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Effects of geometrical parameters on the thermohydraulic characteristics of periodic cross-corrugated channels

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ABSTRACT

Ventilation air heat recovery used in building energy conservation involves simultaneous heat and moisture/mass transfer and is characterized with small temperature and moisture partial pressure differences. It is critical to consider the trade-offs between heat and mass transfer effectiveness and pressure loss. This study is the exploration of using numerical heat transfer analysis for this purpose. Simulations are performed to study the geometric effect on thermohydraulic characteristics of a periodic cross-corrugated channel for the Re range of 200–3000. The effect of Apex angle and aspect ratio on heat transfer, pressure drop and thermohydraulic performance in the corrugated channel is investigated. To accurately predict the transitional flow in the topology, a model performance evaluation is conducted in two steps through the cross comparisons between predictions and related correlations (or experiment results). Of the seven turbulence models selected, the Reynolds stress model fits the correlation and experiment the best and thus is employed for comparative study. The results show that the Apex angle strongly influence the heat transfer and pressure loss in a triangular cross-section corrugated channel. For the purpose of heat transfer enhancement, cross-corrugated triangular channels at the 90° and 120° Apex angles are recommended. The aspect ratio has a relatively greater impact on flow frictional loss, compared to its effect on the heat transfer for the studied cases. For this flow regime, the cross-corrugated triangular duct with the Apex angle of 150° is shown to be the optimum choice over all the studied channels. The JF factor is enhanced by 4.1–7.0 times that in a triangular channel with Apex angle of 90°.

1. Introduction

In recent years, energy crisis and the thrust for energy conservation have driven the development for high efficiency heat exchangers. The demand for economical, high performance, space saving and lightweight heat exchangers has influenced the research of compact surfaces. Compact heat exchangers characterized by high heat transfer surface area to volume ratios have received great attention due to its high heat transfer coefficients compared to other exchanger types [1].

Cross-corrugated channels are the basic channel geometry in plate heat exchangers and are widely used in many applications such as electronic cooling, spacecraft and air conditioning. It has passive enhancement of the heat transfer process where secondary flow structures are created by means of corrugated surfaces. Recently, cross-corrugated channels have also been considered for membrane-based total energy recovery unit design [2]. In such applications, both the heat and mass transfer in the duct and in the membrane itself are important. Encouraging results are emerging with the introduction of new materials that can offer heat and moisture recovery at the same time [3–5]. The use of cross-corrugated exchangers has been proven to increase the mechanical strength of the plates as well as the heat transfer rate [6]. The configuration is shown in Fig. 1, where two unmixed cross flows exchange heat through corrugated plates. Flat membrane sheets are corrugated to form a series of parallel ducts. Sheets of the corrugated plates are then stacked together to form a 90° orientation angle between the neighboring plates, which guarantees the same flow pattern for both fluids. With a pre-designed plastic frame, corrugated duct walls are formed to support the ultrathin membranes and construct the required geometry.

Flow and heat transfer in corrugated channels are complicated and strongly influenced by the geometrical parameters, including the inclination angle and the corrugation profile of the channels. Many studies have been carried out to investigate the forced convection flow in corrugated channels by means of experimental and numerical approaches. Focke et al. [7] experimentally investigated

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the effect of the corrugation inclination angle on the thermohydraulic performance of the heat exchanger through the use of the electrochemical mass transfer analogy. They found that a 90° orientation angle produces the largest driving force that generates swirl in the furrows. Satisk et al. [8] carried out experimental studies to illustrate the geometry effect on the heat transfer and pressure drop of corrugated passages. Muley and Manglik [9] conducted a series of tests to study the thermohydraulic performance of the corrugated plate with different plate configurations. Zimmerer et al. [10] studied the effects of the inclination angle, the wavelength, the amplitude and the shape of the corrugation on the heat and mass transfer of the exchanger. These experimental studies identified that the geometrical parameters have significant effect on the thermohydraulic characteristics of the exchangers.

In addition to these experimental studies, extensive effort has been made to numerically investigate the thermohydraulic characteristics of the corrugated channels [11–12]. Compared with the experimental method, the computational fluid dynamics (CFD) method is an effective and economical tool for obtaining detailed flow structures between the corrugated plates and is widely used in comparative studies. Before investigating geometric effects on the thermohydraulic characteristics in the cross-corrugated channels, the reliability and computational cost of using the numerical method should be evaluated. It is of essential importance to accurately reproduce the flow features and the hydrothermal behavior. It is generally agreed that the flow inside the corrugation plates has an earlier transition to turbulent flow than between conventional parallel plates [12]. Laminar flow model would not serve as an appropriate viscous model for simulating the flow in corrugated channels. The choice of the most suitable turbulence model is essentially the key to successfully modeling the complex flow in the channel. Ciofalo et al. [11] compared the use of different viscous models in the Reynolds number range between 1000 and 10,000. They found that Standard $k-\varepsilon$ model with standard wall functions is completely inapplicable at low Re. Kanaris et al. [13] examined the ability of a general purpose CFD code to predict the flow and heat transfer characteristics in a corrugated channel. A two-equation turbulence model (SST) is used and the simulations are conducted for the Reynolds number range from 400 to 1400. Zhang and Che [14] performed numerical predictions of fluid flow and heat transfer between cross-corrugated plates. Results predicted by eight turbulence models were compared with available experimental data. Han et al. [15] briefly reviewed the viscous models used in the previous investigations of fluid flowing in corrugated plates, and it was found that the most appropriate viscous model is still an open issue. Some researchers simulated the fluid flowing between the whole cross-corrugated plates [13]. Tsai et al. [16] numerically investigated the hydrodynamic characteristics and distribution of flow in two real-size cross-corrugated

