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Research Paper

Decrement in heat transfer effectiveness due to solid heat conduction for a counter-current spiral heat exchanger

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HIGHLIGHTS

- Employing 3-D printing in manufacturing a spiral heat exchanger is proposed.
- The heat exchanger performance at balanced/unbalanced-flow operation is analyzed.
- The decrement in heat transfer effectiveness due to solid heat conduction is graphically presented.
- The optimum Biot number is verified to be in the range of 10^{-4}–10^{-2}.
- Selecting a proper wall material can upgrade the heat exchanger performance.

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ABSTRACT

A new approach employing the 3-D printing technique for manufacturing a counter-current spiral heat exchanger is proposed. The heat exchanger has a thick wall, which could affect its heat transfer performance. Given this characteristic, the decrement in heat transfer effectiveness ($\Delta\varepsilon/\varepsilon$) of the heat exchanger operated at balanced/unbalanced-flow condition and equal/unequal numbers of transfer units on hot-flow and cold-flow sides is numerically solved and graphically presented. The optimum Biot number, resulting from a trade-off between the spiral-direction heat conduction and the radial-direction solid-wall thermal resistance, is verified to be in the range of 10^{-4}–10^{-2}. The $\Delta\varepsilon/\varepsilon$ value at the optimum Biot number nears zero. At a balanced-flow operation, the maximum possible $\Delta\varepsilon/\varepsilon$ values of the heat exchanger for gas-to-gas, liquid-to-liquid and gas-to-liquid waste heat recovery applications are evaluated. It is found that a proper selection of the wall material for the heat exchanger can largely reduce the effect of solid-wall heat conduction on the heat transfer effectiveness.

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1. Introduction

Spiral heat exchangers possess several advantages over other types of heat exchangers. First, the flow pattern in the spiral heat exchangers can be arranged to be counter-current which is an important criterion to achieve an effective heat transfer between two flows. Second, the convective heat transfer coefficient of the spiral flow in the heat exchangers is high, yet the pressure drop is moderate. These properties make the heat transfer efficient. In addition, the heat exchangers usually have high area-to-volume ratios, which is beneficial to shipping and installation. These advantages of the spiral heat exchangers make them comply with the stringent requirements (high heat transfer effectiveness, low consumed pumping power, etc.) for recovering low-grade (low-temperature) waste heat.

The concept of spiral heat exchangers was proposed in the 19th century. In the early years, the heat exchangers specifically addressed the needs in the pulp and paper industry. Later, they were also applied to recovering thermal energy in various industrial processes. However, due to difficulty in fabrication, until now, very few commercial products of this type of heat exchangers are available in the market [1,2]. The 3-D printing technique might initiate a new approach for manufacturing this type of heat exchangers (Fig. 1a and b). Employing this technique (Fig. 2) and a precision casting process, the complex shape of the spiral wall (core structure) constructing a spiral heat exchanger can easily be made. Compared with the conventional sheet-metal manufacturing method, the proposed method has the advantage to cut down the product cost. In the future, it would be a promising alternative approach for manufacturing spiral heat exchangers.

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Nomenclature

a	radius change rate of spiral (a constant), m
b_1, b_2	coefficients in regression analysis
A_t	total heat transfer area of heat exchanger, m^2
Bi_j	Biot number, $h_j\delta_w/k$ (j = 1 or 2)
c_p	constant-pressure specific heat, kJ/kg K
C	ratio of heat capacity rates, $(\dot{m}c_p)_{\min}/(\dot{m}c_p)_{\max}$
C^*	$(\dot{m}c_p)_1/(\dot{m}c_p)_2$
h	convective heat transfer coefficient, W/m^2 K
k	solid thermal conductivity, W/m K
L_t	total length of heat transfer surface, m
L_t^*	dimensionless length, $L_t/4\pi^2a$
$\dot{m}$	mass flowrate, kg/s
N_t	number of turns of spiral, $\phi_o^* - \phi_e^*$
NR	NTU_1/NTU_2
NTU_0	overall number of transfer units, $UA_t/(\dot{m}c_p)_{\min}$
NTU_1	number of transfer units based on hot flow, $h_1A_t/(\dot{m}c_p)_1$
NTU_2	number of transfer units based on cold flow, $h_2A_t/(\dot{m}c_p)_2$
r	radius in polar coordinates, m
T	temperature, K
T^*	dimensionless wall temperature, $(T - T_{2,in})/(T_{1,in} - T_{2,in})$
U	overall convective heat transfer coefficient, $1/(1/h_1 + 1/h_2)$, W/m^2 K

