INTERNATIONAL JOURNAL OF
ENERGY AND ENVIRONMENT

Volume 6, Issue 5, 2015 pp.517-526
Journal homepage: www.IJEE.IEEFoundation.org

Finite-time exergoeconomic performance of a generalized irreversible Carnot heat engine with complex heat transfer law

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Abstract
The finite time exergoeconomic performance of the generalized irreversible Carnot heat engine with the losses of heat resistance, heat leakage and internal irreversibility, and with a complex heat transfer law, including generalized convective heat transfer law and generalized radiative heat transfer law, $q \propto (\Delta T^n)^m$, is investigated in this paper. The focus of this paper is to obtain the compromised optimization between economics (profit) and the energy utilization factor (efficiency) for the generalized irreversible Carnot heat engine, by searching the optimum efficiency at maximum profit, which is termed as the finite time exergoeconomic performance bound. The obtained results include those obtained in many literatures and can provide some theoretical guidelines for the design of practical heat engines.

Keywords: Finite time thermodynamics; Generalized irreversible Carnot heat engine; Exergoeconomic performance.

1. Introduction
Classical thermodynamic processes are based on reversible assumption. However, reversible processes need the processes to operate infinitely slowly and they are difficult to realize in practice. Finite time thermodynamics [1-12] extends the reversible process to include rate constraints. It has been a powerful tool in the thermodynamic analysis and optimization for finite time processes and finite size devices. In the analysis and optimization of heat engine cycles, various optimization objectives have been adopted, including power, specific power, power density, efficiency, efficient power, entropy production, effectiveness, ecological objective function and loss of exergy. Salamon and Nitzan [13] viewed the operation of an endoreversible heat engine as a production process with work as its output. They carried out the economic optimization of the heat engine with the maximum profit as the objective function [14].
A relatively new method that combines exergy with conventional concepts from long-run engineering economic optimization to evaluate and optimize the design and performance of energy systems is exergoeconomic (or thermoeconomic) analysis [15, 16]. Salamon and Nitzan's work [13] combined the endoreversible model with exergoeconomic analysis. It was termed as finite time exergoeconomic analysis [17-27] to distinguish it from the endoreversible analysis with pure thermodynamic objectives

and the exergoeconomic analysis with long-run economic optimization. Similarly, the performance bound at maximum profit was termed as finite time exergoeconomic performance bound to distinguish it from the finite time thermodynamic performance bound at maximum thermodynamic output. A similar idea was provided by Ibrahim *et al*. [28], De Vos [29, 30] and Bejan [31]. Zheng *et al*. [20] obtained the maximum exergoeconomic performance of a class of universal steady flow endoreversible heat engine cycles with Newton heat transfer law. Ding *et al.* [25, 26] provided a unified description of finite time exergoeconomic performance of the universal endoreversible [25] and irreversible [26] heat engine cycles with Newton heat transfer law. Chen *et al*. [19] obtained the maximum exergoeconomic performance of generalized irreversible Carnot engine with Newton heat transfer law.

In general, heat transfer is not necessarily linear. Heat transfer law has the significant influence on the finite time exergoeconomic performance of heat engines [32-34]. Li *et al.* [35, 36] investigated the fundamental optimal relationship between power output and efficiency of the endoreversible [35] and the generalized irreversible [36] Carnot heat engines by using a complex heat transfer law, including generalized convective heat transfer law [$q \propto (\Delta T)^n$] and generalized radiative heat transfer law[$q \propto (\Delta T^n)$], $q \propto (\Delta T^n)^m$, in the heat transfer processes between the working fluid and the heat reservoirs. Li *et al.* [37] further obtained the finite-time exergoeconomic performance of an endoreversible Carnot heat engine with the complex heat transfer law. Sahin *et al.* [38-41] provided a new thermoeconomic optimization criterion, thermodynamic output rates (power, cooling load or heating load for heat engine, refrigerator or heat pump) per unit total cost, investigated the performances of endoreversible heat engine [38], refrigerator and heat pump [39], combined cycle refrigerator [40], combined cycle heat pump [41] as well as irreversible heat engine [42], refrigerator and heat pump [43], combined cycle refrigerator [44], combined cycle heat pump [45], three-heat-reservoir absorption refrigerator and heat pump [46].

