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Research Paper

Comparative performance assessment of plate heat exchangers with triangular corrugation

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HIGHLIGHTS

- Triangular cross-corrugated plate with the largest apex angle, have the highest thermo-hydraulic performance.
- By increasing the apex angle both pressure drop and heat transfer coefficient increase.
- By increasing the apex angle, friction factor and the Colburn j factor follow two distinguished trends.
- The apex angles around of 90°–100° are the transitional angles for the flow regime.
- Peak of turbulence intensity, friction factor and Colburn j factor are observed around angles of 90°–100°.

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ABSTRACT

A three-dimensional computational fluid dynamics approach with the Reynolds stress model is considered to investigate the influence of the apex angle on the thermal and hydraulic features of triangular cross-corrugated heat exchangers for a range of Reynolds numbers 310–2064. The influence of the intensity and complexity of the recirculation zones along with the turbulence intensity on those characteristics and corresponding viscous and pressure forces are studied. The choice of the computational domain as a unitary cell with periodic boundary condition versus a long channel with several cells is discussed. One on one comparison between the Reynolds stress model and experimental results shows less than 5% deviation, which is within the uncertainty of the experiment. By increasing the apex angle both pressure drop and heat transfer coefficient increase, due to the increase of the pressure force and the vorticity magnitude along the flow direction. The pressure force is the dominant force, contrary to pipe flow, where the viscous force is dominant. The influence of the apex angle on the friction factor and the Colburn *j* factor follows two distinguished trends. The apex angles around of 90°–100° are the transitional angles for the flow regime. Peak of turbulence intensity, friction factor and Colburn *j* factor are observed around these angles. The ratio between pressure and viscous forces decays after angle 100°, resulting in a smaller recirculation zone and lower turbulence intensity. Finally, the thermo-hydraulic performance of the considered geometries is compared with respect to each other based on a performance evaluation criterion. It is found that the geometry with the largest apex angle has the highest thermo-hydraulic performance.

1. Introduction

It is well recognized that reducing the energy use of HVAC&R systems is a necessary step in order to meet future energy demands [1]. As the heat exchangers comprise a significant portion of HVAC&R systems, accurate performance evaluation of these devices has to be pursued [2]. Recently, the use of cross-corrugated plates with triangular corrugation (triangular cross-corrugated plates) attracted attention in HVAC&R application [3]. Cross-corrugated plates are a type of heat exchanger where, the heat is transferred between two unmixed flows through corrugated plates. The corrugated plates are stacked on top of each other with different orientation angles (Fig. 1). Over 60 different corrugated patterns have been produced during the past century [4]. A corrugation pattern provides a large heat transfer area, structural strength and enhancement of heat transfer. The heat transfer is enhanced in this kind of geometries due to the repeated disruption of boundary layers, promotion of secondary flow and by using flow passages with small hydraulic diameter [5].

Computational fluid dynamics (CFD) is an effective tool to study the thermal and hydraulic characteristics of corrugated channels. Due to the very high computational effort required for simulations of a complete heat exchanger, researchers such as, Mehrabian and Poulter [6],

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Nomenclature

A	area (m^2)
B	base length (m)
c_p	specific heat capacity (J/kg K)
D_h	hydraulic diameter (m)
f	friction factor
F	safety factor for GCI
h	mean convective heat transfer coefficient (W/m^2 K)
H	grid spacing (m)
j	Colburn j factor
k	turbulent kinetic energy (m^2/s^2)
L	flow length (m)
Nu	mean Nusselt number
p	order of convergence
P	pressure (Pa)
P^*	relative pumping power (m^{-2})
Pr	Prandtl number
q	average heat flux (W/m^2)
r	grid refinement ratio
Re	Reynolds number
T	temperature (K)
u	velocity in x direction (m/s)
u_c	frontal velocity (m/s)
u_f	velocity in the minimum cross-sectional flow area (m/s)
v	velocity in y direction (m/s)
V^*	relative heat exchanger volume (m^3)
w	velocity in z direction (m/s)

Greek symbols

α	apex angle (°)
β	non-periodic pressure gradient (Pa/m)
γ	corrugation inclination angle (°)
Δ	difference
Θ	dimensionless temperature
λ	thermal conductivity (W/mK)
μ	dynamic viscosity (kg/m s)
ν	kinematic viscosity (m^2/s)
ρ	density (kg/m^3)
σ	contraction factor
Φ	general dependent variable
ω	specific dissipation rate (1/s)

