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Performance optimization of irreversible combined Carnot refrigerator based on ecological criterion

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ABSTRACT

This work presents a computational model based on exergy analysis for refrigeration cycles by taking the profit finite-time ecological optimization criterion as the objective. Firstly we investigate a generalized irreversible single refrigeration cycle with losses of heat leakage, internal irreversibility and external irreversibility, using this criterion. Then, we apply this study to a two-stage generalized irreversible combined refrigeration cycle. The optimal coefficient of performance (COP) and corresponding ecological function (E) of the combined cycle with respect to the two combined cycle design parameters (β_1 and β_2) are analyzed. This analysis identifies lower and upper bounds to the maximum ecological function and corresponding COP of the combined cycle. These results were compared with those of the single cycle. Finally we establish the optimal COP and maximum ecological function rational regions that define the design parameter limits of performed combined refrigeration cycles.

Optimisation de la performance d'un réfrigérateur combiné de Carnot irréversible basée sur les critères écologiques

Mots clés : Cycle frigorifique ; Thermodynamique à durée limitée ; Fonction écologique ; Limites du coefficient de performance

1. Introduction

In the last three decades, finite-time thermodynamics has been developed for heat and refrigeration cycle analyses. The correlation of finite-time thermodynamics to classical and nonequilibrium thermodynamics was studied (Bjarne, 1998; Chen et al., 1999; Chen and Sun, 2004; Denton, 2002; Wu et al., 1999). Performance optimization analyses of refrigeration cycles and devices have been investigated by a number of researchers using the concept of finite time thermodynamics by considering finite-time and finite-size constraints (Agnew and Ameli, 2004; Agrawal and Menon, 1990; Bautista and Méndez, 2005; Chiou et al., 1995; Goktun and Yavuz, 2000; Yan and Chen, 1990). Several authors have examined the finite-time thermodynamic performance analyses of refrigeration cycles based on new kinds of

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Nomenclature

A	Exergy output rate of the cycle
c	Temperature ratio
C_i	Heat leak coefficient between the heat sink and the cooled space ($W K^{-1}$)
COP	Coefficient of performance
E	Ecological function (W)
ξ	Dimensionless ecological function
q	Heat leakage constant rate (W)
Q	Heat flow rate (W)
$q_{Subscript}$	Dimensionless heat flow rate
R	Internal irreversibility degree
T	Temperature (K)
W	Work (W)

Greek symbols

α	Thermal conductance ($W K^{-1}$)
β	Thermal conductance ratio (external irreversibility parameter)
β_i	Heat leakage percentage
θ	Temperature ratios of the stage
ε	Carnot temperature ratios
σ	Loss rate of the irreversible refrigerator (W)
ΔS	Entropy generation (J)

Superscripts

I	Single stage cycle
II	Two-stage cycle

Subscripts

1	First stage
2	Second stage
A	Ambient
EI	Intermediate heat exchanger
H	Heat temperature space (condenser)
HC	Carnot heat temperature space
L	Low temperature space (evaporator)
LC	Carnot low temperature space
maxε	Maximum with respect to ε
maxβ	Maximum with respect to β
minβ	Minimum with respect to β

optimization criteria, the thermo-economic approach (Alexandros and Andres, 2014; Bahri and Kodal, 2002; Omid and Ali, 2011), the exergo-economic approach (Chen et al., 2001; Chen et al., 2011; Feng et al., 2011a, 2011b; Ding et al., 2011a, 2011b), the thermo-ecological criteria (Ust and Bahri, 2007), the ecological criteria (Chen et al., 1994, 2002, 2005, 2007a, 2007b, 2010, 2013; Ding et al., 2011a, 2011b; Feng et al., 2011a, 2011b; Ge et al., 2013; Wu et al., 2015), the exergy maximization approach (Bhattacharyya et al., 2007), Exergetic-economic-environmental approach (Aminyavari et al., 2014; Fazelpour and Morosuk, 2014; Sayyaadi and Nejatolahi, 2011) and the exergetic approach (Ahamed et al., 2011; Akhlish and Kaushik, 2008; Morosuk and Tsatsaronis, 2009; Sivakumar and Somasundaram, 2014; Zhang and Xu, 2011).

Most of these researchers focused on the performance optimization of single stage cycles. For optimization studies of combined two-stage cycles, there has been a little range of works. There has been a large range of recent works of combined multi-stage cycles. Agnew and Ameli (2004) studied the performance of a three stage cascade refrigeration system employing two different environmental friendly refrigerants to produce the minimum power consumption for a given refrigeration rate. Goktun and Yavuz (2000) studied the effects of thermal resistances and internal irreversibility on the performance of irreversible combined cycles (combined four stage vapor compression cycles and solar driven combined Brayton power and refrigeration cycles). Bautista and Méndez (2005) developed a generalized internally irreversible three heat source refrigerator with infinite heat capacities. Bahri and Kodal (2002) proposed a thermo-economic criterion for two-stage endoreversible combined refrigeration cycle optimization by defining cooling load per total cost. Omid and Ali (2011) used thermo-economic optimization method to analyze the CO_2/NH_3 cascade refrigeration cycle. In the same field, Alexandros and Andres (2014) investigated thermo-economic and exergy analysis of a decentralized liquefied natural gas-fueled combined-cooling-heating-and-power plant.

Chen et al. (1994) proposed another criterion based on exergy analysis defined as the ecological criterion (E), given as:

$$E = A/\tau - T_A \Delta S/\tau = A/\tau - T_A \sigma \quad (1)$$

where A is the exergy output of the cycle, T_A is the environment temperature, ΔS is the entropy generation of the cycle, τ is the cycle period and σ is the entropy generation rate of the cycle. In the heat field, the ecological criterion was developed by Chen et al. (2007a, 2007b, 2010), Feng et al. (2011a, 2011b) and Ding et al. (2011a, 2011b). Chen et al. (2005) investigated the optimal ecological performance of a Newton's law generalized irreversible Carnot refrigerator with the losses of heat resistance, heat leakage and internal irreversibility by taking the ecological optimization criterion as the objective. They extended this study to apply for a generalized irreversible Carnot heat-pump (Chen et al., 2007a, 2007b). Chen et al. (2002) investigated the optimization of a multi-stage irreversible refrigeration system by considering this ecological criterion under the given optimal performance parameters. An ecological optimization of a model of an irreversible quantum Carnot refrigerator by taking into account heat resistance, internal friction, and bypass heat leakage is investigated (Chen et al., 2013). The optimal ecological performance of an irreversible air-standard Otto cycle with heat transfer, friction and internal irreversibility is analyzed by Ge et al. (2013). Local stability of a non-endoreversible Carnot refrigerator at the maximum ecological function is studied with Newton's heat transfer law between working fluid and heat reservoirs (Wu et al., 2015).

Bhattacharyya et al. (2007) proposed other thermodynamic technique based on exergy analysis to optimize combined refrigeration cycles. They present a CO_2-propane system simulation to evaluate and verify the proposed analytical model. Aminyavari et al. (2014) performed thermodynamic (energetic and exergetic), economic, and environmental analyses as well as multi-objective optimization of a CO_2/NH_3 cascade refrigeration system. They considered the first