This paper will extend the previous work to find the optimal exergoeconomic performance of the generalized irreversible Carnot heat engine by using a complex heat transfer law, $q \propto (\Delta T^n)^m$, in the heat transfer processes between the working fluid and the heat reservoirs of the heat engine.

2. Generalized irreversible Carnot engine model

The generalized irreversible Carnot engine and its surroundings to be considered in this paper are shown in Figure 1. The following assumptions are made for this model [7, 19, 36, 47-49]:

(i) The working fluid flows through the system in a quasistatic-state fashion. The cycle consists of two isothermal processes and two adiabatic processes. All four processes are irreversible.

(ii) Because of the heat transfer, the working fluid temperatures (T_{HC} and T_{LC}) are different from the reservoir temperatures (T_H and T_L). These temperatures satisfy the following inequality: $T_H > T_{HC} > T_{LC} > T_L$. The heat-transfer surface areas (F_1 and F_2) of high- and low-temperature heat exchangers are finite. The total heat transfer surface area (F) of the two heat exchangers is assumed to be a constant: $F = F_1 + F_2$.

(iii) There exists a constant rate of bypass heat leakage (q) from the heat source to the heat sink. This bypass heat leakage model was advanced first by Bejan [50, 51] and was extended by Gordon and Huleihil [52] and Chen *et al.* [53, 54]. Thus, on has $Q_H = Q_{HC} + q$ and $Q_L = Q_{LC} + q$, where Q_{HC} is due to the driving force of $T_H - T_{HC}$, Q_{LC} is due to the driving force of $T_{LC} - T_L$, Q_H is rate of heat transfer supplied by the heat source and Q_L is rate of heat transfer released to the heat sink.

(iv) A constant coefficient Φ is introduced to characterize the additional internal miscellaneous irreversibility effect: $\Phi = Q_{LC} / Q_{LC}^{'} \geq 1$, where Q_{LC} is the rate of heat flow from the cold working fluid to the heat sink for the generalized irreversible Carnot engine, while $Q_{LC}^{'}$ is that for the Carnot engine with the only loss of heat resistance.

If $q = 0$ and $\Phi = 1$, the model is reduced to the endoreversible Carnot engine [35, 37, 55-60]. If $q = 0$ and $\Phi > 1$, the model is reduced to the irreversible Carnot engine with heat resistance and internal irreversibility [61]. If $q > 0$ and $\Phi = 1$, the model is reduced to the Carnot engine with heat resistance and heat leak losses [50, 51, 53, 54].