Subscripts and Superscripts

b	bulk
c	minimum cross section
w	wall
ws	wetted surface
$'$	fluctuation
$*$	periodic

Acronyms

CFD	computational fluid dynamics
GCI	grid convergence index
HVAC&R	heating, ventilation, air conditioning & refrigeration
LES	large eddy turbulence model
LKW	low Reynolds number k-ω
LMTD	logarithmic mean temperature difference
PEC	performance evaluation criterion
RSM	Reynolds stress model
SST	shear stress transport model

Fernandes et al. [7], Freund and Kabelac [8], Han et al. [9] and Etemad and Sundén [10] have employed one periodic unitary cell or several cells as their computational domain.

Authors such as Ghaddar et al. [11] ($0 < Re < 2000$), Sundén and Trollheden [12] ($50 < Re < 1250$), Pereira and Sousa [13] ($0 < Re < 1200$), and Adachi and Uehara [14] ($50 < Re < 500$), studied the flow with low to moderate Re in channels with rectangular corrugation using CFD. It was found that the flow shows a complex behavior such as separation, recirculation, reattachment and deflection. Moreover, self-sustaining geometrically induced oscillations that are present in the flow increase the heat transfer performance. Depending on the geometry under consideration, different transition Reynolds numbers are reported in the literature. It is important to note that most of the studies agree that transition from laminar flow to turbulent flow happens at relatively low Reynolds numbers in cross-corrugated geometries compared to the case of a straight tube. For example Ghaddar et al. [11] reported the transitional Re as approximately 900. Based on Shah and Wanniarachchi [15], the flow in a cross-corrugated channel has a transition at the Reynolds number between 100 and 1500. According to Heggs et al. [16] purely laminar flow does not exist for Reynolds numbers larger than 150. Later, Shah et al. [17] confirmed that for $Re > 200$, the flow is turbulent in the cross-corrugated channel. Furthermore, Focke et al. [18], Liu and Tsai [19] reported that the flow becomes turbulent at low Reynolds number of respectively 400 and 300.

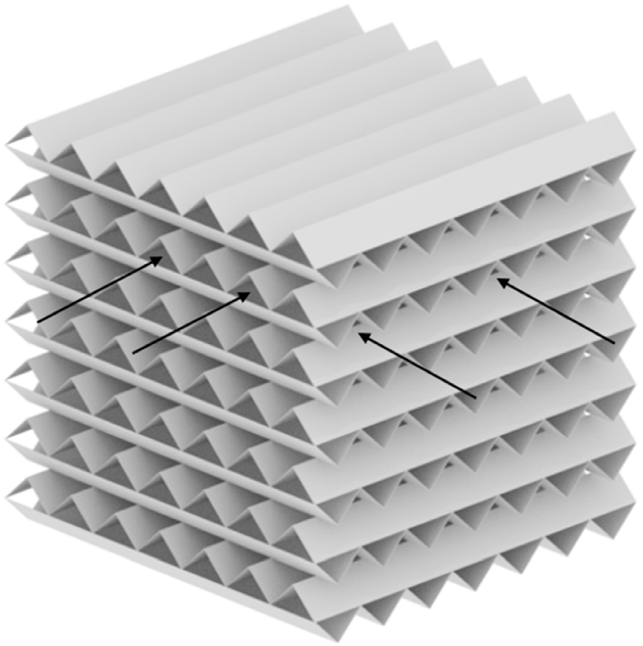

Fig. 1. Schematic of a triangular cross corrugated heat exchanger.

Both steady-state laminar and turbulence models are used by different authors to solve the flow in cross-corrugated channels for the low to moderate Re ($0 < Re < 2000$). Yin et al. [20] investigated the flow and heat transfer in corrugated channels with sinusoidal waves. The authors implemented the steady-state laminar model for the Reynolds number in the range of 100–1500. Guo-Yan et al. [21], studied a sinusoidal cross-corrugated heat exchanger for Reynolds numbers between 84 and 1168 both numerically and experimentally. They claimed that a steady-state laminar model is a reasonable choice for this range of the Reynolds number. The deviation between the numerical and experimental results for Colburn j factor and friction factor were found