Greek symbols

δ_{ch}	channel width, m
δ_w	wall thickness, m
δ_w^*	dimensionless wall thickness, δ_w/δ_{ch}
$\delta_{w,r}$	transverse coordinate for wall, m
$\delta_{w,r}^*$	dimensionless transverse coordinate, $\delta_{w,r}/\delta_w$
ε	heat transfer effectiveness without solid-wall heat conduction effect
ε_c	heat transfer effectiveness of counter-flow heat exchanger
ε_s	heat transfer effectiveness with solid-wall heat conduction effect
ϕ	spiral-direction coordinate for wall and flow, radians
ϕ_o	angle at end point of inner wall surface, radians
ϕ_e	angle at start point of inner wall surface, radians
ϕ^*	dimensionless spiral-direction coordinate, $\phi/2\pi$

Subscripts

1	hot flow
2	cold flow
in	inlet
min	minimum value
o	end point
out	outlet
w	wall

However, it is foreseeable that the spiral wall fabricated through the 3-D printing technique is thick. A thick wall is known to be a factor degrading the heat transfer effectiveness of a heat exchanger.

Bailey [3], Trom [4] and Wilhelmsson [5] described the unique features, operating principles and applications of spiral heat exchangers. Jarzebski [6], Wu [7], Picón-Núñez et al. [8–10] and Li et al. [11] introduced methodologies for sizing spiral heat exchangers. The work indicated above provides basics for constructing geometries of this type of heat exchangers. Strenger et al. [12] examined temperature rise of heated fluid in a double-spiral heat exchanger for catalytic incineration of contaminated air. A discrepancy between their experimental data and analytical result was attributed to an omission of heat loss in the theoretical model. The effects of heat loss, number of spiral turns and configuration of inlet and outlet on the performance of the same heat exchanger were revealed by Targett et al. [13]. They also showed the existence of an optimum NTU value at which the temperature rise of heated fluid is a maximum. Naphon and Wongwise [14], Ho et al. [15] and Wijeysundera et al. [16] investigated heat transfer characteristics of spiral-coil heat exchangers. Useful heat transfer data for designing the heat exchangers were reported. Bes and Roetzel [17,18] developed an analytical method for evaluating thermal performance of spiral heat exchangers. At large NTU values, a maximum in the heat transfer effectiveness was found. Burmeister [19] obtained an approximate heat transfer effectiveness-NTU solution for a spiral-plate heat exchanger. He also showed the existence of the maximum heat transfer effectiveness. Egner and Burmeister [20,21] used commercial software to analyze heat transfer characteristics of laminar flow in a spiral duct of rectangular cross section. Through the analysis, the heat transfer in the entrance region of the duct was understood. Munir [22] analyzed heat transfer effectiveness of a spiral-plate heat exchanger. It was shown that the optimum NTU value at the maximum heat transfer effectiveness linearly increases with the channel length. Adamski [23] conducted an experiment for a longitudinal-flow spiral recuperator, from which heat transfer and fluid friction correlations were obtained. San et al. [24,25] used a numerical scheme to analyze heat transfer performance of a serpentine heat exchanger and a helical heat exchanger. The scheme is modified and adopted in the present work. Rennie and Raghavan [26] analyzed heat transfer performance of a double-pipe helical heat exchanger. The overall heat transfer coefficient was successfully expressed as a function of the Dean number. Lu et al. [27] numerically and experimentally studied heat transfer characteristics of a multilayer spiral-wound heat exchanger. A simple shell-side heat transfer correlation was obtained. In addition to the work mentioned above, San [28] and Nguyen and San [29] analyzed the second-law performance of heat exchangers for waste heat recovery. It was found that the maximum recovered thermal energy of the heat exchangers occurs near to a balanced-flow operation.

Many analytical results on the heat transfer characteristics of spiral heat exchangers are available in the literature. But in these analyses, the solid-wall heat conduction was neglected. In this work, we intend to clearly reveal the effect of solid-wall heat conduction on the heat transfer effectiveness of this type of heat exchangers. In our previous work [30], the heat transfer effectiveness of a counter-current spiral heat exchanger (Fig. 1a) operated at balanced-flow condition ($C = 1$) and equal number of transfer units on hot-flow and cold-flow sides ($NTU_1 = NTU_2 = 2NTU_0$) was obtained. In this work, the decrement in heat transfer effectiveness due to the solid-wall heat conduction for the spiral heat exchanger (Fig. 1a) operated at balanced/unbalanced-flow condition and equal/unequal number of transfer units is analyzed. In addition, the maximum possible decrement in heat transfer effectiveness of the heat exchanger in practical applications is estimated and strategies to reduce the solid-wall heat conduction effect are proposed.

2. Geometry and energy equations of a spiral heat exchanger

In Fig. 1a, a spiral heat exchanger composed of four Archimedes' spirals is shown. The trajectory of the spirals in polar coordinate system can be expressed as [31]:

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