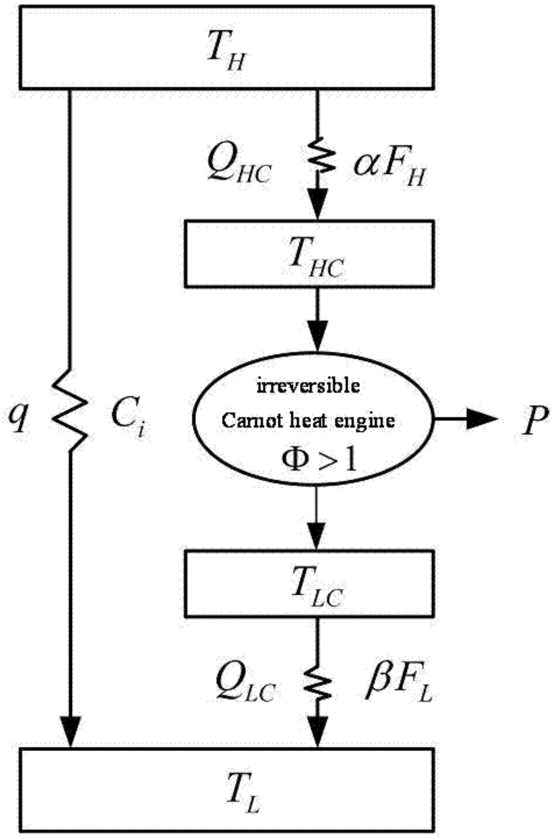

Figure 1. Generalized irreversible Carnot heat engine model

3. Generalized optimal characteristics

The second law of thermodynamics requires that

$$Q_H / T_{HC} = Q_L / T_{LC} \tag{1}$$

The first law of thermodynamics gives that the power output and the efficiency of the heat engine are

$$P = Q_H - Q_L = Q_{HC} - Q_{LC} \tag{2}$$

$$\eta = P/Q_H = P/(Q_{HC} + q) \tag{3}$$

Consider that the heat transfer between the heat engine and its surroundings follow a complex law $q \propto (\Delta T^n)^m$. Then

$$Q_{HC} = \alpha F_1 (T_H^n - T_{HC}^n)^m, \quad Q_{LC} = \beta F_2 (T_{LC}^n - T_L^n)^m \tag{4}$$

where α is the overall heat transfer coefficient and F_1 is the heat transfer surface area of the high-temperature-side heat exchanger; β is the overall heat transfer coefficient and F_2 is the heat transfer surface area of the low-temperature-side heat exchanger.

Defining the heat transfer surface area ratio (f) and working fluid temperature ratio (x) as follows: $f = F_1/F_2$, $x = T_{LC}/T_{HC}$, where $T_L/T_H \le x \le 1$. From Equations (1)-(4), one can obtain

$$P = \frac{\alpha F f (T_H^n x^{-n} - T_L^n)^m (x - \Phi)}{x(1+f)[x^{-n} + (\Phi r f x^{-1})^{1/m}]^m} \tag{5}$$

$$\eta = \frac{\alpha Ff(T_H^n x^{-n} - T_L^n)^m (x-\Phi)}{x\alpha Ff(T_H^n x^{-n} - T_L^n)^m + qx(1+f)[x^{-n} + (\Phi rfx^{-1})^{1/m}]^m} \tag{6}$$

where $r = \alpha/\beta$. Assuming the environment temperature is T_0 and the rate of exergy input of the heat engine is

$$A_{rev} = Q_H(1 - T_0/T_H) - Q_L(1 - T_0/T_L) = Q_H\eta_1 - Q_L\eta_2 \tag{7}$$

where $\eta_1 = 1 - T_0/T_H$ and $\eta_2 = 1 - T_0/T_L$ are Carnot coefficients of the high- and low-temperature reservoirs, respectively. The profit of the heat engine is

$$\Pi = \psi_1 P - \psi_2 A_{rev} \tag{8}$$

where ψ_1 is the price of power output, ψ_2 is the price of exergy input rate. Substituting Equations (1)-(5) and (7) into Equation (8) yields

$$\Pi = \frac{\psi_1 \alpha Ff(T_H^n - T_L^n x^{-n})^m}{(1+f)[1 + (\Phi xrf)^{1/m} x^{-n}]^m}[1 - \Phi x - \frac{\psi_2}{\psi_1}(\eta_H - \Phi x\eta_L)] - \psi_2 q(\eta_H - \eta_L) \tag{9}$$

Equation (9) indicates that the profit of the irreversible Carnot heat engine is a function of the heat transfer surface area ratio (f) for the given T_H, T_L, T_0, α, β, n, m and x. Taking the derivatives of Π with respect to f and setting it equal to zero ($d\Pi/df = 0$) yields

$$f_{opt} = [x^{mn-1}/(\Phi r)]^{1/(m+1)} \tag{10}$$

The corresponding profit is

$$\Pi = \frac{\psi_1 \alpha F(T_H^n - T_L^n x^{-n})^m}{[1 + (\Phi rx^{1-mn})^{1/(m+1)}]^{m+1}}[1 - \Phi x - \frac{\psi_2}{\psi_1}(\eta_H - \Phi x\eta_L)] - \psi_2 q(\eta_H - \eta_L) \tag{11}$$

