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Optimization of fin arrangement and channel configuration in an airfoil fin PCHE for supercritical CO_2 cycle

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HIGHLIGHTS

- The effects of airfoil fin arrangements on heat transfer and flow resistance are investigated.
- Staggered fin arrangement is more suitable than parallel fin arrangement.
- The sparse arrangement of fins is recommended.
- The flow resistance plays a major role in determining the overall performance of a PCHE.
- A modified fin is proposed whose comprehensive performance is effectively improved.

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ABSTRACT

As a new type of discontinuous fin, airfoil fin (AFF) can bring a better thermal-hydraulic performance than Zigzag fin and S-shaped fin when applied to PCHE using supercritical CO_2 as a working fluid. In this study, the effects of AFF arrangements on heat transfer and flow resistance are investigated. The results show that a sparser staggered arrangement of fins can lead to a better thermal-hydraulic performance in an AFF PCHE and the flow resistance plays a major role in determining the overall performance. It concludes that reducing the flow resistance needs to be considered first in the optimal design of a PCHE using supercritical CO_2 as working fluid. Furthermore, a new fin structure (modified AFF) is proposed for flow resistance reduction and is proved to be better than the AFF.

1. Introduction

Supercritical fluids have been widely used in various industrial applications including power engineering [1], aerospace engineering, chemical engineering, Micro-Electro-Mechanical Systems (MEMS) [2], and refrigeration engineering [3]. Supercritical-pressure Reactors (SCRs) [4], refrigeration and air-conditioning systems are gradually using CO_2 as a working fluid due to its attractive physical and transport properties. The character of supercritical fluid is so peculiar that differences between gas and liquid disappear regardless of its temperature when the pressure of the fluid is above the thermal critical value. That is to say, the phase change phenomenon no longer happens under supercritical condition, which is very beneficial for simplifying equipment in the energy conversion system, for example, gas–liquid separator. Heat exchange equipment, as an important part in an energy conversion system, takes up most of the investment, so the efficiency and safety must be carefully considered, especially for high pressure and high temperature system. The high pressure character of supercritical system makes it unreliable using traditional compact plain-fin heat exchanger whose compressive strength is quite weak. However, the request of miniaturization and high compactness in system construction makes it less and less optimistic in using huge shell and tube heat exchanger. A new type heat exchanger called printed circuit heat exchanger (PCHE) attracts people's attention in these years [5–7], which is able to meet the demands in high pressure and high temperature system [8] with characteristics of high security, high compactness, and high efficient. Actually, PCHE is a very special type of plate-fin heat exchanger. In contrast to the traditional machining and welding

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Nomenclature

A_0	total heat transfer area of heat exchanger, m^2
dA	heat transfer area at cross-section A, m^2
dQ	heat load at cross-section A, kW
$h_{inlet,\ A}$	inlet enthalpy at cross-section A, kJ/kg
$h_{outlet,\ A}$	outlet enthalpy at cross-section A, kJ/kg
H	height of fin, mm
l	length of whole heat exchanger, m
L	length of fin, mm
L_a	transverse pitch of fins, mm
L_b	longitudinal pitch of fins, mm
L_c	longitudinal distance of fins in staggered arrangement, mm
$\overline{Nu}$	overall Nusselt number
ΔP	pressure drop of heat exchanger, kPa
Q_0	total heat load of heat exchanger, kW
q_m	mass flux of heat exchanger, kg/m^2 s
Re_{inlet}	inlet Reynolds number
$T_{b,\ A}$	bulk temperature at cross-section A, K
T_w	wall temperature, K
ΔT	temperature difference between inlet and outlet of heat exchanger, K
U_A	heat transfer coefficient at cross-section A, kW/m^2 K
$\overline{U}$	overall heat transfer coefficient, kW/m^2 K
W	width of fin, mm

process, PCHE is mainly based on two technologies called chemical etching and diffusion bonding [9]. Flow channels are etched chemically on the metal plates, and then these etched plates are stacked together and transformed to one block through diffusion bonding.

