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Numerical study of turbulent flow and heat transfer in cross-corrugated triangular ducts with delta-shaped baffles

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ABSTRACT

Cross-corrugated duct is commonly employed in plate heat exchanger. In this study, to further improve heat transfer in cross-corrugated triangular ducts, delta-shaped baffles are added. Three-dimensional turbulent flow and heat transfer in the channels with or without baffles has been numerically studied. A standard k-ε turbulence model together with enhanced wall treatment is applied to solve the turbulent flow in *Re* of 1000–6000. The fully developed cyclic mean Nusselt number and friction factor are obtained and validated by data from references, respectively. Influences of Reynolds number, baffle height and apex angle on heat transfer and pressure drop of the flow channel are investigated and discussed. Field synergy principle is applied to analyze the heat transfer enhancement in flow channels with or without baffles. The results show that when baffles are inserted, clockwise vortices and anticlockwise vortices are respectively generated in the low corrugations and the backward region of the baffles. Synergy effect of velocity and temperature gradient are strengthened in these vortices. Baffle height that is equivalent to corrugation height will lead to an increment of *Nu* by 2.1–4.3 times, but with a penalty of severe pressure loss. Flow channel at 60° apex angle performs best in heat transfer when baffle height equals to corrugation height, but in other two studied cases, apex angle of 90° performs best. When baffle height equals to corrugation height, friction factor is no longer proportional to *Re* in the channel with 60° and 90° apex angle.

1. Introduction

Plate heat exchangers are widely used in industrial applications. Cross-corrugated ducts are the commonly adopted channel geometry in plate heat exchangers. The corrugation profiles are usually cross-sinusoidal or cross-triangular shape. Many corrugated plates are stacked together to form flow channels in a plate heat exchanger. Adjacent plates are inclined with a certain angle to form flow channels, and cold or hot fluids are segregated by these plates. So basic geometrical characteristics in a cross-corrugated duct are inclination angle and parameters of the corrugation profile, including apex angle, corrugation height and corrugation pitch. These corrugation profiles can create secondary flow and vortex generation in the corrugation troughs, which will enhance heat transfer between adjacent flow channels. The enhancement effect relies heavily on geometrical characteristics of the duct.

Many experimental and theoretical studies have been conducted to investigate the thermohydraulic characteristics of the cross-corrugated ducts [1–26]. These researches mainly concerned on flow pattern, heat transfer mechanism, or geometry optimization. Beside the conventional corrugation profile, Doo et al. [27] proposed three kinds of cross-corrugated primary surface geometries, i.e. anti-phase secondary corrugation, in-phase secondary corrugation and full-wave rectified trough corrugation. Secondary corrugations were formed on the primary surface to enhance flow mixing and heat transfer. With these geometry modification, heat transfer coefficient and friction factor are slightly increased in in-phase secondary corrugation, compared to conventional sinusoidal corrugation.

Baffles are widely used in shell and tube heat exchangers to enhance heat transfer performance. However, little work has been conducted on baffle induced heat transfer enhancement in cross-corrugated ducts. Researches about baffle caused periodical flow in straight channel [28–39] are more comprehensive than in cross-corrugated duct. The channel profile is usually rectangular or triangular. And baffle shape is usually consistent with channel profile. Promvonge and Kwankaomeng [40,41] studied periodic laminar flow in rectangular ducts fitted with 30° baffles or 45° staggered V-baffles. They found that Nu can be enhanced as high as 12 times of that in smooth channels, and pressure loss will be enlarged by 90 times. Handoyo et al. [42] numerically investigated

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Nomenclature

A	surface area (m^2)
A_{ci}	cross-sectional area at inlet (m^2)
C	constant
c_p	specific heat of fluid (kJ kg^{-1} K^{-1})
D_h	hydrodynamic diameter (m)
f	friction factor
H	corrugation height (mm)
h	convective heat transfer coefficient (kW m^{-2} K^{-1})
k	turbulent kinetic energy (m^2/s)
L_{cyc}	length of a cycle (m)
Nu	Nusselt number
P	pressure (Pa)
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
V_{cyc}	volume of a flow cycle (m^3)
W	corrugation pitch (mm)
x, y, z	coordinates (m)

Greek letters

ρ	density (kg/m^3)
λ	thermal conductivity (kW m^{-1} K^{-1})
δ_{ij}	kronecker delta function
μ	dynamic viscosity (Pa·s)
ε	energy dissipation rate (m^2 s^{-2} s^{-1})
σ_k	effective Schmidt number for transport of k
σ_ε	effective Schmidt number for transport of ε
θ	apex angle (°)