Maximizing Π with respect to x by setting $\partial\Pi/\partial x = 0$ in Equation (11) directly yields the maximum profit rate and the corresponding optimal working fluid temperature ratio x_{opt}, and substituting it into equation (6) yields the optimal thermal efficiency η_{opt}, that is, the finite-time exergoeconomic performance bound.

4. Discussions

4.1 Effect of different losses on the optimal characteristics

1. If there is no bypass heat leakage in the cycle (i.e., $q = 0$), Equation (11) becomes

$$\Pi = \frac{\psi_1 \alpha F(T_H^n - T_L^n x^{-n})^m}{[1 + (\Phi rx^{1-mn})^{1/(m+1)}]^{m+1}}[1 - \Phi x - \frac{\psi_2}{\psi_1}(\eta_H - \Phi x\eta_L)] \tag{12}$$

The profit versus efficiency characteristic is a parabolic-like one.

2. If there are heat resistance and by pass heat leakage in the cycle (i.e. $\Phi = 1$), Equation (11) becomes

$$\Pi = \frac{\psi_1 \alpha F(T_H^n - T_L^n x^{-n})^m}{[1 + (rx^{1-mn})^{1/(m+1)}]^{m+1}}[1 - x - \frac{\psi_2}{\psi_1}(\eta_H - x\eta_L)] - \psi_2 q(\eta_H - \eta_L) \tag{13}$$

The profit versus efficiency characteristic is a loop-shaped one.

3. If the engine is an endoreversible one (i.e., $\Phi = 1, q = 0$), Equation (11) becomes

$$\Pi = \frac{\psi_1 \alpha F(T_H^n - T_L^n x^{-n})^m}{[1+(x^{1-mn} r)^{1/(m+1)}]^{m+1}}[1 - x - (\psi_2/\psi_1)(\eta_H - x\eta_L)] \quad (14)$$

The profit versus efficiency characteristic is a parabolic-like one.

4.2 Effects of heat transfer law on the optimal characteristics

(1) Equations (11) can be written as follows when $m = 1$

$$\Pi = \frac{\psi_1 \alpha F(T_H^n - T_L^n x^{-n})}{[1+(\Phi r x^{1-n})^{1/2}]^2}[1 - \Phi x - \frac{\psi_2}{\psi_1}(\eta_H - \Phi x\eta_L)] - \psi_2 q(\eta_H - \eta_L) \quad (15)$$

It is the result of the generalized irreversible Carnot heat engine with generalized radiative heat transfer law. If $n = 1$, it is the result of the generalized irreversible Carnot heat engine with Newtown heat transfer law [19]. If $n = -1$, it is the result of the generalized irreversible Carnot heat engine with linear phenomenological heat transfer law. If $n = 4$, it is the result of the generalized irreversible Carnot heat engine with radiative heat transfer law.

(2) Equations (11) can be written as follows when $n = 1$

$$\Pi = \frac{\psi_1 \alpha F(T_H - T_L/x)^m}{[1+(\Phi r x^{1-m})^{1/(m+1)}]^{m+1}}[1 - \Phi x - \frac{\psi_2}{\psi_1}(\eta_H - \Phi x\eta_L)] - \psi_2 q(\eta_H - \eta_L) \quad (16)$$

It is the result of the generalized irreversible Carnot heat engine with generalized convective heat transfer law. If $m = 1$, it is the result of the generalized irreversible Carnot heat engine with Newtown heat transfer law [19]. If $m = 1.25$, it is the result of the generalized irreversible Carnot heat engine with Dulong-Petit heat transfer law [62].

