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Application of entransy-dissipation-based thermal resistance for performance optimization of spiral-wound heat exchanger

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ABSTRACT

The effects of geometrical parameters on thermal resistance based on entransy dissipation caused by heat transfer (R_{ht}) and fluid friction (R_{ff}) of spiral-wound heat exchanger (SWHE) were studied by numerical method. The simulation results show that all geometrical parameters (spiral angle, external diameter, layer pitch, tube pitch) are negatively correlated with R_{ff} because of flow pattern transition caused by the variation of geometrical parameters and the changing of effective flow area which would cause the decrease of entransy dissipation related to fluid friction. For the entransy dissipation due to the heat transfer, the increase of layer pitch are positive to it while both the tube pitch and external tube diameter are negative to R_{ht}, and with the increase of the spiral angle, the R_{ht} decrease at first and then increase. What is more, the MOGA optimization of SWHE was carried out based on different types of objective functions. Compared with the traditional objective functions (minimize ΔP and maximize K), R_{ff} and R_{ht} obtained from minimizing the entransy-dissipation-based thermal resistance reduce by an average of 90.51% and 34.13%, respectively. Compared with original structure, the comprehensive performance evaluation factor ($Nu/f^{1/3}$) of traditional optimal results is improved by an average of 41.02%, while that of optimal structures obtained from entransy theory is strengthened by an average of 76.64%. The results demonstrate that the objective functions of minimizing the entransy-dissipation-based thermal resistance are better than that of traditional objective functions for optimization of spiral wound heat exchanger.

0. Introduction

Spiral-wound heat exchangers (SWHEs), one kind of the most effective heat exchangers, are playing a very important role in some particular applications and being widely used in petrochemical enterprises, pharmaceutical industries, liquefied natural gas plants, air separation plants, and nuclear power stations [1–3]. SWHEs consist of one or more coiled wound tube layers constructing in the shell, and the layers are left-wound and right-wound in sequence to form a lattice pattern. The typical characteristics of the structure enable SWHEs to possess lots of advantages such as highly compact structure, high pressure endurance and good thermal compensation performance [4,5].

Over the last decades, a lot of researches have been carried out on flow and heat transfer characteristics of little attention has been concentrated due to its complicated structure. Neerass et al. [6,7] constructed a test plant to measure the local heat transfer coefficient and frictional pressure drop, and investigated the liquid falling film flow in the shell side of spiral wound LNG heat exchanger. Messa et al. [8], Ghorbani et al. [9] and Jamshidi et al. [10] experimentally analyzed the effects of the geometrical parameters on heat transfer performance. They found that the geometrical parameters have significant effects on flow and heat transfer. All these experimental researches are valuable to the numerical studies of SWHEs which provide the data to validate the numerical model. With a helically coiled-tube heat exchanger, Ferng et al. [11] numerically investigated the effect of pitch size and Dean Number on the thermal-hydraulic characteristics and reasonably captured the complicated phenomena occurred in the helically coiled-tube heat exchanger. Wang et al. [12] proposed a simulation tool of floating LNG SWHE and studied the effects of rolling amplitude on the heat transfer performance. Based on the numerical simulation, Haskins et al. [13] analyzed the friction pressure drop of isothermal flows on the shell side of annular heat exchangers with helically coiled concentric tubes and the developed correlation which agreed with the CFD results was presented.

To reduce unnecessary energy dissipation and improve the heat transfer effectiveness in heat exchanger, there exist two classes of evaluation criteria for heat exchanger: the first one is based on the

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Nomenclature

A	heat transfer area, m^2
B	layer pitch, mm
C_p	specific heat capacity, J kg^{-1} K^{-1}
D_{in}	external diameter of cylinder, mm
D_{out}	internal diameter of shell, mm
D_t	external diameter of tubes, mm
G_{ff}	entransy dissipation caused by fluid friction
G_{ht}	entransy dissipation caused by heat transfer
K	heat transfer coefficient, W m^{-2} K^{-1}
l	tube pitch, mm
$\dot{m}$	mass flow rate, kg s^{-1}
Nu	Nusselt number
Q	quantity of heat transfer, W
R_{ff}	thermal resistance based on entransy dissipation caused by fluid friction
R_{ht}	thermal resistance based on entransy dissipation caused by heat transfer
Re	Reynolds number
S_ϕ	source term
ΔP_s	shell-side pressure drop, Pa
ΔP_t	tube-side pressure drop, Pa
ΔP_t	unit pressure drop of shell side, Pa m^{-1}
Pr	Prandtl number
T	temperature, K
Δt_m	log-mean temperature difference, K
U	velocity, m s^{-1}
V_{sin}	shell-side inlet velocity, m s^{-1}
V_{tin}	tube-side inlet velocity, m s^{-1}

