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Thermal-hydraulic and entropy generation analysis for turbulent flow inside a corrugated channel

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ABSTRACT

Using corrugated plates is shown to have some advantages over flat plates in transferring heat to or from fluid flow. Here a thermal-hydraulic and entropy generation analysis are performed for turbulent flow inside a corrugated channel. The goal was to find the best parameters that maximize the thermal performance and minimize the irreversibility. The influence of different parameters, which includes Reynolds number (Re), wave amplitude (α), and wavelength (λ) of the corrugated wall, on the heat transfer, pressure drop, performance and entropy generation are studied. A SST k–ω turbulence model is utilised in this numerical simulation, where the Reynolds number is in the range of 5000–50,000. Three different values of wave amplitude of the corrugated wall (i.e. $\alpha = 0.1$, 0.2, and 0.3) and three values of wavelengths for the corrugated wall (i.e. $\lambda = 1$, 2, and 3) were considered in this analysis. The influence of different parameters, which includes Reynolds number, wave amplitude, and wavelength of the corrugated wall, on the heat transfer, pressure drop, performance and entropy generation are studied. The results indicated that the overall thermal performance has improved greatly by using the corrugated channel with $\alpha = 0.1$ for all Reynolds numbers. It was found that the total entropy generation has a minimum value at $Re = 20{,}000$ for all values of wave amplitude and wavelength of the corrugated wall, which makes this specific Reynolds number the optimum value from the second law point of view.

1. Introduction

Improving the efficiency of thermal devices is a concern for designers. Engineers have used many techniques to enhance the heat transfer rate in such devices. Some examples of these techniques are treated surfaces, rough surfaces [1], using porous material with high thermal conductivity [2,3], using nanoparticles [4,5], incorporating of turbulators or swirl flow equipment [6], and using of wavy surfaces [7], etc. Using channel with wavy surfaces is one of the most effective ways to enhance the heat transfer in many engineering applications such as cooling devices in automotive vehicles, heat exchanger systems, heat sinks for electronic components, solar energy collectors, and cooling towers.

Recently, many numerical and experimental studies are performed in this field, where the most important ones are being reviewed here. Rush et al. [8] used experimental approach to study flow and heat transfer in sinusoidal wavy channel for laminar and transitional regimes. They concluded that instabilities and macroscopic mixing, created by wavy walls, transfer toward the channel entrance for higher values of Reynolds numbers. The macroscopic mixing leads to a significant increase in the local heat transfer rate in wavy channels. In another study, Singh et al. [9] performed an experimental study on corrugated plate heat exchangers for different channel inclination angles in the range of 0–80° and the Reynolds number in the range of 450–600. They reported that the maximum overall heat transfer coefficient is occurred at 20° inclination angle.

Beside above-mentioned experimental works, there are some numerical studies about fluid flow and heat transfer in corrugated channels. Naphon and Kornkumjayrit [10] used numerical approach to study fluid flow and heat transfer in a channel with V-shaped wavy lower plate for $Re < 1555$. They found that breaking and destabilizing in the thermal boundary layer are occurred by flowing the fluid through the corrugated walls. Ramgadia and Saha [11] performed a numerical study on fully developed flow and heat transfer in a wavy channel for the Reynolds number in the range of 25–1000. They reported that the maximum heat transfer rate along with the best performance occurs at the highest considered Reynolds number (i.e. 1000). Grant Mills et al. [12] investigated

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Nomenclature

a	amplitude of wave (m)
C_p	specific heat at constant pressure (J kg^{-1} K^{-1})
D_h	hydraulic diameter (m) (D_h = 4H)
h	heat transfer coefficient (W m^{-2} K^{-1})
H	half of the average distance between corrugated walls (m)
k	thermal conductivity (W m^{-1} K^{-1})
L	channel length (m)
L_w	wavelength of the corrugated walls (m)
N_g	dimensionless local volumetric entropy generation rate (-)
Nu	Nusselt number (-)
p	pressure (Pa)
q''	heat flux (W m^{-2})
Re	Reynolds number (-)
S_g'''	entropy generation rate (W m^{-3} K^{-1})
$S(x)$	corrugated wall profile (-)
PEC	performance evaluation criteria (-)
T	temperature (K)
u, v	velocity in x and y directions, respectively (m s^{-1})
u_i, u_j	velocity components (m s^{-1})
U_{in}	inlet velocity (m s^{-1})
x, y	rectangular coordinates components (m)