4.3 Effects of price ratio on the profit and finite-time exergoeconomic performance bound

From Equation (11), it can be seen that besides T_H, T_L and T_0, ψ_2/ψ_1 also has the significant influences on the profit of generalized irreversible Carnot heat engine. Note that for the process to be potential profitable, the following relationship must exist: $0 < \psi_2/\psi_1 < 1$, because one unit of power input must give rise to at least one unit of exergy output rate. When the price of work output becomes very large compared with the price of the exergy input, i.e. $\psi_2/\psi_1 \to 0$, Equation (11) becomes

$$\Pi = \frac{\psi_1 \alpha F(T_H^n - T_L^n x^{-n})^m}{[1+(\Phi r x^{1-mn})^{1/(m+1)}]^{m+1}}(1 - \Phi x) = \psi_1 P \quad (17)$$

That is the profit rate maximization approaches the power maximization, where P is the power output of the generalized irreversible Carnot heat engine cycle [36].

When the price of work output approaches the price of the exergy input, i.e. $\psi_2/\psi_1 \to 1$, Equation (11) becomes

$$\Pi = \frac{\psi_1 \alpha F(T_H^n - T_L^n x^{-n})^m}{[1+(\Phi r x^{1-mn})^{1/(m+1)}]^{m+1}}(1 - \Phi x - \eta_H + \Phi x\eta_L) - \psi_1 q(\eta_H - \eta_L) = -\psi_1 T_0 \sigma \quad (18)$$

where σ is the entropy production rate of the heat engine. That is the profit maximization approaches the entropy production rate minimization, in other word, the minimum waste of exergy. When the cycle is endoreversible cycle, $\eta_{opt} = \eta_C = 1 - T_L/T_H$, that is the profit rate maximization approaches the reversible performance bound.

Therefore, for any intermediate values of ψ_2/ψ_1, the finite-time exergoeconomic performance bound (η_{opt}) lies between the finite-time thermodynamic performance bound and the reversible performance bound. η_{opt} is related to the latter two through the price ratio, and the associated thermal efficiency bounds are the upper and lower limits of η_{opt} .

5. Numerical examples

To show the profit vs. efficiency characteristic of the irreversible Carnot heat engine with the complex heat transfer law, one numerical example is provided. In the numerical calculations, $T_H = 1000K$, $T_L = 400K$, $T_0 = 300K$, $\alpha F = 4W / K^{mn}$, $\psi_1 = 1000$ yuan$/W$ and $q = C_i(T_H^n - T_L^n)^m$ are set, where C_i is the heat conductance of the heat leakage.

The effects of heat-leakage and internal irreversibility on the relation between profit and efficiency are shown in Figure 2. In this case, $\Phi = 1.0$, 1.05, 1.1, 1.2 , $C_i = 0.00W/K^5$, $0.02W/K^5$, $0.04W/K^5$ and $0.06W/K^5$, $\psi_2/\psi_1 = 0.3$, $n = 4$ and $m = 1.25$ are set. It shows that the internal irreversibility change the profit versus efficiency relationship quantitatively. The maximum profit and the finite-time exergoeconomic performance bound decrease with the increase of the internal irreversibility. The heat leakage changes the profit versus efficiency relation quantitatively and qualitatively. The characteristic of profit versus efficiency is become the loop-shaped curve from the parabolic-like one if the engine suffers a heat leakage loss. The maximum profit and the finite-time exergoeconomic performance bound decrease with increase of the heat leakage.

