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Optimization strategies of heat transfer systems with consideration of heat transfer and flow resistance

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ABSTRACT

Performance optimization of heat transfer systems with consideration of both heat transfer and flow resistances is critical for energy conservation. This paper compares two different optimization strategies to trade off heat transfer enhancement and flow resistance reduction. One is to convert multiple objectives to a single one by some individual optimization criteria, such as minimization of entropy generation and other dimensionless entropy generation-based numbers, and the other is to select the maximum heat transfer rate or the minimum flow resistance as the objective directly and adapt the others as constraints by Pareto Optimality. After optimizing a practical multi-loop heat exchanger network (HXN), the optimized results by the former strategy with individual optimization criteria are probably unsuitable for practical operations. Nevertheless, it needs the energy conservation and heat transfer equations of all heat exchangers as the constraints, which makes the optimization more complex. Oppositely, the latter strategy provides a series of maximum heat transfer rates with different flow resistances, i.e. Pareto front, which can be applied according to different practical requirements. The equivalent thermal circuit diagram offers the systematical constraint without involving any intermediate fluid temperatures. The systematic constraint shows advantages and convenience to optimize HXN with consideration of heat transfer and flow resistance, which is pivotal and general for the synergy of heat transfer enhancement and flow resistance reduction in heat transfer system optimization.

1. Introduction

Heat transfer enhancement is promising in almost all thermal systems for energy conservation, but it does not always work due to the increased fluid flow resistance [1,2]. That is, flow resistance should also be taken into consideration for thermal system optimization to achieve the synergy of heat transfer and flow resistance [3]. Because heat transfer processes occur in heat exchangers and heat exchangers are the basic units in thermal systems, it is necessary to consider flow resistance from three levels: (1) the flow resistance during a heat transfer process, (2) the pressure drop in a heat exchanger, and (3) the pumping power consumption in a thermal system.

For heat transfer processes, in order to estimate the heat transfer performance from the aspects of both heat transfer and viscous effects, Bejan [4] introduced the concept of entropy generation into heat transfer analysis, and used the entropy generation minimization (EGM) as a criterion for heat transfer process optimization, where the total entropy generation was the sum of those caused by both heat transfer and flow resistance. Many researchers applied the entropy generation rate and some other dimensionless entropy generation numbers as criteria to analyze or optimize heat transfer components. For example, Poulikakos and Bejan [5] optimized the fin geometry by minimize the entropy generation, Sekulic et al. [6] analyzed the irreversibility phenomena associated with heat transfer and fluid friction in laminar flows, Sara et al. [7] optimized several rectangular channels with square pin fins with the minimization of entropy generation, and Siavashi et al. [8] analyzed the heat transfer characteristics of natural convection processes in porous media with entropy generation. Meanwhile, Paoletti et al. [9] proposed the criterion of Bejan number and Mahmud et al. [10] derived the corresponding expression for some typical convective heat transfer processes to evaluate the ratio of entropy generations due to heat transfer and flow resistance.

Thereafter, it is natural to apply the entropy generation-based criteria in heat exchanger analysis to take both heat transfer and flow resistance into consideration, and then obtain the target of lower investment and operating costs [11–14]. Recently, Manjunath and Kaushik [15] reviewed more than 100 literatures on the second law of thermodynamic analysis of heat exchangers to highlight the importance of second law investigation for heat

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Nomenclature

A	area, m^2
a	characteristic parameter of VSP
Be	Bejan number
b	dynamic coefficient of head loss
c_p	specific heat at constant pressure, J/(kg K)
d	diameter, m
f	Darcy friction-factor
H	head loss, m
H_s	static head, m
H_d	dynamic head, m
K	minor loss coefficient
k	heat transfer coefficient, W/(m^2 K)
L	length, m
m	mass flow rate, kg/s
P	energy consumption, W
Q	heat transfer rate, W
R	thermal resistance, K/W
S	cross-sectional areas of the pipe, m^2
S_g	entropy generation, W/K
T	temperature, K
α, β, γ	Lagrange multipliers
η	dimensionless number
ξ	heat exchanger effectiveness
Π	Lagrange function
ρ	density, kg/m^3
φ	dimensionless number

Subscripts

c	cold fluid
d	dynamic
e	evaporator
h	hot fluid
i	inlet; the ith one
m	mixing process
o	outlet
p	pressure differential
s	static
t	total
Δp	pressure difference
ΔT	temperature difference

exchangers, where entropy generation, exergy destruction, and Bejan number were acknowledged as the basic performance criteria. Laskowski et al. [16] applied the entropy generation rate as a thermodynamic objective to optimize the diameter of condenser tubes.