Greek symbols

α	non-dimensional wave amplitude (-) $\left(\alpha = \frac{a}{H}\right)$
λ	non-dimensional wavelength (-) $\left(\lambda = \frac{L_w}{H}\right)$
μ	dynamic viscosity (kg m^{-1} s^{-1})
ν	kinematic viscosity (m^2 s^{-1})
θ	dimensionless temperature (-)
ΔP	pressure drop (Pa)
ΔP^*	dimensionless pressure drop (-)
ρ	density of the fluid (kg m^{-3})

Subscripts/superscripts

ave	average value
in	inlet
w	wall
x	local value

numerically heat transfer and fluid flow in laminar flow through asymmetric wavy channel. They observed that the performance of a wavy channel with small amplitude is higher than that of a straight one. Pham et al. [13] simulated turbulent flow and heat transfer in a wavy channel for the Reynolds number in the range of 750–4500. Their results indicated that the turbulent regime did not detect for $Re < 1500$ but a strong unsteadiness occurred in the entire computational domain for this range of Reynolds number.

There are some studies about the entropy generation analysis in a wavy channel. Ko [14] performed an entropy generation analysis for laminar flow through a double-sine duct. He concluded that the contribution of thermal entropy generation increases by an increase in the wall heat flux. Ko [15] studied the effects of corrugation angle on entropy generation in a wavy channel for laminar regime. He concluded that there is an opposite effect for corrugation angle on frictional and thermal entropy generations as it leads to enhance in frictional irreversibility and drop in thermal irreversibility. Bahaidarah and Sahin [16] investigated entropy generation of laminar fluid flow in channels with wavy sinusoidal walls. They found that the height ratio of the channel has a significant effect on the distribution of the irreversibility. The distribution of the entropy generation becomes more uniform in axial direction by increasing the height ratio.

Thermal-hydraulic and entropy generation analysis is essential for a thermal system as it can be used to improve the second law efficiency and the performance for such systems. Considering above literature review, there is no research about thermal-hydraulic and entropy generation analysis on corrugated channels for turbulent regime. Therefore, this paper focuses on turbulent regime and investigates the influence of different parameters including Reynolds number, wave amplitude, and wavelength of the corrugated wall on the heat transfer, pressure drop, performance and frictional and thermal types of entropy generation. Such analysis is very useful in selecting different parameters of corrugated channels for designing a plate heat exchanger.

2. Computational model

A schematic view of the geometry and the coordinate system for the considered problem are depicted in Fig. 1(a). A two dimensional channel with the height of "2H" and length of "L = 20H" is considered. The channel is parted to three sections containing a heated corrugated wall section with the length of "12H" which is under constant heat flux, and two adiabatic smooth wall sections at the start and the end of the corrugated wall section. These adiabatic sections have the length of "3H" and "5H", respectively. The amplitude and wavelength of the corrugated wall are denoted with "a" and "L_w", respectively as shown in Fig. 1(b).

To simulate this problem numerically, following assumptions are invoked:

- The flow is turbulent, steady and two dimensional.
- The ranges of Reynolds number, non-dimensional amplitude and non-dimensional wavelength are $5000 \le Re \le 45000$, $0.1 \le \alpha \le 0.3$ and $1 \leqslant \lambda \leqslant 3$, respectively.
- The corrugated wall profile is a sinusoidal curve which is defined by following function in the bottom wall:

$$S(x) = -H - a\sin\left(\frac{\pi(x-3H)}{H}\right), \quad 3H < x < 15H \tag{1}$$

where a and H are amplitude and height of the corrugated wall, respectively.

2.1. Governing equations

Two dimensional steady state conversation equations of mass, momentum and energy are used to simulate this problem. These equations are utilised as follows [17]:

- Continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{2}$$

where ρ and u_i are the density of liquid and the velocity component, respectively.

- Momentum equation:

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial P}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_j}\right)\right] + \frac{\partial}{\partial x_j}\left(-\rho\overline{u_i' u_j'}\right) \tag{3}$$