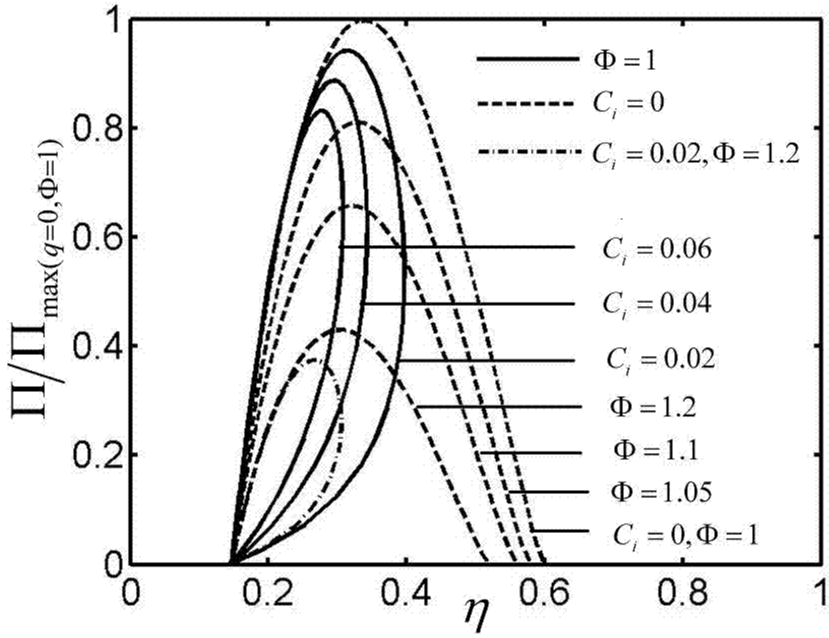

Figure 2. The effects of heat leakage and internal irreversibility on optimal relation of $\Pi - \eta$ of generalized irreversible Carnot heat engine with $\psi_2/\psi_1 = 0.3$, $n = 4$ and $m = 1.25$

The effects of heat transfer law on relations between profit and efficiency are shown in Figure 3. In the calculations, $\psi_2/\psi_1 = 0.3$, $\Phi =$ 1.2 and $C_i = 0.02W/K^{mn}$ are set. From Figure 3, it can be seen that heat transfer law changes the profit versus efficiency relation quantitatively and the bigger the value of mn , the smaller the efficiency at $\Pi = \Pi_{\max}$ point is when $n > 0$, and the bigger the absolute value of mn , the smaller the efficiency at $\Pi = \Pi_{\max}$ point is when $n < 0$.

Figure 4 shows the effects of the price ratio on the profit versus the efficiency for the generalized irreversible heat engine. In this case, $n = 4$ and $m = 1.25$ are set. In Figure 4, $\Pi_{\max,\psi_2/\psi_1=0}$ is the maximum profit when $\psi_2/\psi_1 = 0$. It can be seen that the price ratio has significant influences on the relation between the profit and efficiency, and the price ratio changes the profit versus efficiency relation quantitatively. When $\psi_2/\psi_1 = 0$, the profit rate maximization approaches the power maximization. From Figure 4, one can see that the larger the price ratio, the smaller the maximum profit.

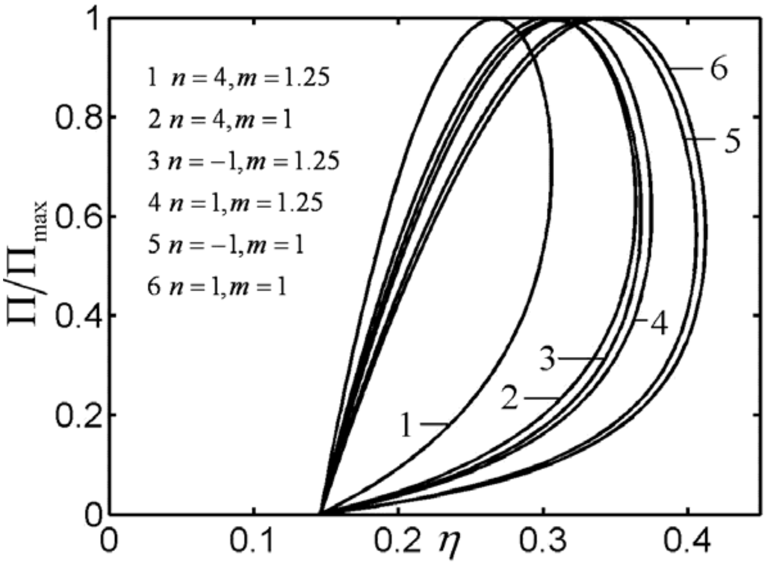

Figure 3. The effects of heat transfer laws on optimal relation of $\Pi-\eta$ of generalized irreversible Carnot heat engine with $\psi_2/\psi_1=0.3$