After the confirmation of the reliability of the diffusion bonding [10], the performance research of PCHE mainly focuses on the shape of channel and the plates superimposed manner. Nikitin [11] investigated the heat transfer and pressure drop of a PCHE with zigzag channel based on a supercritical CO_2 experimental system. They found that the compactness of the exchanger core and the maximal power density are very large. They concluded that the PCHE is a promising compact heat exchanger for heat pumps, gas turbine reactors, etc. In order to enhance the heat transfer performance and reduce the friction loss, Lee and Kim [12] used a multi-objective method to optimize the shape of zigzag channel. Ngo [13] proposed a new channel called S-shaped channel, which was found extremely excellent in volume and pressure drop reduction. Later, Ngo [14] experimentally compared the heat transfer and pressure drop performance of two PCHEs with S-shaped fins and Zigzag fins respectively. Their results showed that, with a 24–34% reduction in *Nu*, the pressure drop factor of the PCHE with S-shaped fins was 4–5 times less than that with zigzag fins in a certain range of *Re*. Tsuzuki [15] pointed out that the pressure drop reduction was mainly caused by a superior uniform flow velocity profile in the flow area after using S-shaped fin, and the elimination of reverse flows and eddies appearing in the corners of zigzag flow channels also made great contribution in pressure drop reduction. Later research done by Kim [16] showed that airfoil shaped fin could suppress the generation of separated flow, which might be more excellent in pressure drop reduction than S-shaped fins. In fact, the physical properties of fluid will be changed significantly under high pressure and high temperature, and thus the placement manner of PCHE will have a significant impact on the flow uniformity. Kim [17] recommended the vertical installation of the PCHE for stable operation, and Serrano [18] pointed out that 30% of the total heat release happened in the vicinity of critical point in PCHE which meant that a large part of the heat exchanger length had not been effectively utilized.

According to the studies above, the previous researches mainly focused on investigating the applicability of a new fin structure, but little study has been done to explore the direction and method of optimizing the arrangement and structure of fins applied in a PCHE using supercritical CO_2 as a working fluid. In this article, based on a numerical study of the effects of fin arrangements on the heat transfer and pressure drop characteristics of an AFF PCHE (AFF PCHE), the method of improving thermal-hydraulic performance and the direction of optimizing fin structure are studied. Based on the numerical results, a new fin structure is further proposed.

2. Methodology

2.1. Physical properties and data reduction

Different from the traditional flow and heat transfer, the physical properties of supercritical CO_2 change substantially with the temperature in the heat transfer process, as shown in Fig. 1, which results in magnitude variations in non-dimensional parameters in the axial and radial directions, such as Reynolds number and Prandtl number. So, local dimensionless parameters are not able to represent the heat transfer and resistance performance of the entire flow field. Through a careful research on the average temperature difference of the supercritical CO_2, Utamura et al. [19] pointed out that employing integration method was much more safety than directly using logarithmic mean temperature difference method (LMTD) in calculating the heat transfer performance of a PCHE. So, the integration method is used in this study. The local heat transfer coefficient based on the average cross-sectional physical properties is calculated first, and then an integration of these local heat transfer coefficients is applied along the flow direction. The overall heat transfer coefficient of the heat exchanger can be expressed as:

$$\overline{U} = \frac{1}{A_0}\int_0^{Q_0} U_A \mathrm{d}A \tag{1}$$

where Q_0 and A_0 are the total heat load and the total heat transfer area. U_A is the local heat transfer coefficient, which can be calculated as:

$$U_A = \frac{\mathrm{d}Q}{\mathrm{d}A(T_w - T_{b,A})} \tag{2}$$

where T_w and $T_{b,A}$ are the wall temperature and local bulk temperature in the cross section A. dA and dQ are the local heat transfer area and local heat load, and $\mathrm{d}Q = q_m \mathrm{d}A(h_{outlet,A} - h_{inlet,A})$. q_m is the mass flux of the heat exchanger. $h_{inlet,A}$ and $h_{outlet,A}$ are the local inlet enthalpy and outlet enthalpy of the A cross section.

According to Eqs. (1) and (2), the overall heat transfer coefficient of the heat exchanger can be expressed as: