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Analyses of entropy generation and heat entransy loss in heat transfer and heat-work conversion

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ABSTRACT

Heat entransy loss is defined and both the concepts of entropy generation and heat entransy loss are applied to the analyses of heat-work conversion and heat transfer processes in this paper. In heat-work conversion, it is found that the minimum entropy generation rate relates to the maximum output power under the conditions of the prescribed heat absorption and the equivalent thermodynamic forces corresponding to the heat absorption and release of the system, while the maximum heat entransy loss relates to the maximum output power under the conditions of the prescribed heat absorption and the equivalent temperatures corresponding to the heat absorption and release of the system. In heat transfer, the maximum entropy generation rate is consistent with the maximum heat transfer rate with prescribed equivalent thermodynamic force difference, while the minimum entropy generation rate corresponds to the minimum equivalent thermodynamic force difference with prescribed heat transfer rate. Furthermore, when the concept of heat entransy loss is used, the maximum heat entransy loss rate corresponds to the maximum heat transfer rate with prescribed equivalent temperature difference, while the minimum heat entransy loss rate corresponds to the minimum equivalent temperature difference with prescribed heat transfer rate. The numerical results of some examples verify the theoretical analyses.

1. Introduction

The optimization of heat transfer and heat-work conversion has been attracting the attention of researchers due to energy situation. In recent decades, some progresses contribute to the heat transfer optimizations and heat-work conversion optimizations [1–3].

The constructal method was first applied to the Volume-to-Point problem [1]. The basic structure of the high conductivity material that covers a part of the domain is first determined and the aspect ratio of the structure is optimized to reduce its highest temperature. Then the next order of construct that resembles the first order one is expended until the whole domain is covered. Later, the constructal method was used for heat convection optimization [4–6]. However, it was found that a more optimal construct is obtained without the premise that the new-order assembly construct must be assembled by the optimized last-order construct in the constructal theory [7]. The heat flow performance does not essentially improve if the internal complexity of the heat generating area increases, and the construct does not contribute to the heat transfer performance beyond the first order [8,9]. In heat convection, it was noticed that employing a fractal microchannel network in a heat sink does not improve thermal performance relative to that of a heat sink with parallel microchannels [10]. The parallel channel network can achieve a more than fivefold higher performance coefficient at a constant flow rate than the bifurcating tree-like network, and almost four times more heat can be removed for a constant pressure gradient across the networks [11].

The thermodynamic optimization method is widely used in heat transfer and heat-work conversion. From the viewpoint of the second law of thermodynamics, the practical heat transfer processes and heat-work conversion processes are both irreversible. Therefore, entropy generation is a measure of the irreversibility of these processes, and describes the loss of the ability to do work [12]. Therefore, the decrease of entropy generation would decrease the loss of the ability to do work and increase the output work. Researchers have done much work on heat-work conversion optimizations [13–18]. Furthermore, the entropy generation minimization method was also related to the heat transfer optimizations [1,19–21].

However, it was found that the entropy generation minimization is not always related to the largest COP [22] of refrigeration systems or the largest effectiveness of heat exchangers [23,24]. The investigation of the refrigeration systems showed that minimizing the entropy generation rate does not always result in the same design as maximizing the system performance unless the refrigeration capacity is fixed [22]. In heat transfer, entropy generation is not

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Nomenclature

A	area, m^2
C	heat capacity flow rate, W/K
dU	change of internal energy, W
G_{dis}	entransy dissipation rate, WK
G_{f}	heat entransy flow rate, WK
G_{loss}	heat entransy loss rate, WK
k	heat transfer coefficient, W/m^2
P	thermodynamic force, 1/K
Q	heat flow rate, W
$\dot{Q}$	inner heat source, W/m^3
q	heat flux density, W/m^2
S_{f}	entropy flow rate, W/K
S_{g}	entropy generation rate, W/K
T	temperature, K
T_0	environment temperature, K
V	volume, m^3
W	output power, W

Subscripts

H	high temperature stream
in	into the system
L	low temperature stream
out	out of the system

monotonically related to the effectiveness of heat exchangers [23,24]. The effectiveness may not increase with the decrease of entropy generation number, but decrease under some conditions. In addition, entropy generation minimization may lead to contradictory results for some of the performance evaluation criteria during the optimization of fully-developed laminar flow through square ducts with rounded corners [25].