Greek symbols

ε	turbulent energy dissipation
ν	dynamic viscosity, Pa s
ρ	density, kg m^{-3}
λ	thermal conductivity, W m^{-1} K^{-1}
θ	spiral angle, °
κ	turbulent kinetic energy

Subscripts

c	cool side
h	hot side
i	inlet
o	outlet
s	shell side
t	tube side

first law of thermodynamics and the other is based on the second law of thermodynamics. However, the latter one has attracted lots of attention in recent decades [14]. To describe the heat transfer ability, Guo et al. [15] proposed a new physical concept, which named entransy, based on the analogy with the electrical conduction. They found that, in the heat transfer processed, the entransy is dissipated, and the more dissipation of entransy implies the higher degree of irreversibility [16]. The decrease of entransy is called entransy dissipation which could be used to describe the irreversibility of the heat transfer [17–19]. Furthermore, Guo et al. [15] derived the extreme entransy dissipation principle and defined the equivalent thermal resistance of the heat transfer system based on the entransy dissipation. With the development of the entransy theory, these principles are used to study heat conduction, heat convection and thermal radiation [20–25]. To evaluate the heat transfer performance of helical coiled tube, Guo and Huai [26] proposed the entransy dissipation augmentation number, which is found to suitable to evaluate heat transfer augmentation techniques.

Based on an effectiveness-thermal resistance method, Guo et al. [27] analyzed the heat transfer process in heat exchanger, they found that the effectiveness of heat exchanger decreases monotonically with the increasing entransy-dissipation-based thermal resistance (EDTR) and the thermal resistance based on the entransy dissipation represents the heat transfer irreversibility in heat exchanger. Cheng and Liang [28] analyzed the relationship between the EDTRs of two-stream heat exchanger networks and its effectiveness. They found that the EDTR always decreases monotonously with the increase of effectiveness. Wu et al. [29] developed the entransy-theory-based method in the field of thermal radiation problems to define the generalized thermal resistance for multi-dimensional steady state thermal radiation systems and they found that the generalized thermal resistance is better to optimize some thermal radiation problems compared with minimum entropy generation.

For the design optimization of heat exchangers, the minimum thermal resistance principle is also applicable. The entransy dissipation in heat exchanger can be classified into two groups: the first is caused by heat transfer; and the other is associated with fluid friction. Guo et al. [30] carried out an optimization analysis of main heat exchanger in a Brayton cycle system based on entransy theory. The results shown that the decrease of the entransy dissipation related to heat transfer inevitably leads to the increase of entransy dissipation due to the fluid friction, and vice versa. Cheng et al. [31] analyzed and discussed two-/ three-stream heat exchangers based on the concepts of entransy-dissipation–based thermal resistance of multi-stream heat exchanger and found the principle of the minimum thermal resistance based on entransy dissipation always corresponds to the best performance of heat exchanger. Wang et al. [32] Chen [33] and Xu et al. [34] also optimized the heat exchanger (networks) based on the EDTR.

Spiral-wound heat exchanger is one of the most complicated heat exchangers. A lot of geometrical parameters impact its flow and heat transfer characteristics significantly such as spiral angle, tube pitch, layer pitch and external tube diameter [35]. The published papers show the advantages of entransy theory on analysis and optimization of heat exchanger. However, little attention has been concentrated on the studies of SWHEs based on entransy theory. In this paper, to evaluate effectiveness of SWHE based on entransy theory, the effects of different geometrical parameters on EDTR caused by heat transfer (R_{ht}) and EDTR related to fluid friction (R_{ff}) would be study firstly by numerical simulation. Furthermore, the geometrical parameters and working condition optimal analysis of SWHEs, which minimizing the R_{ht} and R_{ff} are selected as objective functions, would be carried out and the optimal results would be compared with that obtained by traditional objective functions (pressure drop and overall heat transfer coefficient).

1. Numerical method

1.1. Physical model

The schematic diagram of a typical spiral-wound heat exchanger is shown in Fig. 1. The different structures of SWHE are obtained by altering the geometrical parameters (spiral angle, external diameter, layer pitch, tube pitch). The ranges of geometri-