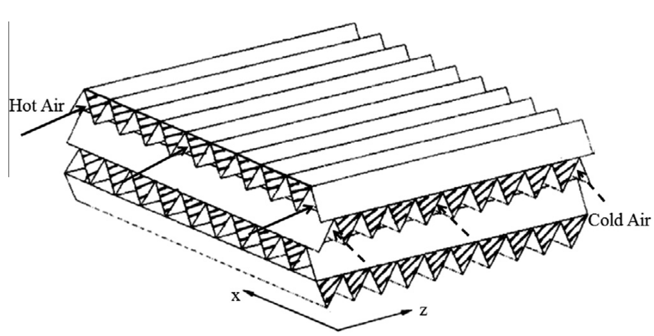

Fig. 1. Schematic of the cross-corrugated exchanger applied in heat recovery application.

channels. However, a whole-size simulation results in an increase of computational cost, which is not desired in comparative studies and optimization analysis. Due to the modular nature of a compact heat exchanger, a common practice for computational expense reasons is to think of it as composed of a large number of unit cells. An alternative method is using a single cell as the computational domain, which is the smallest and repeated element in the cross-corrugated channels [11,12,17–19]. Periodicity conditions are imposed across its boundaries in the streamwise direction, by which it is meant that the outlet condition is identical to the inlet condition of the computation domain. A considerable amount of computational cost could be saved by utilizing the unitary cell.

For the novel cross-corrugated channels used in membrane recovery application, with corrugation angle of 90° between two neighboring plates, the duct geometry is expected to influence the flow and heat transfer capacity of the exchanger. Shah and London [20] studied the heat transfer characteristics of laminar flow in a wide variety of channel shapes for an extensive range of thermal boundary conditions. Besides the sinusoidal cross-section ducts that usually used in metal plate heat exchangers, there have been several reports on heat transfer and friction characteristics in channels with other-shaped cross-sections, such as semi-circular, triangular and trapezoidal shapes. Zheng et al. [21] numerically studied the flow and heat transfer characteristics of channels with a semi-circular cross-section in the laminar flow regime for different Reynolds numbers and Prandtl numbers. Leung and Probert [22] experimentally investigated the thermal behaviors of turbulent air-flows through triangular passages in compact heat-exchangers with three different apex-angles. Chen et al. [23] studied numerically the flow and heat transfer characteristics of smooth triangular ducts with different Apex angles for fully-developed laminar flow conditions. Gupta et al. [24] performed simulations to study the heat transfer behavior of an equilateral triangular section duct for fully-developed laminar flows with Reynolds numbers below 200. Wu and Cheng [25] measured the friction factor of laminar flow of deionized water in smooth silicon microchannels of trapezoidal cross-section. The results showed that the friction constant of these microchannels is greatly influenced by the cross-sectional aspect ratio, which is defined as the ratio of small base to big base of the trapezoid. McHale et al. [26] numerically studied the heat transfer in the thermal entrance region of trapezoidal microchannels. The effects of sidewall angle and the aspect ratio (small base of trapezoid to channel height) upon the local and average heat transfer coefficients in the trapezoidal duct are explored. These previous studies illustrated that the cross-section shape of the channel is a major parameter in influencing the thermohydraulic characteristics of heat exchangers. However, such geometric effect on flow and heat transfer in the novel cross-corrugated channels used in membrane recovery application has not been studied previously.

Yang et al. [27] investigated the transitional flow and heat transfer in fully developed corrugated duct in the Reynolds number range of 100–2500, while Zhang [28] examined the flow structure and heat transfer characteristics in a fully developed cross-corrugated duct in transitional flow regime between Re = 100 and 6000. In comparison, very little work has been undertaken on the duct geometry effects on the thermohydraulic characteristics in this flow regime. In this paper, the effect of Apex angle and aspect ratio upon the thermohydraulic characteristics of the corrugated channel is explored. The present study is aimed to numerically investigate the geometrical effect on the thermohydraulic characteristics of periodic cross-corrugated channels in typical transitional flow regime with Reynolds number between 200 and 3000. This study covers a wide range of Apex angles from 30° to 150° for isosceles triangular cross-section channel, and the cross-sectional aspect ratios (small base to big base of the trapezoid)