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Generalized irreversible heat-engine experiencing a complex heat-transfer law

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Abstract

The fundamental optimal relation between optimal power-output and efficiency of a generalized irreversible Carnot heat-engine is derived based on a generalized heat-transfer law, including a generalized convective heat-transfer law and a generalized radiative heat-transfer law, $q \propto (\Delta T^n)^m$. The generalized irreversible Carnot-engine model incorporates several internal and external irreversibilities, such as heat resistance, bypass heat-leak, friction, turbulence and other undesirable irreversibility factors. The added irreversibilities, besides heat resistance, are characterized by a constant parameter and a constant coefficient. The effects of heat-transfer laws and various loss terms are analyzed. The results obtained corroborate those in the literature.

Keywords: Finite-time thermodynamics; Entropy-generation minimization; Irreversible Carnot heat-engine; Optimal performance; Heat-transfer law

1. Introduction

In the analysis of finite-time thermodynamics or entropy-generation minimization [1–8], the basic thermodynamic model is the Newtonian-law system endoreversible one, in which only the irreversibility of linear finite-rate heat-transfer is considered. Curzon and Ahlborn [9] derived the maximum power-output and the corresponding efficiency of an endoreversible Carnot heat-engine cycle with a Newtonian heat-transfer law $q \propto \Delta T$. Yan [10] derived the relation between the optimal efficiency and the optimal power-output for an endoreversible Carnot heat-engine, i.e., the fundamental optimal relation for the Carnot heat-engine with the Newtonian heat-transfer law. Sun et al. [11–13] obtained the holographic power versus efficiency spectrum, and formed the finite-time thermodynamic optimization criteria for the parameter selection of an endoreversible Carnot heat-engine with the Newtonian heat-transfer law.

However, real heat-engines are usually devices with internal and external irreversibilities. Besides the irreversibility of the finite-rate heat-transfer, there are also other sources of irreversibilities, such as the

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bypass heat-leaks, dissipation processes inside the working fluid, etc. Some authors have assessed the effects of the finite-rate heat-transfer, together with major irreversibilities on the performance of heat-engines using the heat resistance and bypass heat-leak model [14–17], heat resistance and internal irreversibility model [18]. Chen [8], Chen and Sun [19] and Chen et al. [20–23] established a generalized irreversible Carnot heat-engine model, which accounted for the effect of heat resistance, bypass heat-leak, and other internal irreversibilities, and derived its optimal performance assuming the Newtonian heat-transfer law applies.

In general, the heat transfer is not necessarily Newtonian. Some authors have assessed the effects of the linear phenomenological heat-transfer law $q \propto \Delta(T^{-1})$ and radiative heat-transfer law $q \propto \Delta(T^4)$ on the performance of endoreversible Carnot heat-engines [14,24–26], Gutowicz-Krusion et al. [27] first derived the efficiency bounds of an endoreversible Carnot heat-engine with one general heat-transfer law, i.e., the generalized convective heat-transfer law, $q \propto (\Delta T)^n$. Chen et al. [28], Angulo-Brown et al. [29] and Huleihil and Andresen [30] derived the optimal relation between power-output and efficiency based on this heat-transfer law. De Vos [31,32] first derived the optimal relation between power-output and efficiency of an endoreversible Carnot heat-engine with heat resistance between heat source and engine based on another general heat-transfer law, i.e., the generalized radiative heat-transfer law, $q \propto \Delta(T^n)$. Chen and Yan [33] and Gordon [34] further derived the optimal relation between power-output and efficiency of the endoreversible Carnot heat-engine based on this heat-transfer law. Feidt et al. [35] tried to find the optimal performance of endoreversible heat-engines with a universal heat-transfer law. Chen et al. [36,37] derived the optimal configurations for endoreversible heat-engines experiencing either the generalized radiative heat-transfer law or the mixed heat-transfer law.

Chen et al. [38] investigated the fundamental optimal relation between power-output and efficiency of the generalized irreversible Carnot heat-engine, assuming the generalized radiative heat-transfer law $q \propto \Delta(T^n)$, based on Refs. [20–23]. Zhou et al. [39] considered generalized convective heat-transfer law $q \propto (\Delta T)^n$ and obtained the fundamental optimal relation of the generalized irreversible Carnot heat-engine based on Refs. [20–23]. The effects of the linear phenomenological heat-transfer law, generalized radiative heat-transfer law and generalized convective heat-transfer law on the ecological optimal performance were analyzed by Chen et al. [40] and Zhu et al. [41,42].

One of aims of finite-time thermodynamics is to pursue generalized rules and results. This paper will extend the previous study to find the fundamental optimal relationship between power-output and efficiency of the generalized irreversible Carnot heat-engine based on Refs. [20–23] by using a new generalized heat-transfer law, including the generalized convective heat-transfer law and generalized radiative heat-transfer law, $q \propto (\Delta T^n)^m$ for 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 Fig. 1. The following assumptions are made for this model [8,19–22,38–42]:–

- 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.
- Because of the heat-transfer, the working fluid temperatures (T_{HC} and T_{LC}) are different from the corresponding reservoir temperatures (T_{H} and T_{L}). These temperatures satisfy the following inequalities: $T_{\mathrm{H}} > T_{\mathrm{HC}} > T_{\mathrm{LC}} > T_{\mathrm{L}}$. 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 heat-exchangers is assumed to be a constant: $F = F_1 + F_2$.
- 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 [14,15] and was extended by Gordon and Huleihil [43] and Chen et al. [16,17]. Thus $Q_{\mathrm{H}} = Q_{\mathrm{HC}} + q$ and $Q_{\mathrm{L}} = Q_{\mathrm{LC}} + q$, where Q_{HC} is due to the driving force of $T_{\mathrm{H}} - T_{\mathrm{HC}}$:$Q_{\mathrm{LC}}$ is due to the driving force of $T_{\mathrm{LC}} - T_{\mathrm{L}}$. 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.