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Theoretical and numerical investigation on the fin effectiveness and the fin efficiency of printed circuit heat exchanger with straight channels

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ABSTRACT

Theoretical and numerical studies were conducted on the fin effectiveness and the fin efficiency of printed circuit heat exchanger (PCHE). A heat conduction equation for the fins of PCHE with straight channels was derived, from which the longitudinal temperature distribution of the fins can be obtained. And the expressions of the fin effectiveness and the fin efficiency were developed. Based on their expressions, an understanding of the heat transfer process between the fin surface and the bulk fluid was improved. Results show that the PCHE fin effectiveness is enhanced by the choices of high fin thermal conductivity, decreasing the ratio of the fin thickness to the radius of the channels, or under conditions for which the convective coefficient is small. As for the fin efficiency of PCHE, it's improved with high fin thermal conductivity, thick fin and low convective coefficient of the working fluid. For the cases with large Biot number, the PCHE fin effectiveness and the PCHE fin efficiency can be weakened up to 20%, which should be considered in the modeling of thermal-hydraulic. Moreover, the theoretical investigations were validated against the numerical simulation, and they agree with each other very well.

1. Introduction

Recently the tendency is growing to use energy in the way of more efficiency, more flexibility, and more sustainability. And some new innovative techniques and applications are being put forward continuously, such as small modular reactors [1,2], the power generation systems with advanced operating parameters (high operating temperature/pressure) [3], and advanced power conversion cycles [4]. In the innovative applications above, the heat exchangers with high thermal effectiveness are strongly pertinent to the overall plant thermal efficiency. Besides, considering the limited construction, the compactness of the heat exchangers is another important performance factors.

Ideal heat exchanger candidates for these applications should maintain the large heat transfer area while its size should be reduced drastically. Various technologies of heat exchangers have been evaluated according to their potential ability to fit with the requirements [5]. It showed that the plate fin heat exchanger (as shown in Fig. 1 (a)) and the printed circuit heat exchanger (PCHE) (as shown in Fig. 1 (b)) are likely to be the most outstanding candidates due to their superior compactness and some other excellent performances. The plate fin heat exchanger is based on very thin fins assembled by brazing on flat foils in order to increase the heat exchanger performances, but it's less robust than the PCHE. PCHE is based mainly on the two techniques of chemical etching and diffusion bounding. Employing these techniques enables the construction of highly elaborate PCHE with flow channel diameters much smaller than those in standard plate heat exchangers. There is almost no constraint for the compactness of PCHE. And the main advantage of this exchanger is high pressure/strength performance, flexibility in design, and high thermal effectiveness.

Previous researchers have invested a considerable amount of effort in attempting to understand the flow and thermal characteristics of PCHEs. For example, Kim and NO [8] investigated thermal-hydraulic performance of the PCHE in a helium-water condition through experimental tests and numerical simulations with horizontal and vertical arrangements, and a Fanning factor correlation and a Nusselt number correlation were proposed. Ngo et al. [9] evaluated a PCHE with an S-shaped fin configuration based on 3D numerical simulations with a CO_2 side and an H_2O side. Kim et al. [10] investigated the thermal-hydraulic performance of a PCHE in a helium-helium test loop both experimentally and numerically for application to an internal heat exchanger or a recuperator in Very High Temperature Reactors. Nikitin et al. [11] investigated the performance of a PCHE in an experimental supercritical CO_2 loop. Alan [12] studied the heat transfer and pressure drop performance of carbon dioxide flowing in a PCHE prototype experimentally and numerically. These studies have advanced the understanding the thermal-hydraulic characteristics of PCHE. However, there are still

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Nomenclature

a_0, a_1, a_2	constants, 1
A_c	cross-sectional area, m^2
A_s	fin surface area, m^2
h	convective heat transfer coefficient, $W/m^2/K$
k	thermal conductivity of the fin, W/m/K
L	length of the fin, m
m	defined dimensionless number, $= hR/k$
t	fin thickness, m
t^*	normalized fin thickness, 1
T	temperature, °C or K
T^*	excess temperature, °C or K
T_1, T_2	base temperature of the fin, °C or K
T_1^*, T_2^*	base excess temperature of the fin, °C or K
R	the radius of the channels, m
x, y	rectangular coordinates, m
x^*, y^*	normalized rectangular coordinates, 1

