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The entransy degeneration and entransy loss equations for the generalized irreversible Carnot engine system

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ABSTRACT

Basis of the generalized irreversible Carnot engine model and the generalized heat transfer law $Q \propto (\Delta T^m)^n$, the exergy loss methodology and the entransy loss methodology are employed to investigate the irreversibility of the generalized irreversible Carnot engine system (GICES). The mathematical expression of entransy loss and the exergy loss for different types of the GICES are derived. Additionally, two novel physical variables defined as potential entransy loss and entransy degeneration are proposed. Then, the entransy loss equilibrium and the entransy loss equation are derived. Moreover, with the Newton's heat transfer law and the generalized heat transfer law, the characteristics of entransy loss, exergy loss and entransy degeneration for the GICES are investigated. Finally, with the entransy degeneration, the entransy loss coefficient (φ) is defined, which can synthesize the entransy loss for the GICES and the entransy dissipation for the heat transfer system.

1. Introduction

Engineering technology has been developed at a high speed, which brings out the first and the second laws of thermodynamics [1]. The First Law provides the basic definition of thermodynamic energy, which states the rule of energy conservation in nature; while the Second Law indicates that a natural process runs only in one sense and is not reversible [1]. Based on the Second Law (or the entropy theory), the non-equilibrium thermodynamics was developed. Finite time thermodynamics is an important progress of the non-equilibrium thermodynamics [2–5]. The researches into identifying the performance limits of thermodynamic processes and optimization of thermodynamic cycles has made tremendous progress by using finite time thermodynamics [6–9].

Real heat engines are usually devices with internal and external irreversibilities. Therefore, based on the finite time thermodynamics, the generalized irreversible Carnot engine model [10–16] was established to describe all the irreversibilities of real heat engines. which accounted for the effect of heat resistance, bypass heat leakage and other irreversibilities, that is, the generalized irreversible Carnot engine combined the finite heat transfer and the heat-work conversion processes.

Heat transfer process is one the most important parts of the real heat engine, which mainly determines the energy utilization of the heat engines. Thus, to explore the effect of the heat transfer process to the heat engine, Chen et al. [17–23] proposed a generalized heat transfer law $Q \propto (\Delta T^m)^n$ to synthesize all kinds of the heat transfer laws: when $m = n = 1$, it is the Newton's heat transfer law; when $m = 4, n = 1$, it is the radiative heat transfer law.

In addition, heat transfer process is a typical non-equilibrium process. The application of the entropy theory in heat transfer and thermal design was firstly described in detail by Bejan [24–29]. With the increasing utilization of entropy generation in heat transfer engineering, the "entropy generation paradox" [30] exists when the entropy generation minimization is used as the optimization objective for counter-flow heat exchangers. As an attempt to resolve this paradox, Guo et al. [31] defined two new physical concepts, entransy and entransy dissipation, that is the entransy theory, which are analogous to the capacitance and the electric energy dissipation rate in an electric resistor [31,32]. For a system whose stored heat is Q and temperature is T, its entransy is defined as [31,32]:

