepsilon_2 - \varepsilon_1) \tag{22}$$

where $B_{en} = k_1 F_T / [x^{0.5} + (x^n k_1/k_2)^{0.5}]^2$. Eqs. (21) and (22) are the relations between profit rate and efficiency of the irreversible Carnot heat engine with heat resistance and heat leakage losses.

If $\varphi > 1$ and $q = 0$, Combining Eq.(19) and Eq.(20) gives

$$\pi = B_{en}\phi\psi_1\{T_H^n - [\phi T_L/(1-\eta)]^n\}[(1-\varepsilon_1\psi_2/\psi_1)/(1-\eta) - (1-\varepsilon_2\psi_2/\psi_1)] \tag{23}$$

Eq. (23) is the relation between profit rate and efficiency of the irreversible Carnot heat engine with heat resistance and internal irreversibility losses.

If $\varphi = 1$ and $q = 0$, Eq. (23) is reduced to

$$\pi = B_{en}\psi_1\{T_H^n - [T_L/(1-\eta)]^n\}[(1-\varepsilon_1\psi_2/\psi_1)/(1-\eta) - (1-\varepsilon_2\psi_2/\psi_1)] \tag{24}$$

Eq. (24) is the relation between profit rate and efficiency of the endoreversible Carnot heat engine [11].

3.2 Special cases

(1) Case of $n = 1$

In the case of $n = 1$, Eq.(19) and Eq.(20) become:

$$\eta = (x - \varphi)(T_H x^{-1} - T_L) / (T_H - xT_L + qB^{-1}) \tag{25}$$

$$\pi = B\psi_1(T_H x^{-1} - T_L)[x(1-\varepsilon_1\psi_2/\psi_1) - \varphi(1-\varepsilon_2\psi_2/\psi_1)] + q\psi_2(\varepsilon_2 - \varepsilon_1) \tag{26}$$

where $B = k_1 F_T / [1 + (\varphi k_1/k_2)^{0.5}]^2$. Maximizing π with respect to x by setting $d\pi/dx = 0$ in Eq. (26) yields the optimal temperature ratio and the maximum profit rate of the heat engine:

$$x_{opt} = (\varphi \frac{T_H}{T_L} \frac{\psi_1 - \varepsilon_2\psi_2}{\psi_1 - \varepsilon_1\psi_2})^{0.5} \tag{27}$$

$$\pi_{\max} = B\{[T_H(\psi_1 - \varepsilon_1\psi_2)]^{0.5} - [\varphi T_L(\psi_1 - \varepsilon_2\psi_2)]^{0.5}\}^2 + \psi_2 q(\varepsilon_2 - \varepsilon_1) \tag{28}$$

Substituting Eq. (27) into Eq. (25) gives η_π, which is the finite-time exergoeconomic bound of generalized irreversible Carnot heat engine with Newton's heat transfer law

$$\eta_\pi = \frac{T_H + \varphi T_L - (\varphi T_H T_L)^{0.5}\{[(\psi_1 - \varepsilon_1\psi_2)/(\psi_1 - \varepsilon_2\psi_2)]^{0.5} + [(\psi_1 - \varepsilon_2\psi_2)/(\psi_1 - \varepsilon_1\psi_2)]^{0.5}\}}{T_H - (\varphi T_H T_L)^{0.5}[(\psi_1 - \varepsilon_2\psi_2)/(\psi_1 - \varepsilon_1\psi_2)]^{0.5} + qB^{-1}} \tag{29}$$

(2) Case of $n = -1$
In the case of $n = -1$, Eq.(19) and Eq.(20) become

$$\eta = B_1(x - \phi)(T_L^{-1} - xT_H^{-1}) / [B_1 x(T_L^{-1} - xT_H^{-1}) + q] \tag{30}$$

$$\pi = B_1\psi_1[T_L^{-1} - xT_H^{-1}][x(1 - \varepsilon_1\psi_2/\psi_1) - \phi(1 - \varepsilon_2\psi_2/\psi_1)] + q\psi_2(\varepsilon_2 - \varepsilon_1) \tag{31}$$

where $B_1 = k_1F_T / [x + (\phi k_1/k_2)^{0.5}]^2$. Maximizing π with respect to x by setting $d\pi/dx = 0$ in Eq. (29) yields the optimal temperature ratio and the maximum profit rate of the heat engine

$$x_{opt} = \frac{2T_H\phi(1 - \varepsilon_2\psi_2/\psi_1) + (\varphi k_1/k_2)^{0.5}[T_L\phi(1 - \varepsilon_2\psi_2/\psi_1) + T_H(1 - \varepsilon_1\psi_2/\psi_1)]}{2T_L(\varphi k_1/k_2)^{0.5}(1 - \varepsilon_1\psi_2/\psi_1) + T_L\phi(1 - \varepsilon_2\psi_2/\psi_1) + T_H(1 - \varepsilon_1\psi_2/\psi_1)} \tag{32}$$

$$\pi_{\max} = B_\pi\psi_1[T_L^{-1} - x_{opt}T_H^{-1}][x_{opt}(1 - \varepsilon_1\psi_2/\psi_1) - \varphi(1 - \varepsilon_2\psi_2/\psi_1)] + q\psi_2(\varepsilon_2 - \varepsilon_1) \tag{33}$$

