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Numerical study on novel airfoil fins for printed circuit heat exchanger using supercritical CO_2

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ABSTRACT

The Printed Circuit Heat Exchanger (PCHE) has attracted a lot of attentions recently due to its high efficiency and compactness, and the airfoil fin has excellent thermal–hydraulic performance compared with the zigzag channel in PCHE. Two novel fins were proposed in this study based on the configuration of NACA 0020 airfoil fin, in order to further improve the performance of airfoil fin PCHE. The thermal–hydraulic performance and the enhancement mechanism of the fins were numerically investigated using supercritical CO_2 as the working fluid. The results showed that one of the novel fins has better comprehensive performance and less entransy dissipation than the NACA 0020 airfoil fin used in PCHE, since the j factor of this novel fin is 2.97–6.15% larger, and the pressure drop is 0–4.07% less than the NACA 0020 airfoil fin under the selected conditions. And the staggered arrangement and the proper shape of fins could reduce the effect of boundary layer and improve the thermal–hydraulic performance effectively. In addition, the enhancement mechanism of the novel fin PCHE could be explained with field synergy principle very well.

1. Introduction

With the development of Generation IV (Gen IV) nuclear reactors, the interest in the alternatively high thermal efficiency and environmentally friendly power conversion system is increasing. The supercritical carbon dioxide (S—CO_2) Brayton power cycle is regarded as one of the promising alternatives in the mild turbine inlet temperature region for its high efficiency, stability, safety, compactness, as well as the less influence on the environment [1].

As one of the key components in the S—CO_2 Brayton cycle, heat exchanger has a significant effect on the efficiency and compactness of the whole system. The Printed Circuit Heat Exchanger (PCHE) is regarded as one of the most promising candidates for S—CO_2 Brayton cycle [2]. PCHE is manufactured by diffusion bonding the photo-chemically etched plates. It has strong core to ensure the safety and stability, as well as the high heat transfer efficiency, and its unit could up to 85% smaller and lighter than the traditional shell-and-tube heat exchangers.

The continuous zigzag channel is one of the most widely used channels in PCHE. Ishizuka et al. [3] investigated the performance of PCHE with zigzag channel in an experimental S—CO_2 loop with various pressures, temperatures and mass flow rates. Nikitin et al. [4] proposed empirical correlations for heat transfer coefficient and pressure drop factor based on the experimental performance of zigzag PCHE using S—CO_2 as working fluid. Kim et al. [5] investigated the thermal–hydraulic performance of zigzag channel using helium test loop and three-dimensional numerical simulation, and found that the local pitch-averaged Nusselt number correlation developed from CFD simulations is more appropriate than the global Nusselt number correlation developed from experimental data. Kim et al. [6] optimized the PCHE design for intermediate heat exchangers (IHX) through the cost analysis. Lee and Kim [7–9] investigated numerous channel cross-sectional shapes and channel configurations to optimize the zigzag channel, and they found that rectangular channel has the best thermal performance and the worst hydraulic performance while the circular has the worst thermal performance. Ma et al. [10] studied the thermal–hydraulic performance of zigzag-type PCHE using helium as the working fluid at the typical temperature of 900 °C in the very high temperature reactor. Meshram et al. [11] studied and evaluated the performance of PCHE with straight and zigzag channels using FLUENT software, and developed correlations for Nusselt number and friction factor.

The zigzag channel suffers the drawback of a significant pressure drop, so some novel channels were proposed to avoid the significant pressure drop for PCHE. Ngo et al. [12] proposed S-

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Nomenclature

c_p	specific heat capacity at constant pressure [J/(kg·K)]
C	thermal capacity [J/K]
D_h	hydraulic diameter [m]
E	entransy [J·K]
E^*	nondimensional entransy dissipation number
f	Fanning friction factor
h_L	local heat transfer coefficient [W/(m^2·K)]
H	height of specific volume [m]
i	specific enthalpy [J/kg]
j	Colburn j factor
L	length of specific volume [m]
L_c	chord length [m]
L_h	horizontal pitch [m]
L_s	staggered pitch [m]
L_t	airfoil thickness [m]
L_v	vertical pitch [m]
$\dot{m}$	mass flow rate [kg/s]
Nu	Nusselt number
Pr	Prandtl number
p	pressure [Pa]
P_a	perimeter of the fin [m]
q	heat flux [W/m^2]
Q	heat load [W]
Re	Reynold number
S	wet area [m^2]
S_a	top surface area of the specific fin [m^2]
T	temperature [K]
$\nabla\overline{\mathbf{T}}$	nondimensional temperature gradient
U	nondimensional velocity
$\overline{\mathbf{U}}$	nondimensional velocity vector
W	width of specific volume [m]
Vh	volume of the shape [m3]
X	active flow length [m]