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Nomenclature

A	the total heat transfer area, m^2
A_1	the heat transfer area between the hot reservoir and the endothermic temperature, m^2
A_2	the heat transfer area between the environment and exothermal temperature, m^2
$E_{x,H,C}$	the exergy of the hot reservoir in the Carnot engine system, J
$E_{x,H,i}$	the exergy of the hot reservoir in the common irreversible Carnot engine system, J
$E_{x,L,C}$	the exergy of the environment in the Carnot engine system, J
$E_{x,1,C}$	the exergy of the endothermic temperature in the Carnot engine system, K
$E_{x,1,i}$	the exergy of the endothermic temperature in the common irreversible Carnot engine system, K
$E_{x,2i,C}$	the exergy of exothermal temperature in the Carnot engine system, K
$E_{x,2i,i}$	the exergy of exothermal temperature in the common irreversible Carnot engine system, K
$G_{a,n}$	the entransy flow of anergy in the GICES, J·K
$G_{e,loss}$	the entransy flow of exergy loss in the GICES, J·K
$G_{g,HE}$	the entransy degeneration of exergy loss caused by the heat transfer resistance, J·K
$G_{g,HE,CA}$	the entransy degeneration of exergy loss caused by the heat transfer resistance corresponding to the state of NCCA efficiency, J·K
$G_{g,IE}$	the entransy degeneration of exergy loss caused by the irreversible Carnot engine, J·K
$G_{g,IE,CA}$	the entransy degeneration of exergy loss caused by the irreversible Carnot engine corresponding to the state of NCCA efficiency, J·K
$G_{g,leak}$	the entransy degeneration of exergy loss caused by the heat leakage, J·K
G_{diss}	The entransy dissipation of the heat transfer system (the special irreversible Carnot engine system), J·K
G_g	the total entransy degeneration of exergy loss in the whole generalized irreversible Carnot engine system, J·K
$G_{g,CA}$	the total entransy degeneration of exergy loss in the whole generalized irreversible Carnot engine system corresponding to the state of NCCA efficiency, J·K
$I_{g,HE,C}$	the exergy loss caused by the heat transfer resistance in the Carnot engine system, J
$I_{g,HE,CA}$	the exergy loss caused by the heat transfer resistance of the state of NCCA efficiency, J
$I_{g,HE,i}$	the exergy loss caused by the heat transfer resistance in the common irreversible Carnot engine system, J
$I_{g,IE}$	the exergy loss caused by the irreversible Carnot engine in the common irreversible Carnot engine system, J
$I_{g,HE,CA}$	the exergy loss caused by the irreversible Carnot engine of the state of NCCA efficiency, J
$I_{g,i}$	the exergy loss of (the irreversible influence to) the output mechanical work, J
$I_{g,leak}$	the exergy loss caused by the heat leak, J
$I_{total,C}$	the total exergy loss of the Carnot engine system, J
$I_{total,CA}$	the total exergy loss corresponding to the state of NCCA efficiency, J
$I_{total,i}$	the total exergy loss of the common irreversible Carnot engine system, J
$I_{total,s}$	the total exergy loss of the heat transfer system (the special irreversible Carnot engine system), J
Q_H	the heat discharged by the hot reservoir (T_H), J
Q_L	the heat absorbed by the environment (T_L), J
Q_1	the heat absorbed by the working fluid in the generalized irreversible Carnot engine, J
$Q_{1,a,n}$	the anergy of Q_1 in the GICES, J
$Q_{2,i}$	the heat discharged by the working fluid in the generalized irreversible Carnot engine, J
T_H	the temperature of the hot reservoir, K
T_L	the temperature of environment, K
T_1	the endothermic temperature of working fluid, K
$T_{2,i}$	the exothermal temperature of the working fluid, K
$W_{net,C}$	the effective output mechanical work of the Carnot engine system, J
$W_{net,CA}$	the effective output mechanical work corresponding to the state of NCCA efficiency, J
$W_{net,i}$	the effective output mechanical work of the common irreversible Carnot engine system, J
W_{out}	The output mechanical work of the generalized irreversible Carnot engine, J
a	the heat-transfer surface area ratio
m, n	the exponent of the generalized heat transfer law
q	the heat leakage, J
$q_{a,n}$	the anergy of the heat leakage, J
$q_{e,x}$	the exergy of the heat leakage, J
r	the heat transfer coefficient ratio
x	the temperature ratio of the endothermic and exothermal temperatures of the generalized irreversible Carnot engine
y	the temperature ratio between hot reservoir (T_H) and the environment (T_L)
k	the total heat transfer coefficient, $J \cdot m^{-2} \cdot K^{-1}$
k_1	the heat transfer coefficient between the hot reservoir and the endothermic temperature, $J \cdot m^{-2} \cdot K^{-1}$
k_2	the heat transfer coefficient between the environment and exothermal temperature, $J \cdot m^{-2} \cdot K^{-1}$
ΔG_{loss}	The entransy loss equation for the generalized irreversible Carnot engine system, J·K
$\Delta G_{loss,C}$	the entransy loss of the Carnot engine system, J·K
$\Delta G_{loss,CA}$	the entransy loss of the of the irreversible Carnot engine system corresponding to state of NCCA efficiency, J·K
$\Delta G_{loss,i}$	the entransy loss of the common irreversible Carnot engine system, J·K
$\Delta G_{loss,s}$	the entransy loss of the heat transfer system (the special irreversible Carnot engine system), J·K
$\Delta G_{loss,pot,C}$	the potential entransy loss of the Carnot engine system where the Carnot engine is working between the hot reservoir and the environment without any heat transfer resistance, J·K
$\Delta G_{W,net}$	the entransy variation caused by the effective output mechanical work, J·K
$\Delta G_{W,net,CA}$	the entransy variation caused by the effective output mechanical work corresponding to state of NCCA efficiency, J·K
ΔQ_{2i}	the irreversible influence to the heat discharged by the working fluid in the common irreversible Carnot engine system, J

Greek symbols

η	the efficiency of the generalized irreversible Carnot engine system
η_C	the efficiency of the Carnot engine
η_{CA}	the NCCA efficiency
η'_{IE}	the relative efficiency of the generalized irreversible Carnot engine system
$\eta_{net,i}$	the effective efficiency of the generalized irreversible Carnot engine system
$\eta_{net,CA}$	the effective efficiency of the generalized irreversible Carnot engine system corresponding to the state of NCCA efficiency
ϕ	the relative heat ratio
φ	the entransy loss coefficient