Greek symbol

ε_f	fin effectiveness, 1
η_f	fin efficiency, 1
θ	angle, °

Subscripts

Bulk	at the bulk fluid

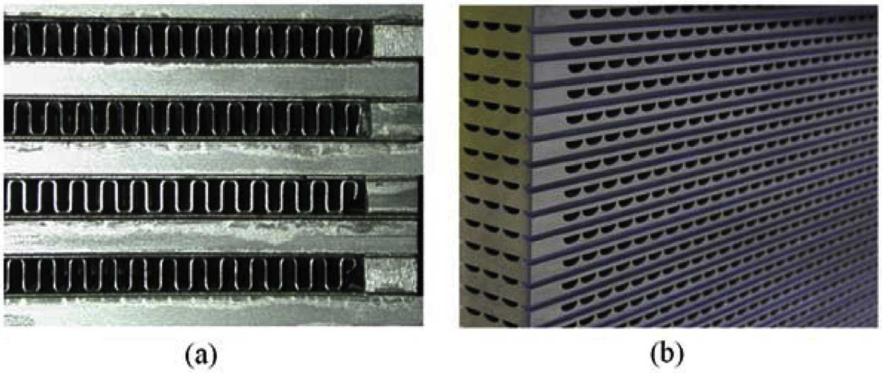

Fig. 1. Two compact heat exchangers, (a) plate fin heat exchanger [6], (b) printed circuit heat exchanger [7].

many assumptions in the thermal-hydraulic modeling of PCHE. For instance, Dostal [13] once calculated the thermal-hydraulic performance of PCHE by modeling the hot and the cold channels based on the assumptions that the wall channel temperature is uniform along channel periphery at every axial location, that the heat conduction area is assumed to be equal to the heat transfer area in the channel, and that the heat conduction length is equal to the distance between the hot and cold channel. Actually the modeling process above can be improved by the study on the fin effectiveness and the fin efficiency of PCHE which is still not able to be found in the publications up to new.

PCHE is categorized as a plate-fin type heat exchanger, as shown in Fig. 2. Something special for the fins in PCHE is that one of its important functions is to maintain the channel strength with diffusion-bounded technique, and the other is influencing the thermal performance of PCHE. In the PCHE fins, the heat transfer direction from the boundaries is often thought to be perpendicular to the principal direction of heat transfer in the solid strut. Temperature gradients in the principal direction sustain heat transfer by conduction in the strut. There is concurrent convective heat transfer between the surface and the bulk fluid (combined conduction-convection effect), and hence the magnitude of the temperature gradient to change with the distance increasing along the principal direction. The measures of the fin thermal performance are often provided by the fin effectiveness (ε_f) and fin efficiency (η_f). Studies on the fin effectiveness and the fin efficiency of PCHE are helpful for the thermal design of PCHE, especially providing foundation on the heat exchanger modeling, and can give useful insight on the heat transfer process between the hot and cold fluids. The theoretical model could also be a useful tool for scoping analysis when it comes to thermal-stress calculations.

The research presented herein represents a contribution to the analysis of the fin effectiveness and the fin efficiency of PCHE with straight channels theoretically and numerically. First, a general thermal conduction analysis on the fin of PCHE is conducted. After solving the differential equation, the expressions of ε_f and η_f were obtained. Moreover, the effects of the fin dimensions, thermal conductivity of the solid fin, and convective heat transfer coefficient of the working fluids on the fin effectiveness and fin efficiency were also investigated. Theoretical results were also compared with the results from numerical simulation.

2. A general heat conduction analysis on the fins of PCHE

2.1. Physical model of the PCHE fins

The fin configurations of PCHE with straight channels are illustrated in Fig. 3. The PCHE fins connect two walls at different temperatures and around which the cold and hot fluid flows are arranged alternately, as shown in Fig. 2. And here the cold fluid is considered flowing through

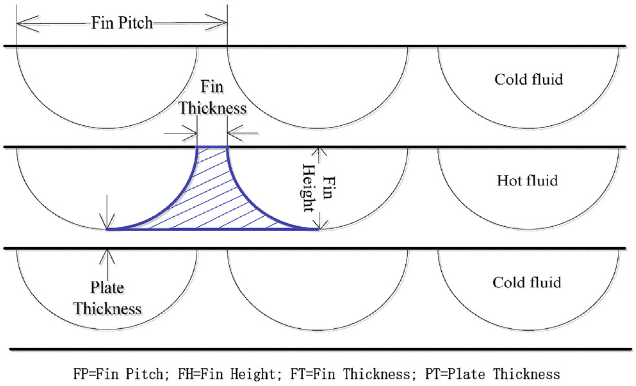

Fig. 2. The fin structure in the PCHE.