Substituting Eq. (32) into Eq. (30) gives η_π, which is the finite-time exergoeconomic bound of generalized irreversible Carnot heat engine based on linear phenomenological heat transfer law

$$\eta_\pi = (x_{opt} - \varphi) / \{x_{opt} + qT_HT_L / [B_\pi(T_H - x_{opt}T_L)]\} \tag{34}$$

where $B_\pi = k_1F_T / [x_{opt} + (\varphi k_1/k_2)^{0.5}]^2$.

(3) Case of $n = 4$
In the case of $n = 4$, Eq.(19) and Eq.(20) become

$$\eta = B_4(x - \varphi)[T_H^4 - (xT_L)^4] / \{B_4 x[(T_H)^4 - (xT_L)^4] + q\} \tag{35}$$

$$\pi = B_4\psi_1[T_H^4 - (xT_L)^4][x(1 - \varepsilon_1\psi_2/\psi_1) - \varphi(1 - \varepsilon_2\psi_2/\psi_1)] + q\psi_2(\varepsilon_2 - \varepsilon_1) \tag{36}$$

where $B_4 = k_1F_T / [x^{0.5} + x^2(\varphi k_1/k_2)^{0.5}]^2$. Eqs (35) and (36) are the relations between profit rate and efficiency of the irreversible Carnot heat engine based on the radiative heat transfer law.

The relationships between the profit rate and efficiency of the irreversible Carnot heat engine for all discussed cases are shown in Figure 2 and Figure 3. It can be concluded from the figure that the profit rate versus efficiency is a loop-shaped curve for all cases with heat leakage. For the cases without heat leakage, the profit rate decreases when the irreversibility factor φ increases with the shape of the curve remaining parabolic. For the case of $n < 0$, the optimal efficiency at the maximum profit rate increases with the increase of n as shown in Figure 2. While, for the case of $n > 0$, the optimal efficiency at the maximum profit rate decreases with the increase of n as shown in Figure 3. When n increases, the influence of temperature on power becomes more remarkable. Hence, when n is relatively large, by slightly sacrificing the efficiency, a significant increase of power can be achieved.

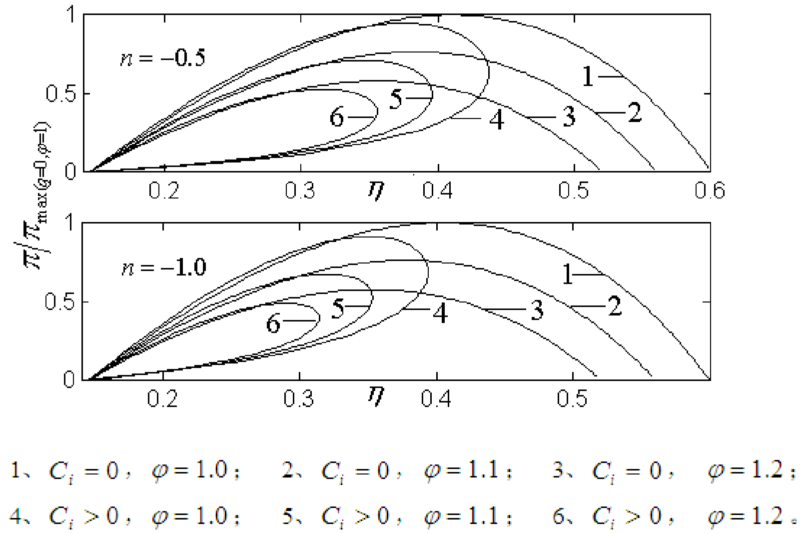

Figure 2. The influences of heat leak, internal irreversibility and heat transfer law on $\pi-\eta$ characteristic for $n<0$

