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A thermal circuit method for analysis and optimization of heat exchangers with consideration of fluid property variation

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ABSTRACT

Fluid property variation has significant impact on heat transfer performance in cryogenic and supercritical applications, as well as in condensers and evaporators involving phase change of fluid. This study introduced the thermal circuit diagrams of heat exchangers and their networks based on the definition of entransy dissipation-based thermal resistance (EDTR) to take fluid property variation into account for accuracy. By subdividing the heat transfer area into several segments, a heat exchanger is approximately represented by a heat exchanger network, where the fluid properties in each segment are considered constant. By analyzing the relations of the EDTRs of each segment and the arithmetic average temperatures of both hot and cold fluids, the governing equations are established to depict the equivalent thermal circuits of such three typical types of heat exchangers as parallel-flow, counter-flow and cross-flow. Furthermore, the combination of these basic thermal circuits gives the equivalent circuit for any heat exchanger network consisting of such typical heat exchangers. Based on the thermal circuit together with Kirchhoff's laws, it's easy to derive the mathematical relations among all decision parameters and design requirements without introducing any intermediate variables, which contributes to the optimization of heat exchanger networks. Analysis of a cross-flow heat exchanger by the thermal circuit method and the traditional ε-NTU method without and with consideration of fluid property variation validated and showed the superior of the thermal circuit method. Meanwhile, the effects of fluid property variation on the optimization of heat exchanger networks were investigated. It was found that the fluid property variation significantly impacted the optimal mass flow rates of each fluid, while it had little effects on the optimal allocation of thermal conductance.

1. Introduction

Heat exchangers play an indispensable role in petroleum, air conditioning and food storage industries, and heat exchanger performance significantly influences the energy utilization efficiency of the corresponding system. Therefore, performance analysis and optimization of heat exchangers are of vital importance for energy conservation. In engineering, the logarithmic mean temperature difference (LMTD) method and the heat exchanger effectiveness-number of transfer units (ε-NTU) method are commonly used to design and check heat exchanger performance, respectively. However, these methods rely on neglecting some effects including fluid property variation, heat leakage, longitudinal thermal conduction and flow maldistribution [1], which are suitable for normal working conditions. However, for supercritical fluid [2–4] and cryogenic heat exchangers [5,6], fluid property is sensitive to temperature, and the influence of fluid property variation should be taken into account. Pacio and Dorao [6] summarized the relative importance of the aforementioned effects and found that the non-negligible effect of fluid property variation ranked first in increasing order of accuracy. Meanwhile, Soyars [7], Oonk and Hustvedt [8] investigated the applicability of constant property approach in cryogenic helium heat exchangers and found that the approximate error on the heat exchanger performance was noticeable between 4 and 20 K, which gave rise to even larger inaccuracy of the system performance. Moreover, the phase change of fluid in evaporators and condensers also induces the variations of fluid properties.

In order to deal with fluid property variation, scientists have developed two groups of approaches. One is to subdivide a heat exchanger into several heat transfer segments appropriately, where the fluid properties are treated as constants, and then analyze each region by applying the traditional constant property methods [7–9]. However, in the ε-NTU method, the fluid heat

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Nomenclature

A	area, m^2
C	heat capacity rate ratio
c_p	constant pressure specific heat, $J\,kg^{-1}\,K^{-1}$
F	Lagrange Function
G	heat capacity rate, $W\,K^{-1}$
U	heat transfer coefficient, $W\,m^{-2}\,K^{-1}$
UA	thermal conductance, $W\,K^{-1}$
m	mass flow rate, $kg\,s^{-1}$
N	number of segments
NTU	dimensionless number of transfer units
Q	heat transfer rate, W
R	thermal resistance, $K\,W^{-1}$
T	temperature, K
ε	thermal motive, K; effectiveness
λ, φ, ψ	Lagrange multiplier

Subscripts

a	middle fluid
h	hot fluid
l	cold fluid
m	arithmetic average value

capacity rates should be compared first. When the fluid properties vary rapidly versus the temperature, the variable expressions of NTU and heat capacity rate ratio result in the complexity of ε-NTU method. On the other hand, in the LMTD method, it is inevitable to introduce numerous intermediate fluid temperatures at the inlets and the outlets of each segment, which accounts for a large number of variables and makes it hard to seek the inherent relationship of decision parameters and design requirements for heat exchangers. The other approach is based on numerical calculation of the differential and the algebraic equations of heat exchangers [10,11]. This method contributes to analyze the heat exchangers with complex configurations and investigate the dynamic characteristics of heat transfer processes, but numerical solutions require certain initial and boundary conditions, such as the thermal conductances of heat exchangers and the mass flow rates of fluids, which sometimes need to be optimized. Therefore, this method is recommended in the modeling of heat transfer processes rather than the optimization of heat exchangers and heat exchanger networks. On the lack of effective analysis method for heat exchangers with fluid property variation, the previous design and optimization of heat exchanger networks usually adopted constant fluid property assumption or single parameter analysis [12–14].

