International Journal of Heat and Mass Transfer 108 (2017) 712–720

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

An alternative energy flow model for analysis and optimization of heat transfer systems

Qun Chen *, Jun-Hong Hao, Tian Zhao

Key Laboratory for Thermal Science and Power Engineering of Ministry of Education, Department of Engineering Mechanics, Tsinghua University, Beijing 100084, China

ARTICLE INFO

Article history:
Received 25 May 2016
Received in revised form 22 November 2016
Accepted 23 December 2016

Keywords:
Heat transfer system
Energy flow model
Thermo-electricity analogy
Thermal resistance
Overall constraint

ABSTRACT

The common existence of heat transfer phenomena in energy utilization systems highlights the importance of appropriate design and optimization methods of heat transfer systems to an unprecedented level. In this contribution, we defined an alternative thermal resistance for heat exchangers based on the inlet temperature difference of hot and cold fluids, which was influenced by such two aspects as the finite heat capacity rates of hot and cold fluids and the entransy dissipation-based thermal resistance of heat exchangers. Meanwhile, the corresponding energy flow models are proposed to analyze the heat transfer performance of both individual heat exchangers and three basic heat exchanger networks, i.e. series, parallel and multi-loop by the thermo-electrical analogy method, which offer the solution for constructing the energy flow models of any heat transfer system. For validation, we constructed the energy flow model of a double-loop thermal management system. On this basis, the heat transfer characteristic was described on the system level and the overall system constraints were obtained by the Kirchhoff's Law without introducing any intermediate variables. With these system constraints, the optimization equations for the system were derived theoretically by applying the Lagrange multiplier method. Simultaneously solving these equations gave the optimal thermal conductances of each heat exchanger and the best allocations of heat capacity rate directly, which benefited energy conservation. That is, the energy flow model is reliable and convenient for the analysis and optimization of heat transfer systems.

1. Introduction

Heat exchangers are widely applied and play an increasingly important role in different energy utilization fields, including power and environment engineerings, chemical and food industries and space-vehicles [1,2]. Performance improvement of heat exchangers, especially the corresponding heat transfer systems, becomes more significant for energy conservation and pollution reduction [3]. However, all possible geometrical and operational parameters of each heat transfer system are coupled with specified design requirements, which makes the design and optimization become a complex process [4–6].

For a single heat exchanger, when the inlet and outlet temperatures are specified or can be easily determined, the logarithmic mean temperature difference (LMTD) method is usually convenient to design the geometrical structures [7–9]. However, when the fluid outlet temperature is not given in advance but to be determined by the heat exchanger geometry and fluid flow rates, the LMTD approach requires tedious procedure iterations [8]. At this time, the effectiveness number of transfer units (ε-NTU) method is preferable. The complementary of LMTD and ε-NTU method had a comprehensive range of applications [10] under whatever the design or the analysis of heat exchangers. On the other hand, for design and optimization of a heat transfer systems consisting of several different heat exchangers, the structural and operating parameters are essential and have to be carefully considered for establishing the system constraint. At this time, the application of LMTD method needs a large number of intermediate variables for building the constraints due to the intrinsic characteristic of nonlinear of LMTD [11], which would increase the complexity. Meanwhile, the ε-NTU method is difficult to construct the constraints including the detailed structural and operating parameters of heat transfer systems directly [12].

In both the LMTD and the ε-NTU methods, more attention has always been paid to the local variation of working fluid temperatures. That is, these two methods are essentially proposed and developed from the perspective of working fluid flow. Based on this research perspective, the pinch method [13] has been proposed for the synthesis of heat transfer systems. Besides, for optimizing the performance of heat transfer systems, the thermodynamic method [14] and the heuristic algorithm method

* Corresponding author.
E-mail address: chenqun@tsinghua.edu.cn (Q. Chen).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2016.12.080
0017-9310/

Nomenclature

a	intermediate variable
A	area, m^2
G	heat capacity rate flow, W K^{-1}
J	Lagrange function
K	overall heat transfer coefficient, W m^{-2} K^{-1}
L	length, m
Q	heat flux, W
R	thermal resistance, K W^{-1}
T	temperature, K
α, β	Langrange multiplier
Φ	entransy dissipation rate, K W

Subscripts

c	cold fluid
e	external
en	entransy
h	hot fluid
i	inlet
j	number
m	intermediate heat exchanger
o	outlet

[15] had been developed in many optimization-related literatures. In these researches, the constraints of each component are also constructed from the perspective of working fluid flow. Using these constraints has to introduce many intermediate variables and nonlinear equations, which becomes the obstacle to reveal the overall system characteristic and increases the optimization complexity.

