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Research Paper

An integral identification method of characteristic parameters and optimization of parallel connection heat transfer systems based on the power flow method

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HIGHLIGHTS

- Integral identification of heat transfer and fluid flow characteristic parameters.
- Proposed method can flexibly select proper parameters to measure in identification.
- Combining power flow and fluid flow models offer an integral optimization model.
- Results show the limitation of fixed node-temperature method and balanced flow criterion.

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ABSTRACT

Optimization of heat transfer systems benefits energy conservation, but the conventional fixed node-temperature operation strategy hardly offers the optimal performance under changing working conditions. This paper utilizes the power flow method to construct the integral heat transfer model and combines the overall flow resistance model to set up the integral constraints of heat transfer systems with independent variables. On this basis, we develop an integral identification method to identify the free degree of systems and the characteristic parameters of each component, and propose the corresponding optimization method, which is universal and has been applied to many kinds of heat transfer systems. For the convenience and economy of experiment, a parallel-connected counter-flow heat exchanger network is studied to validate the identification method and the optimization method. The experimental results show that the identified characteristic parameters by the newly proposed method have enough accuracy for practical use; while the optimization method offers the optimal operating parameters with the least power consumption under given conditions. When the operating frequency of the pump in a cold-water loop deviates the optimal one of 10%, the total pumping power consumption of the system increases up to 18.2%. Meanwhile, a bigger deviation will lead to a larger pumping power consumption. Besides, the node temperatures in the optimal cases vary with the heat loads, which illustrates the limitation of fixed node-temperature operation strategy.

1. Introduction

Heat transfer systems perform significant roles in many engineering fields, such as central air conditioning systems, urban central heating systems, waste-heat recovery systems and spacecraft thermal control systems. Improving the performance of heat transfer systems is of great importance to energy conservation, which has been attracting more and more attention. As a result, many scholars have come up with all kinds of optimization methods [1–3].

The traditional analysis method of heat transfer systems is to introduce some intermediate variables, such as temperatures, into the system [4–7] to divide the whole system into individual components. Apply both heat transfer and energy conservation equations of working fluids to build the constraints of each component, and simply combine these constraints together to analyze the whole system. However, this method cannot reflect the integral heat transfer laws in thermal systems. Besides, introducing additional intermediate variables will complicate the mathematical calculation.

In order to simplify mathematical calculation in practice, engineers usually fixed the temperatures of certain nodes by long-term

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Nomenclatures

A	area, m^2
a	simplified characteristic parameter of VSP
c_p	constant pressure specific heat, $J\,kg^{-1}\,K^{-1}$
d	diameter, m
d_i	dynamic coefficient of head loss
f	Darcy friction-factor
H	pump head, m
h	installation height, m
h_f	Moody-type friction loss, m
h_m	minor loss, m
K	minor loss coefficient
k	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
L	length, m
m	mass flow rate, $kg\,s^{-1}$
P	pumping power consumption, W
Q	heat transfer rate, W
R	thermal resistance, $K\,W^{-1}$
S	cross-sectional areas of the pipe, m^2
T	temperature, K
α,β,γ	Lagrange multipliers
δ	deviation
Π	Lagrange function
ρ	density, $kg\,m^{-3}$
ω	rotation frequency, Hz

Subscripts

c	cold fluid
cal	calculated value
d	dynamic
exp	experiment value
h	hot fluid
in	Inlet
i	Number
max	Maximum
min	Minimum
out	outlet
ref	the referenced value for calculation
s	static head
t	Total

engineering experience. For instance, the inlet and outlet water temperatures of the central chilled water systems for air condition are 7 °C/ 12 °C or 6 °C /13 °C in China. The inlet and outlet water temperatures of the secondary pipe network in central heating systems are 75/50 °C or 85/60 °C in China [8]. Besides, Kaya [9] designed a chiller system with fixed chilled water temperature. Thielman [10] adjusted the operating parameters of an energy management system according to a fixed condensation temperature. Jin et al. [11] used the chilled water temperature to control and optimize the volume flow rates in a central chiller system. Kusiak et al. [2] reduced the energy consumption of an air conditioning system with prescribed supply air temperature and static pressure in the air-handling unit.

The fixed node-temperatures offer reference boundaries for heat transfer and fluid flow processes in the heat transfer systems simultaneously, which simplify the complicated calculation processes for system design and operation and bring great convenience to practical use. However, the node-temperatures should deviate from the fixed values with the variation of the heat loads during operation. That is, the optimal working condition will be hard to achieve with fixed node-temperatures. Gonzalez et al. [12] illustrated that utilizing the method of fixed node-temperatures to optimize the operation parameters actually omits the characteristics of heat transfer processes. Wang et al. [13] exclaimed that operation optimization regardless of the characteristics of heat transfer processes would limit the performance of heat transfer systems. In addition, the fixed node-temperatures actually separates heat transfer processes from fluid flow processes, which couples with each other in heat transfer systems. That is, it ignores the effect of pumping power consumption caused by fluid flow resistance on system optimization.

In order to take both the heat transfer and the fluid flow characteristics of heat transfer systems into consideration, scholars have proposed many approaches, where a widely used method is to regard entropy generation as evaluation criterion for optimization. Alebrahim and Bejan [14] applied the criterion of entropy generation minimization to optimize the areas of two heat exchangers in a temperature control system under some given conditions. Lavric et al. [15] used the principle of entropy generation minimization to design a chemical chilling system, and obtained the corresponding design and operating parameters with the minimum entropy generation. Nevertheless, this optimization method must utilizes intermediate temperatures, which complicate the calculation. What's more, the optimization objective is the minimum of entropy generation, which is actually different from the practical objective of the minimum of pumping power consumption under certain required heat transfer rates.

Recently, Guo et al. [16] introduce a new physical quantity named entransy to describe the ability of an object to transfer heat to the environment during an isometric process. On this basis, they define the entransy dissipation-based thermal resistance, which can describe the irreversibility of heat transfer process. Chen [17] substitutes the heat transfer equation and the energy conservation equation into the definition of entransy dissipation-based thermal resistance and deduces the formula of it, which has been used for optimization of several different heat transfer systems [18–20], including central chilled water systems, district heating networks and regenerative air refrigeration systems.

Besides, Chen [21] proposes a new optimization method for heat transfer systems, named the power flow method [22–24], to construct the integral heat transport and fluid flow models. In these two models, there are two different types of parameters, one is the characteristic parameters of each component and the other is the operating parameters. Wang and Chen [25] take the characteristics of both heat transfer and fluid flow processes in each component into consideration and identify them before optimization. However, they did not identify the characteristic parameters in the heat transfer systems as a whole, but identified them by component, which brings inconvenience in practical systems because of the difficulty in measurement of some parameters.

This article adapts the power flow model [22] to set up the integral heat transport model, and combines it with the overall flow resistance model to set up the integral model of a heat transfer system. On this basis, a general approach is developed to identify the free degree of systems and the characteristic parameters of each component, which is of great use in practice because engineers could flexibly select proper parameters to measure according to different situations. Then, together with the Lagrange multiplier method, the article utilizes the Pareto optimality to optimize the operation parameters of heat transfer systems by taking heat transfer and fluid flow processes into consideration together. The optimization method based on the power flow model is universal and has been applied to many kinds of heat transfer systems. For the convenience and economy of experiment, a parallel-connected counter-flow heat exchanger network is studied in this paper to validate the newly proposed identification approach as well as the optimization method and show the superiority experimentally. As the thermal conductance of heat exchangers varies with the mass flow rates of working fluids, it is assumed as a constant during the optimization and is revised