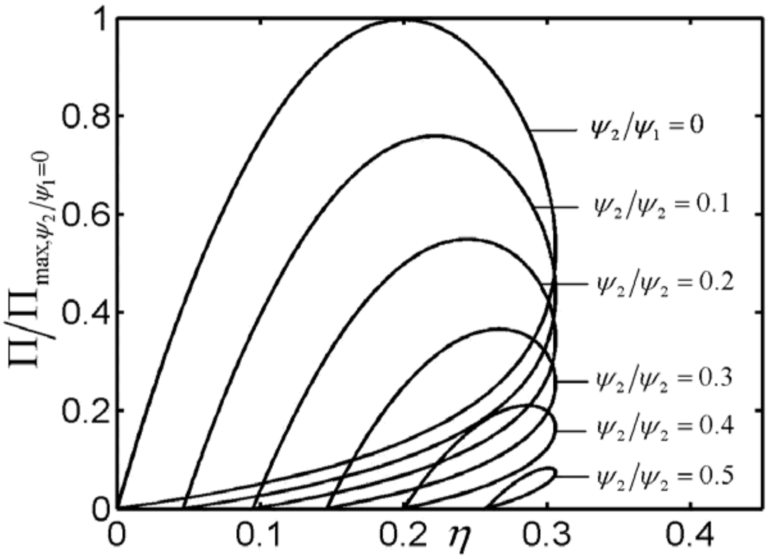

Figure 4. The effects of the price ratios on optimal relation of $\Pi-\eta$ of generalized irreversible Carnot heat engine with $n=4$ and $m=1.25$

6. Conclusion

This paper analyzes the exergoeconomic performance of a generalized irreversible Carnot heat engine with a complex heat transfer law, including generalized convective heat transfer law and generalized radiative heat transfer law. One seeks the economic optimization objective function instead of pure thermodynamic parameters by viewing the heat engine as a production process. It is shown that the economic and thermodynamic optimization converged in the limits $\psi_2/\psi_1\to 0$ and $\psi_2/\psi_1\to 1$. When the profit margin for exergy conversion is small, the maximum profit operation is near the minimum loss of exergy operation, while when the work is very cheap compared to the price of energy, the maximum profit operation is near the maximum power operation.

The results include those obtained in recent literatures, such as the optimal exergoeconomic performance of endoreversible Carnot heat engine with different heat transfer laws ($m=1$, $n\neq 0$, $q=0$, $\Phi=1$ and $m\neq 0$, $n=1$, $q=0$, $\Phi=1$), the optimal exergoeconomic performance of the Carnot heat engine with heat resistance and internal irreversibility ($m=1$, $n\neq 0$, $q=0$, $\Phi>1$ and $m\neq 0$, $n=1$, $q=0$, $\Phi>1$), the optimal exergoeconomic performance of the Carnot heat engine with heat resistance and heat leakage

($m=1$, $n\neq 0$, $q>0$, $\Phi=1$ and $m\neq 0$, $n=1$, $q>0$, $\Phi=1$ $q>0$), and optimal exergoeconomic performance of the generalized irreversible Carnot heat engine performance with generalized radiative heat transfer law $q\propto\Delta(T^n)$ ($m=1, n\neq 0$) and generalized convective heat transfer law $q\propto(\Delta T)^m$ ($n=1, m\neq 0$).

Acknowledgements
This paper is supported by The National Natural Science Foundation of P. R. China (Project No. 10905093).

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