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Multi-objective optimization of heat exchanger based on entransy dissipation theory in an irreversible Brayton cycle system

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ABSTRACT

A multi-objective optimization of main heat exchanger in a regenerative Brayton cycle system is carried out based on entransy dissipation. The best trade-off between the entransy dissipation numbers caused by heat transfer and fluid friction is achieved in the Pareto optimal solutions, the decrease of entransy dissipation related to heat transfer inevitably leads to the increase of entransy dissipation due to fluid friction, and vice versa. The entransy dissipation due to heat transfer rather than that due to fluid friction plays a decisive role in the net work output. The Pareto optimal schemes are widely superior to the random design schemes at both component and system levels. The diversity of Pareto design schemes is very convenient for users to choose the most appropriate design scheme according to the practical needs.

1. Introduction

Heat exchanger has been widely used as an important device in power engineering, petroleum and chemical industries, etc. Therefore, to reduce the unnecessary energy dissipation in heat exchanger is of great importance for energy saving. There exist two classes of evaluation criteria for heat exchanger: one is based on the first law of thermodynamics; the other is based on the second law of thermodynamics. In recent decades, the latter one has attracted a lot of attention [1]. The entropy generation minimization (EGM) approach to heat exchanger optimization design is proposed by Bejan [2,3], in which the irreversibilities in heat exchanger include two types: the first is caused by heat transfer, the second is associated with fluid friction, and the total irreversibility is the sum of the two groups. Guo et al. [4] demonstrated that the entropy generation caused by heat transfer is far larger than that associated with fluid friction in conventional liquid-to-liquid heat exchanger, which results in the ineffectiveness of entropy generation caused by fluid friction in the entropy generation minimization approach. Also, some inconsistencies and paradoxes of EGM approach have been found in heat transfer processes [5].

Guo et al. [6] defined a new physical concept to describe the heat transfer ability through the analogy with the electrical conduction. It is found that the entransy is dissipated in heat transfer processes, and the more dissipation of entransy implies the higher degree of irreversibility [7]. Therefore, the entransy dissipation could be adopted as a figure of merit to evaluate the performance of heat exchanger. Guo et al. [8] established an entransy dissipation number to assess the performance of heat exchanger, which overcomes the 'entropy generation paradox'. Xia et al. [9] derived the optimum parameter distributions in the two-fluid heat exchanger by taking etnransy dissipation minimization as optimization objective under the fixed heat load condition. Chen et al. [10] carried out the optimization of heat exchanger couple by entransy dissipation minimization; they found that there is one-to-one correspondence of the minimum entransy dissipation and the maximum heat transfer. Guo et al. [11] presented that the total entransy dissipation reaches the minimum when the local entransy dissipation is distributed uniformly along the heat exchanger under constant heat load condition. The entransy dissipation in heat exchanger can be classified into two groups: the first is caused by heat transfer; the second is associated with fluid friction [12]. After analysis, it is demonstrated that the entransy dissipation caused by heat transfer is far larger than that due to fluid friction, which leads to the ineffectiveness of the entransy dissipation due to fluid friction in the optimization of heat exchanger based on entransy dissipation minimization [13]. In an

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Nomenclature

A_s	crossflow area at the centerline of shell for one crossflow between two baffles (m^2)
Bs	baffle spacing to the shell inner diameter ratio
c_p	the specific capacity at constant pressure (J/kg K)
d_i	inner diameter of heat exchange tube (m)
d_o	out diameter of heat exchange tube (m)
f	friction factor
f_i	function i
$\dot{G}$	entransy dissipation rate (W K)
G^*	entransy dissipation number
j_o	heat transfer factor
k	specific heat ratio
K_o	total heat transfer coefficient (W/m^2 K)
L	total length of tube pass (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of heat exchange tube
N_b	the number of baffles
Ntu	the number of heat transfer units
Pe	Peclect number
PF*	Pareto front
Pr	Prandtl number
$\dot{Q}$	heat duty (W)
r	fouling resistance (m^2 K/W)
R	correct factor for pressure drop
R_c	heat capacity rate ratio
Re	Reynolds number
s	tube pitch (m)
T	temperature (K)
v	velocity (m/s)
W_{net}	net work output (W)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
δ	thickness (m)
ε	effectiveness
η	efficiency
θ	central angle of baffle cut
λ	thermal conductivity (W/m K)
μ	fluid dynamic viscosity (Pa s)
π	cycle pressure ratio
ρ	density (kg/m^3)
ΔP	pressure drop (Pa)

Subscripts

c	compressor
He	helium gas
LB	liquid Pb–Bi
i	inlet
j	correct factor
o	outlet
R	regenerator
s	shell side
t	tube side
w	wall
ΔT	temperature difference
ΔP	pressure drop

attempt to overcome this drawback, a multi-objective optimization design approach for heat exchanger was developed based on entransy dissipation minimization, in which the entransy dissipations caused by heat transfer and fluid friction are taken as two separate objective functions [13].

The existing literature indicates that the most of researches relating to the applications of entransy dissipation in optimization of heat exchanger are conducted at the component level. Heat exchanger is one component of a system in numerous engineering applications, and the design of a heat exchanger is inevitably influenced by system requirements [14]. Therefore, the optimization design of heat exchanger is more practical applicable at the system level rather than at the component level. In the present work, the multi-objective optimization design of main heat exchanger is conducted based on entransy dissipation minimization in an accelerator driven subcritical (ADS) regenerative Brayton cycle system. The variations of performance of main heat exchanger and the system in the optimization process are presented, and the influences of main heat exchanger on the performance of the cycle system are analyzed.

2. Theoretical analysis

2.1. System description

A regenerative Brayton cycle based on accelerator driven subcritical (ADS) power system is illustrated in Fig. 1 (a), and the temperature–entropy diagram for the system is shown in

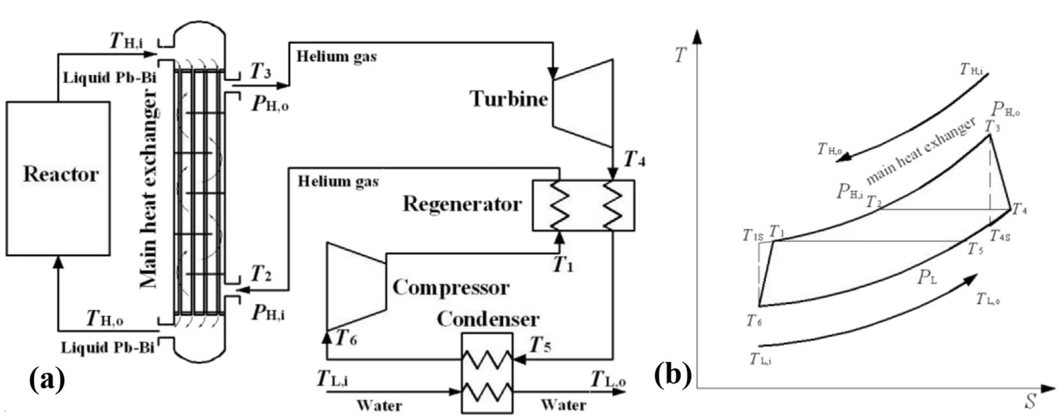

Fig. 1. (a) System diagram of regenerative Brayton cycle, (b) The temperature–entropy diagram of the system.