Besides, heat exchangers always serve as fundamental components in thermal systems [17], where flow resistances exist in both heat exchangers and transport pipelines [18]. Therefore, several flow resistance models for different thermal systems were deduced. They were also introduced into the optimization objectives with the aid of entropy generation. For instance, Huang et al. [19] optimized the mass flow rates of working fluids and the geometrical parameters of pipes in a vertical U-tube ground heat exchanger network (HXN) with the criterion of entropy generation minimization. Shojaeefard et al. [20] optimized a fin-and-flat tube condenser with entropy generation number to obtain the optimal heat transfer rate with fixed pressure drop.

Simultaneously enhancing heat transfer and reducing flow resistance are actually a multi-objective optimization problem. The aforementioned studies focused on introducing different evaluation criteria, including entropy generation rate [4,5,13,14,21] and entropy generation-based dimensionless numbers [9,15], to convert multiple objectives to a single one. However, due to different practical applications, the optimization objectives of different thermal systems differ. In this case, a single optimization criterion is hard to correspond to all different optimization objectives. It is why several different entropy generation-based numbers are proposed to make them have a better correspondence with practical optimization objectives as is indicated in Manjunath and Kaushik's review paper [15], but no one could cover all the cases. What's more, the least total entropy generation rate in the entire system were always obtained by minimize the entropy generation of each component separately. However, optimization of complex heat transfer systems cannot be done by using the optimized results with specific objectives obtained from subsequent heat transfer processes and elemental exchangers when operating standalone [22].

On the other hand, besides converting multiple objectives to a single one by regarding flow resistance as a part of criteria, the multi-objective optimization can also be solved through Pareto Optimality [23], a method to provide a series of optimal solutions for further selection with different preferences after optimization. In this optimization method, one objective is selected for optimization, e.g. heat transfer rates, and the other objectives, e.g. pressure drops, are given a set of choices and be considered as constraints. For optimization of a heat transfer process, Mereu et al. [24] maximized the overall thermal conductance of a 2-D space filled with a stack of heat generating boards under different pressure drops, which is cooled by forced convection. Yilmaz et al. [25] optimized the geometrical structures of ducts to maximize the convective heat transfer coefficient with a given pressure loss. In these studies, some simplifications were required to find the explicit relations between the heat transfer rates and the pressure drops. Instead, Chen et al. [26,27] derived a general quantitative relation between the boundary heat transfer coefficient and other local physical parameters over the entire heat transfer domain by the concept of entransy dissipation [28], which was hard to derive by conventional heat transfer analysis. Based on this relation together with the variational principle, they obtained different optimal fluid flow fields for different heat transfer processes to guide the design of different heat transfer facilities [29].

Similarly, the pressure drop was also adopt as a constraint for heat exchanger optimization. Mioralli and Ganzarolli [30] optimized the heat capacity rates of working fluids in a rotary regenerator with fixed pressure drops, and Kara and Guraras [31] optimized the heat transfer area of a shell-and-tube heat exchanger with various specified pressure drops. In addition, in order to consider the flow resistances in fluid transportation pipelines simultaneously, Rhee et al. [32] provided an emulation method to evaluate the performance of a hydronic radiant heating system by combining the hydronic balance with a flow limit valve and a pressure differential control valve. Wemhoff and Frank [33] optimized the energy efficiency of a heating, ventilating, and air conditioning system with consideration of flow resistance balance.

In summary, there are two main strategies to trade off heat transfer enhancement and flow resistance reduction. One is to convert multiple objectives to a single one by regarding the flow resistance as a part of different evaluation criteria, where entropy