Superscripts

$*$	dimensionless
$'$	fluctuating value

Subscripts

a	air
cyc	cyclic
H	corrugation height
i	inlet
m	mean
o	outlet
t	turbulent

the spacing effect of delta-shaped obstacles on the heat transfer and pressure drop in V-corrugated channels. Observed spacing to height ratio of obstacles ranges from 0.5 to 2. They indicate that Nusselt number can enhance 3.46 times and friction factor will increase 19.9 times when spacing to height ratio is 0.5. It can be deduced that heat transfer in cross-corrugated triangular duct can also be enhanced by using baffles, although the pressure drop will increase dramatically.

In conventional cross-corrugated triangular ducts, the fluid mainly flows straight in the upper half channel, only a small part of the fluid impinges into the lower corrugations and generates streamwise vortices. These vortices play a role to exchange the fluid between the wall and core region of the main region of the flow field [43]. If more fluid feeds into the lower corrugations, the vortex may be stronger and thereby cause an enhanced heat transfer. Based on this assumption, delta-shaped baffles are added in the upper flow channel to change the main flow direction into the lower corrugations in this study. Fig. 1 shows the schematic and geometrical parameters of this channel structure. To focus baffle height and apex angle effect, inclination angle and hydrodynamic diameter of the flow channel are identical in this study, while baffle height and apex angle of the corrugation are changed and considered to be critical geometrical parameters. To investigate turbulent behaviors, Reynolds number ranging from 1000 to 6000 which is practical in cross-corrugated plate heat exchangers [15,25], are studied in this work.

2. Numerical method and equations

2.1. Governing equations

Many numerical studies [14–18,21,22,24,25] utilize different turbulent models to capture turbulence flow behaviors in cross-corrugated ducts. However, no turbulent model is acknowledged as the best one. Generally, low-Reynolds number k-ω, low-Reynolds number k-ε and shear-stress transport k-ω models are recommended for 2000 < Re < 6000, while standard k-ε and large-eddy simulation models are applicable for Re > 6000. In Ref. [25], eight turbulent models are selected. They recommend low Reynolds number k-ε, shear-stress transport k-ω and standard k-ε model with enhanced wall treatment for numerical simulation. That is one reason we selected standard k-ε model with enhanced wall treatment in this study. The other reason is that the transition of laminar flow to turbulent flow in cross-corrugated ducts occurs at much lower Reynolds number than in parallel plate ducts. Zhang [14,15] indicate that flow in cross-corrugated ducts is usually laminar flow when Re < 500, and in transition flow regime or low Re turbulent flow regime when Re < 6000. Only when Re > 6000 the flow becomes fully turbulent. So it is a kind of low Reynolds number flow or transitional flow when Reynolds number ranges from 1000 to 6000. That is why turbulent models suitable for low Reynolds number flow are more commonly adopted in cross corrugated duct, but not standard k-ε model (usually used in fully turbulent flow). However, if baffles are added in the cross-corrugated duct, the flow becomes more turbulent than that in ducts without baffles at the same Reynolds number. That probably means flow become fully turbulent when Re is far below 6000. Thus in this study, the standard k-ε turbulence model, usually applicable for fully turbulent flow, is applied to simulate fluid flow and heat transfer in baffled cross-corrugated triangular duct.

The working fluid is assumed as air, so the steady state continuity, momentum and energy equations for incompressible flow are applied. Both of the velocities and mass fractions are time-averaged, and divided into a mean and a fluctuating value, $u_j = \overline{u}_j + u'_j$ and $T = \overline{T} + T'$.

$$\frac{\partial(\rho\overline{u}_i)}{\partial x_i} = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho\overline{u_i u_j}) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left(\mu\frac{\partial\overline{u}_i}{\partial x_j} - \rho\overline{u'_i u'_j}\right) \tag{2}$$

$$\frac{\partial}{\partial x_j}(\rho\overline{u_j T}) = \frac{\partial}{\partial x_j}\left(\left(\frac{\mu}{Pr} + \frac{\mu_t}{Pr_t}\right)\frac{\partial\overline{T}}{\partial x_j}\right) \tag{3}$$

where ρ is the density of the fluid, P is the pressure, u_i is velocity component and μ is the dynamic viscosity.