The concept of entransy was proposed by the analogy between heat and electrical conductions [3]. Heat flow corresponds to electrical current, thermal resistance to electrical resistance, temperature to electrical voltage, and heat capacity to capacitance [3]. Therefore, entransy is actually the "potential energy" of the heat in a body, corresponding to the electrical energy in a capacitor [3]. Entransy is always dissipated during heat transfer, and entransy dissipation can be used to describe the irreversibility of heat transfer [3,26,27]. With the concept of entransy dissipation, the principles of the extremum entransy dissipation and the minimum thermal resistance were developed [3]. These principles were adopted to optimize heat conduction [3,28–30], heat convection [3,31–33], thermal radiation [34,35], heat exchangers and heat exchanger networks [36–40], and are proved to be effective for heat transfer optimization. When the Volume-to-Point problem was optimized with these principles, the average temperature of the heated domain is lower than those by the constructal method and the entropy generation minimization method [3,29]. When the entransy theory was used to analyze heat exchangers, it was found that a smaller entransy-dissipation-based thermal resistance corresponds to a better heat transfer performance [36,37,40].

The applicability of the entransy theory to heat-work conversion was discussed from different viewpoints. Chen et al. [18] found that the concept of entransy dissipation could not be used to optimize heat-work conversion. Wu [41] defined the concept of conversion entransy and used the definition to optimize thermodynamic cycles. Cheng and Liang [42,45], Cheng et al. [43,44] defined the concept of heat entransy loss, which is the difference between the total input heat entransy and output entransy and is also the sum of the entransy dissipation due to the irreversible heat transfer and the entransy variation due to the work doing processes (i.e. work entransy). Heat entransy loss is the entransy reduction of the system, which is the entransy consumed during the heat-work conversion processes. In the analyses of the irreversible Brayton cycle [42], the endoreversible Carnot cycle [43], the air standard cycle [44], the one-stream heat exchanger networks [45], the Stirling cycle [46] and the Rankine cycle [47], it was found that the concept of heat entransy loss can be used to describe the change in output power for the systems, and the increase in heat entransy loss rate relates to the increase in output power.

It could be noted from the above discussions that the thermodynamic optimization method is not always effective in heat-work conversion optimization and heat transfer optimization. The entransy theory is appropriate for heat transfer optimization but there is still no definite conclusion for its applicability to heat-work conversion optimization. The present work is to make further investigation on the applicability of the thermodynamic optimization method and the entransy theory on heat transfer optimization and heat-work conversion optimization.

2. Analyses of entropy generation

For the common closed thermal system as shown in Fig. 1, Q_{in} is the input heat rate, while Q_{out} is output heat flow rate, and W is the output power. The energy conservation gives

$$Q_{\mathrm{in}} = Q_{\mathrm{out}} + W. \tag{1}$$

For any infinitesimal element of the system, the entropy balance equation gives [12]

$$\mathrm{d}S = \mathrm{d}S_{\mathrm{f}} + \delta S_{\mathrm{g}}, \tag{2}$$

where dS is the entropy change with time, dS_{f} is the entropy flow rate, and δS_{g} is the entropy generation rate of the system. When the system is steady, dS equals to zero. For a differential volume dV, the entropy flow dS_{f} includes two parts, one is associated with the heat flow rate, and the other is from the inner heat source. Considering both parts, we have

$$\mathrm{d}S_{\mathrm{f}} = -\nabla\cdot\left(\frac{\mathbf{q}}{T}\right)\mathrm{d}V + \frac{\dot{Q}}{T}\mathrm{d}V. \tag{3}$$

where $\dot{Q}$ is the inner heat source in dV, $\mathbf{q}$ is heat flux vector, and T is the temperature. The first term on the right-hand side is the net entropy flow associated with the heat transfer at the boundary, and the second term is that associated with the inner heat source.

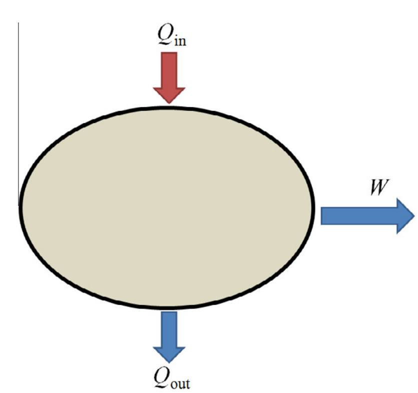

Fig. 1. Sketch of a common closed thermal system.