Greek symbols

β	field synergy angle between fluid velocity and temperature gradient [°]
ρ	density [kg/m^3]
Φ	energy dissipation due to viscosity [W/m^2]
μ	dynamic viscosity [Pa·s]
μ_{eff}	effective viscosity [Pa·s]
μ_t	turbulence viscosity [Pa·s]
λ	thermal conductivity [W/(m·K)]
η	enhanced ratio

Subscript

a	airfoil fin
bulk	fluid bulk
cold	cold
eff	effective
enhance	enhanced structure
hot	hot
in	inlet
i, j, k	tensor indices
L	local plane
out	outlet
x, y, z	x, y, z-directions

shaped fins for PCHE, whose pressure drop is far less than the zigzag channel with the penalty of a slight decrease of heat transfer. Ngo et al. [13] investigated the thermal and hydraulic performance of S—shape fins and zigzag fins numerically and experimentally, and proposed the Nusselt number and pressure-drop factor correlations for S-shape and zigzag fins. Tsuzuki et al. [14] numerically investigated the flow of CO_2 in the S-shape fin PCHE and found that the S-shape fin PCHE has one-fifth pressure drop of the zigzag PCHE. Tsuzuki et al. [15,16] studied the effect of fin shape on thermal–hydraulic performance of PCHE with S-shape fins numerically, and proposed the relevant Nusselt number correlations.

Kim et al. [17] conducted a numerical investigation on the airfoil fin PCHE, and the results showed that airfoil shape fin PCHE has almost the same heat transfer ability but one-twentieth pressure drop of zigzag channel PCHE. Kim et al. [18] numerically analyzed the performance of airfoil fin PCHE in S—CO_2 power cycle, and concluded that the fully staggered arrangement has the best performance. Xu et al. [19] explored the effect of airfoil fin arrangements on heat transfer and flow resistance, and found the staggered arrangement has the best thermal–hydraulic performance, and they proposed a new fin structure similar to swordfish. Yoon et al. [20] proposed Fanning factor and Nusselt number correlations for airfoil PCHE based on the simulation results, and they compared the cost of straight, zigzag, S-shape and airfoil PCHEs for intermediate heat exchangers (IHXs) in the high temperature gas-cooled reactors (HTGRs) and the sodium-cooled fast reactors (SFRs). Ma et al. [21] performed the photochemical etching experiment to manufacture the airfoil PCHE plate and found the airfoil fin is not an ideal airfoil profile and it has a fin-endwall fillet, then they numerically investigated the effect of fin-endwall fillet on the thermal–hydraulic performance of airfoil PCHE. Kwon et al. [22] performed CFD analysis for various airfoil fin configurations and made correlations for Nusselt number and Fanning friction factor. Besides, they used cost based objective function to evaluate and optimize the configuration of airfoil fin PCHE. Chu et al. [23] studied the thermal–hydraulic performance of printed circuit heat transfer surface with distributed NACA 0025 airfoil fins and proposed the correlations of *j* and *f* factors. Chen et al. [24] compared the comprehensive performance of airfoil fin PCHEs with NACA 00XX series airfoil fins, and found the pressure drop of NACA 0020 airfoil fin PCHE reduces remarkably in comparison with the zigzag PCHE, and the comprehensive performance of NACA 00XX airfoil fin PCHE degrades as airfoil thickness increases.

Guo et al. [25] proposed the field synergy principle to evaluate and optimize the single phase convective heat transfer, in which the heat transfer performance depends not only on the velocity vector and the temperature gradient, but also on their synergy. Guo et al. [26] investigated the heat transfer characteristics of helically coiled tube numerically in terms of field synergy principle, and found the heat transfer enhancement mechanism of the tube could be well described by the field synergy principle. Zhai et al. [27] analyzed the hydraulic and thermal performance of double-layered microchannel with cavities and ribs in terms of the intensity of secondary flow and field synergy principle.

Guo et al. [28] proposed a physical quantity of entransy to describe the heat transfer ability of an object, which was defined as half of the product of internal energy and the thermal tempera-