Recently, Chen [15] substituted the energy conservation and the heat transfer equations of heat transfer processes into the definition of entransy dissipation-based thermal resistance (EDTR) of heat exchangers [16], and gave the formulas of EDTRs for different types of heat exchangers with constant fluid property. Furthermore, Chen et al. [17] proposed an equivalent thermal circuit diagram for heat transfer processes in such three basic layouts of heat exchanger networks as multiple-loop, series and parallel, and utilized this method in the optimization of complex heat exchanger networks. In comparison with traditional approaches, the equivalent thermal circuit focuses on the energy flow during the heat transfer processes rather than the trends of mass flow, and it constructs the inherent relations among decision parameters and design requirements without involving numerous intermediate temperatures.

From this new sight in heat transfer analysis, a heat exchanger involving fluid property variation can be subdivided into several segments and the fluid properties in each segment can be treated as constants. By analyzing the relations of the EDTRs of each segment and the arithmetic average temperatures of fluids, the mathematical relations among all decision parameters and design requirements are deduced without introducing any intermediate temperatures, which contributes to construct the equivalent thermal circuit diagram for the whole heat exchanger. In addition, for a heat exchanger network, the heat transfer processes in each heat exchanger are connected by the energy conservation equations of each fluid, so the thermal circuits of each heat exchanger are used as standard modules to construct the integrated thermal circuit of the whole heat exchanger network with fluid property variation. On this basis, with the aid of Kirchhoff's laws, it's easy to derive the governing equations for analysis and optimization of the heat transfer processes in both individual heat exchanger and their networks. Finally, several different heat exchangers and a heat exchanger network are analyzed and optimized to show the applications of the newly proposed method.

2. Equivalent thermal circuits for heat exchangers with consideration of fluid property variation

2.1. Parallel-flow heat exchangers

Fig. 1 is the sketch of a parallel-flow heat exchanger, where the hot fluid, h, releases heat to the cold one, l, and the corresponding inlet and outlet temperatures are $T_{h,1}$, $T_{h,2}$, $T_{l,1}$ and $T_{l,2}$, respectively. The symbol A stands for the total heat transfer area, while U stands for the heat transfer coefficient, which is assumed constant. Fig. 2 gives the T–q diagram of the corresponding heat transfer process, where T stands for the temperature and q for the heat transfer rate [15]. The curves from $T_{h,1}$ to $T_{h,2}$ and from $T_{l,1}$ to $T_{l,2}$ represent the heat release process of hot fluid and the heat absorption process of cold fluid, respectively. The total heat transfer rate is Q. Meanwhile, the slopes of curves are the reciprocals of the heat capacity rates of working fluids, which vary versus the corresponding temperature, meaning that the constant pressure specific heats of working fluids are not constant during the heat transfer process.

After dividing the heat exchanger into N parts equally by the vertical dotted lines shown in Fig. 1, each part is identified by i ($i = 1,2,\ldots,N$) successively along the flow direction of working fluids. In the segment i, $T_{h,m,i}$ and $T_{l,m,i}$ are the arithmetic average values of the corresponding inlet and outlet temperatures of hot and cold fluids, respectively, and Q_i is the heat transfer rate in this segment. The area of each segment decreases versus the increase of N, so do the temperature variations of each fluid, and thus the fluid properties in each segment tend to be constant. In this case, the constant pressure specific heats of hot and cold fluids in each

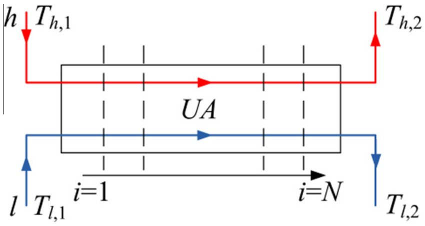

Fig. 1. The sketch of a parallel-flow heat exchanger.