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Exergetic efficiency optimization for an irreversible Brayton refrigeration cycle

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Abstract

Exergetic efficiency optimization that combines exergy concept and finite-time thermodynamic theory has been carried out for an irreversible Brayton refrigeration cycle. Multi-irreversibilities considered in the system include finite rate heat transfer, internal dissipation of the working fluid and heat leak between heat reservoirs. Exergetic efficiency defined as the ratio of rate of exergy output to rate of exergy input of the system is considered as the objective index. The goal of exergetic efficiency optimization is to maximize this index. The maximum value of the exergetic efficiency can be determined analytically. The results are compared with those obtained from the traditional coefficient of performance. The influences of heat leak between heat reservoirs and temperature ratio of two reservoirs on the exergetic efficiency are investigated by numerical calculations. The allocation of a fixed total thermal conductance between the two heat exchangers is also discussed. The results show that the method of exergetic efficiency optimization is an important and effective criterion for the evaluation of an irreversible Brayton refrigeration cycle.

Keywords: Exergetic efficiency; Optimization; Irreversible; Brayton; Refrigeration cycle

1. Introduction

Finite time thermodynamics is more practical than classical thermodynamics for evaluating the power output and thermal efficiency of a thermodynamic cycle [1]. Many important works about Brayton power or refrigeration cycles applying finite-time thermodynamic theory have been published in recent years. De Vos [2] investigated the efficiency of some heat engines at maximum power conditions. Bejan [3] built the theory of heat transfer-irreversible refrigeration plants. Wu [4] defined the endoreversible heat engine and optimized the power output of an endoreversible Brayton heat engine. Sahin et al. [5] analyzed the maximum power density of an irreversible Joule–Brayton engine. Wu et al. [6] analyzed and optimized the cooling load of the endoreversible simple Brayton refrigeration cycles coupled to constant- and variable-temperature heat reservoirs, and compared the performance with that of endoreversible Carnot refrigeration cycles coupled to constant- and variable-temperature heat reservoirs. Chen et al. [7] analyzed the performance of a regenerative closed Brayton cycle. The analysis considered all the irreversibilities associated with finite-time heat transfer processes. Chen et al. [8] analyzed the cooling load and *COP* performance of endoreversible regenerated Brayton refrigeration cycles coupled to constant- and variable-temperature heat reservoirs. Cheng and Chen [9] determined the maximum power output and the corresponding thermal efficiency for an irreversible closed-cycle Brayton heat engine. Later, Cheng and Chen [10] calculated the maximum thermal efficiency and the corresponding power output for the same system. Chen et al. analyzed the cooling load and *COP* performance of irreversible simple [11] and regenerated [12] Brayton refrigeration cycles coupled to constant- and variable-temperature heat reservoirs. Sahin et al. [13] analyzed a comparative performance of irreversible regenerative reheating Joule–Brayton engines

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Nomenclature

A	heat transfer area	$\mathrm{m^2}$
C_1–C_{16}	coefficients	
$\dot{C}_I$	heat transfer rate between reservoirs	$\mathrm{W{\cdot}K^{-1}}$
$\dot{C}_w$	heat capacitance rate of working fluid	$\mathrm{W{\cdot}K^{-1}}$
COP	coefficient of performance	
$\dot{E}$	rate of exergy	W
N	number of transfer units of heat exchangers	
$\dot{Q}$	rate of heat transfer	W
$\dot{Q}_I$	rate of heat leak	W
T	temperature	K
U	heat transfer coefficient of heat exchanger	$\mathrm{W{\cdot}m^{-2}{\cdot}K^{-1}}$
$\dot{W}_{\mathrm{in,net}}$	net power input	W
y	isentropic temperature ratio	
z	allocation factor	

Greek symbols

ε	effectiveness of heat exchanger
η	efficiency

Subscripts

0	typical environment
c	compressor
d	destruction
e	expansion
ex	exergetic
H	hot side
HC	process at hot side
in	input
L	cold side
LC	process at cold side
max/opt	maximum/optimum condition
out	output

under maximum power density and maximum power conditions. The performance of real regenerated air heat pumps was analyzed by Chen et al. [14]. Cheng and Chen [15] determined the maximum ecological function, its corresponding thermal efficiency and power output of an irreversible Brayton heat engine. The ecological function of a heat engine was defined as the power output minus the loss power. Chen et al. [16] analyzed the performance of a closed regenerated Brayton heat pump with internal irreversibilities via methods of entropy generation minimization. An exergy analysis based on an ecological optimization criterion was carried out for an irreversible Brayton engine with an external heat source by Huang et al. [1]. Kodal et al. [17] investigated the effects of internal irreversibility and heat leakage on the finite time thermoeconomic performance of refrigerators and heat pumps. Chen et al. [18] optimized the power density for an irreversible regenerated closed Brayton cycle. Chen et al. [19] analyzed and optimized the power density of an irreversible regenerated closed Brayton cycle coupled to variable-temperature heat reservoirs. Chen et al. [20] optimized the power density of an irreversible closed Brayton cycle coupled to constant-temperature heat reservoirs in the viewpoint of entropy generation minimization. Luo et al. [21] optimized cooling load and *COP* performance of irreversible simple Brayton refrigeration cycle coupled to constant-temperature heat reservoirs. Zhou et al. analyzed and optimized cooling load density of the endoreversible simple Brayton refrigeration cycles coupled to constant- [22] and variable- [23] temperature heat reservoirs, of the irreversible simple Brayton refrigeration cycle coupled to constant- [24] and variable- [25] temperature heat reservoirs, and of irreversible regenerated Brayton refrigeration cycles coupled to constant- [26] and variable- [27] temperature heat reservoirs. The cooling load density was defined as the ratio of cooling load to the maximum specific volume in the cycle.

In recent years, the research combining exergy concept and finite time thermodynamics is becoming increasingly important. Yan and Chen [28] optimized the rate of exergy output for an endoreversible Carnot refrigerator. Sahin et al. [29] also determined the optimum values of design parameters of the cogeneration cycle at maximum exergy output. Yilmaz [30] investigated the effects of design parameters on the exergetic performance for cogeneration systems with external irreversibilities. They carried out the optimum analysis on the performance of exergy, incorporating time or rate constraints in the conditions defining the system. However, the optimization of an irreversible Brayton refrigeration cycle based on the performance of exergetic efficiency has not been investigated.

In this paper, exergetic efficiency optimization for an irreversible Brayton refrigeration cycle is reported. The purpose of this paper is to maximize the exergetic efficiency of the refrigeration system. The multi-irreversibilities considered are finite rate heat transfer, internal dissipation of the working fluid and heat leak between heat reservoirs. The exergetic efficiency optimization performed in this paper helps to better understand the performance of the irreversible Brayton refrigeration cycle.

2. Theoretical model

A steady-flow irreversible Brayton refrigeration cycle coupled to two regions at a temperature T_{L} and another higher temperature T_{H} is shown in Fig. 1. The refrigeration cycle consists of two isobaric processes (processes 2-3 and 4-1) and two non-isentropic processes (the compres-