As well known, for one-dimensional heat transfer through a composite wall, the thermal resistance was proposed by the electrical analogy to solve the complex multi-layer heat transfer problem involving both series and parallel combinations [9]. Meanwhile, in thermal radiation, the surface radiative resistance and the space resistance construct the radiation-network [9] to calculate the radiation exchange by combining the Kirchhoff's Law. The thermo-electrical analogy method and the radiation-network approach are particularly useful and convenient for analyzing system heat transfer processes without introducing any intermediate temperature, which essentially represent the perspective of energy flow. However, for a heat exchanger, the existing thermal resistance is defined as the ratio between the LMTD and the heat transfer rate, i.e. the reciprocal of the product of heat transfer coefficient and heat transfer area. Actually, the LMTD-based thermal resistance is an extension of Newton's law of cooling [16] for partially representing the heat transfer ability of heat exchanger from the perspective of working fluid flow without consideration of the heat capacity rates of fluids. That is, for individual heat exchangers or heat transfer systems, the research perspective of working fluid flow is not enough, and a new perspective is highly desired for performance analysis and optimization.

Recently, Guo et al. [10] introduced the concept of entransy in heat transfer analysis and defined the entransy dissipation-based thermal resistance (EDTR) of a heat exchanger from the nature of heat transfer irreversibility. On this basis, Chen [17] connected the EDTR directly to the fluid flow rates and the heat transfer areas for different types of heat exchangers, which has been used to construct the overall system constraints between the design parameters and the system requirements [18] for optimization of some typical thermal systems including heat exchanger networks in a spacecraft [19], evaporative cooling system [20], building central chilled water systems [21], absorption thermal energy storage system [22], gas refrigeration cycle [23] and regenerative air refrigeration system [24,25]. Furthermore, Chen et al. [26] introduced an equivalent thermal circuit to represent the heat transfer processes in a heat transfer system, and then analyze the overall system performance. In summary, the entransy-based method provides a feasible and convenient approach for optimizing heat transfer system. However, the characteristic temperature difference in the entransy-based method is the arithmetic mean temperature difference (AMTD), which is applicable when the fluid inlet temperatures are known and the outlet temperatures could be easily conducted by the energy conservation equations. However, if only the fluid inlet temperatures are known, applying the AMTD as the characteristic temperature difference is not very convenient.

In this article, we define an alternative thermal resistance for heat exchanger by merely employing the inlet temperature difference as the characteristic temperature difference, deduce the expressions of such thermal resistance as a function of fluid flow rates and heat transfer areas for different types of heat exchangers, and give a comprehensive understanding about this thermal resistance by referring to the T-Q diagram. On this basis, applying the thermo-electricity analogy method gives the energy flow models of three basic heat exchanger layouts and a double-loop thermal management system, which offers the overall constraints of each parameter for these heat transfer systems, respectively, and reveals the overall heat transfer characteristic of these systems. Finally, we apply these constraints to optimize the thermal management system to validate the energy flow model.

2. An alternative thermal resistance of a heat exchanger based on inlet temperature difference

2.1. The characteristic temperature difference of a heat exchanger

The analogy between heat conduction and electricity conduction provides a useful tool for both conceptualizing and quantifying heat transfer problems [23]. For the one-dimensional heat conduction process through an infinite plate, the thermal resistance, R is defined as the ratio of the characteristic temperature difference between the hot and cold ends, $T_h - T_c$, to the total heat flux, Q. Fig. 1 shows the corresponding energy flow model, where heat driven by the temperature difference flows through the thermal resistance. Herein, the driving potential, the temperature difference $T_h - T_c$, is not related to such parameters as the thermal conductivity and the thickness of the plate [6].

For a heat exchanger, the hot fluid flows through the heat exchanger and transfers heat to the cold fluid, and the corresponding heat transfer performance could be expressed by Eq. (1) [6]. The outlet temperatures of hot and cold fluids, $T_{h,o}$ and $T_{c,o}$, and the heat transfer rate, Q, are generally depend on the inlet temperatures, $T_{h,i}$ and $T_{c,i}$, and the heat capacity rates (the product of mass flow rate and heat capacity), G_h and G_c, of both hot and cold fluids, and the overall heat transfer coefficient, K, the heat transfer area, A, and the flow arrangement of the heat exchanger.

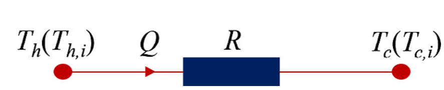

Fig. 1. The energy flow model of a one-dimensional heat transfer process.