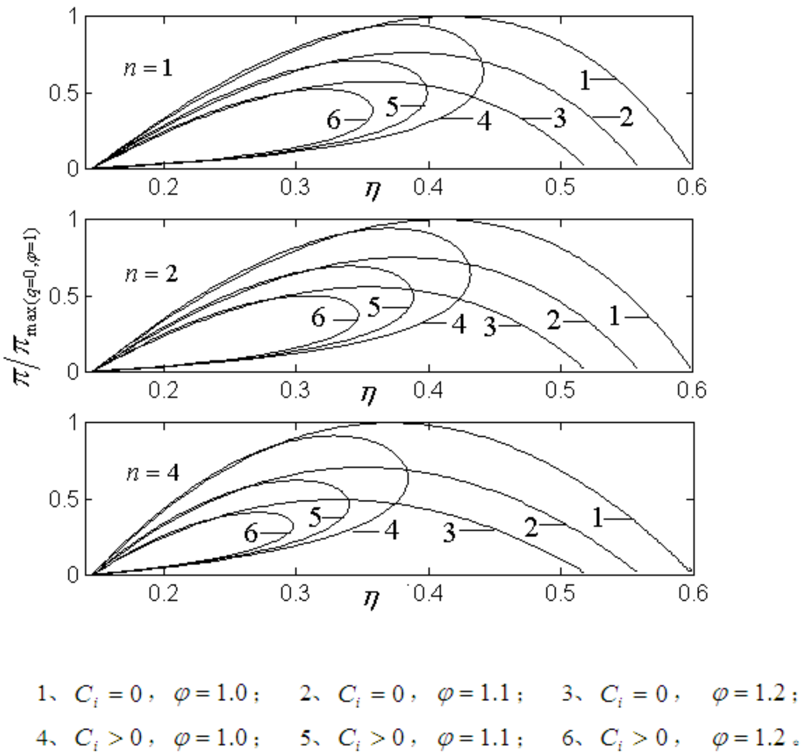

Figure 3. The influences of heat leak, internal irreversibility and heat transfer law on $\pi-\eta$ characteristic for $n>0$

3.3 The effect of price ratio ψ_2/ψ_1

The finite-time exergoeconomic performance bound at the maximum profit rate is different from the classical reversible bound and the finite-time thermodynamic bound. It is dependent on T_H, T_L, T_0 and ψ_2/ψ_1. In order to ensure the process being potential profitable, $0<\psi_2/\psi_1<1$ is required.

As the price of work output becomes very large compared with that of exergy input, i.e., $\psi_2/\psi_1\to 0$, the function of the profit rate becomes

$$\pi = B\psi_1(x-\varphi)[T_H^n - (xT_L)^n] = \psi_1(Q_{Hc} - Q_{Lc}) = \psi_1 P \tag{37}$$

The optimization of the profit rate also leads to the maximization of the power output P of the generalized irreversible heat engine cycle.
On the other hand, with the price of work output approaching the price of the exergy input, i.e. $\psi_2/\psi_1 \to 1$, the function of the profit rate becomes

$$\pi = -\psi_1 T_0[(Q_{LC} + q)/T_L - (Q_{HC} + q)/T_H] = -\psi_1 T_0 \sigma \tag{38}$$

where σ is the rate of entropy production of the generalized irreversible heat engine cycle. When maximizing the profit under this condition, minimization of the losses of exergy can be achieved. Eq. (38) indicates that the heat engine is always operating at a loss, unless it operates reversibly to reach the break-even point.
Therefore, for any intermediate values of ψ_2/ψ_1, the finite-time exergoeconomic performance bound (η_π) lies between the finite-time thermodynamic performance bound and the reversible performance bound.

4. Conclusion

The relationship between the optimal profit rate and efficiency of a generalized irreversible Carnot heat engine is derived based on generalized radiative heat transfer law. The influence of different heat transfer laws and irreversibilities on this relationship has been discussed. The results are helpful for establishing a link among finite-time exergoeconomic performance bound, finite-time thermodynamic performance bound and the reversible performance bound.

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Yi Zhang is currently pursuing his PhD in Zhejiang University of Technology, P R China. He received his BS Degree in 2009 and MS Degree in 2010 in Electromechanical Engineering from Group T-International University College, Belgium. His work covers topics in finite time thermodynamics for Carnot and Brayton cycles.

Lingeng Chen received all his degrees (BS, 1983; MS, 1986, PhD, 1998) in power engineering and engineering thermophysics from the Naval University of Engineering, P R China. His work covers a diversity of topics in engineering thermodynamics, constructal theory, turbomachinery, reliability engineering, and technology support for propulsion plants. He had been the Director of the Department of Nuclear Energy Science and Engineering, the Superintendent of the Postgraduate School, and the President of the College of Naval Architecture and Power. Now, he is the Direct, Institute of Thermal Science and Power Engineering, the Director, Military Key Laboratory for Naval Ship Power Engineering, and the President of the College of Power Engineering, Naval University of Engineering, P R China. Professor Chen is the author or co-author of over 1400 peer-refereed articles (over 620 in English journals) and nine books (two in English).
E-mail address: lgchenna@yahoo.com; lingenchen@hotmail.com, Fax: 0086-27-83638709 Tel: 0086-27-83615046.

Guozhong Chai received his BS Degree in 1982 and MS Degree in 1984 in Chemical Process Machinery from Zhejiang University of Technology, P R China, and received his PhD Degree in 1994 in Chemical Process Machinery from East China University of Science and Technology, P R China. His work covers topics in computational mechanics, fracture and damage mechanics and their engineering applications. He has been the Dean of the College of Mechanical Engineering, Zhejiang University of Technology, P R China. Now he is the Dean of the Faculty of Engineering II, Zhejiang University of Technology, P R China. Professor Chai is the author or co-author of over 126 peer-refereed papers.