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Effect of skewness on flow and heat transfer characteristics of a wavy channel

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ABSTRACT

Three-dimensional numerical investigations have been carried out to study effect of skewness in wavy channels on flow and heat transfer characteristics. Computations are performed using ANSYS Fluent 16.1 for different values of wave amplitude, skewness angle, Reynolds number (*Re*) and fixed values of channel width, wavelength. Streamline plots are presented in various planes for different values of skewness angle to understand the flow field characteristics of skewed wavy channels. Volume-averaged as well as span-averaged variation of secondary flow intensity for different skewness angles have been shown to elucidate the strength of induced secondary flow. Effect of secondary flow on heat transfer in skewed wavy channels has been quantified with the help of field synergy angle. Finally, effect of skewness on thermodynamic as well as overall thermo-hydraulic performance of the channel has been presented. Introduction of skewness in the wavy channel induces stronger secondary flow which makes the flow three-dimensional. The stronger secondary flow influences both thermodynamic as well as overall thermo-hydraulic performance of the channel.

1. Introduction

Introduction of corrugated surfaces is considered to be an efficient passive method for heat transfer enhancement. These are widely used in compact plate heat exchangers to increase heat transfer area and produce turbulence even at low flow rates. In channel confined flows, wall corrugations generate longitudinal and transverse vortices that lead to destabilization of thermal boundary layer and enhance mixing of the fluid. These surfaces act as promoters of unsteadiness and may induce turbulence in the flow [1]. For low Reynolds number (*Re*) flows, separated flows in the form of trapped vortices remain confined within the grooves of the corrugations having almost no interaction with the core fluid [2]. With increase in *Re*, the increased inertia of core flow leads to growth of instability in the trapped vortices due to tearing effect of the shear layers. Tearing of the vortices brings a self-sustained oscillation in the flow, causing rupture of thermal boundary layer thereby heat transfer enhancement [3]. Hence, unsteady flow regimes are normally associated with higher heat transfer enhancement in corrugated channels [4]. Conventionally, corrugations may be introduced in the form of waviness of various preferred shapes due to ease of manufacture. Numerous studies in literature deal with performance of such wavy channels towards heat transfer enhancement and pressure drop penalty [5,6]. It has been reported that the factors influencing flow and heat transfer characteristics of wavy channels are wave shape [7,8], wave amplitude [9], wavelength [10,11], channel height [12] and phase difference between the waves of top and bottom walls [13].

Pioneering work has been done by Goldstein and Sparrow [1] on heat transfer studies related to flow through wavy channels in laminar, transition and low-Reynolds number turbulent regimes ($150 \leqslant Re \leqslant 8550$). They reported relatively higher heat transfer coefficient in laminar regime, and increase by factor of three in low-Re turbulent regime, as compared to that for plane channel. Islamoglu and Parmaksizoglu [12] carried out experimental investigations on effect of channel spacing (H) in triangular wavy channel for *Re* in the range of 1200–4000. They reported that for smaller channel spacing, the overall performance coefficient is high, even though both friction factor (f) and Nusselt number (Nu) are relatively lower. Effect of channel spacing and phase difference between the waves of top and bottom walls were experimentally investigated by Elshafei et al. [14] for a triangular wavy channel. It is reported that the effect of channel spacing is more prominent on heat transfer and pressure drop than that of phase shift variation. Effect of 'aspect ratio' (AR), i.e. ratio of height (H) to width (W) of the channel, on flow and heat transfer has been extensively studied for a triangular wavy channel by Comini et al. [15]. They

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Nomenclature

A	cross-section area at inlet
a	amplitude of the wave
A_h	total heat transfer area
C_P	specific heat capacity of fluid
D_H	hydraulic diameter ($D_H = 2WH/(W+H)$)
E	total energy
f	friction factor
G_k	turbulent kinetic energy due to mean velocity gradient
H	channel height
h	heat transfer coefficient
I_o	turbulence intensity
J	vorticity flux
k	turbulent kinetic energy
k_f	thermal conductivity of fluid
k_{eff}	effective thermal conductivity
L	distance between the sections A and B
Nu	Nusselt number
p	pressure
Pr	Prandtl number
Re	Reynolds number
S	modulus of mean rate of strain tensor
S_g	entropy generation
Se	non-dimensionalised secondary flow intensity
$Se(x)$	local intensity of secondary flow
T	temperature
u, v, w	components of velocity vectors
W	width of the channel

Greek

δ_{ij}	Kronecker delta
ε	turbulent dissipation rate
θ	field synergy angle
λ	wave length of the channel
μ	dynamic viscosity
ρ	density of fluid
σ_k	turbulent Prandtl number
$\tau_{ij\ eff}$	deviatoric stress tensor
ϕ	skewness angle
ω	vorticity

Subscripts

ABS	absolute value
in	inlet of the channel
o	value corresponds to unskewed wavy channel
T	heat transfer
t	turbulent
V	viscous
w	wall

Superscripts

n	direction normal to the cross-section or wall surface

Abbreviations

AR	aspect ratio
FSA	field synergy angle
FSP	field synergy principle
SFI	secondary flow intensity

considered wide range of *AR* for fixed values of corrugation angle (20°) and height to wavelength ratio (H/λ = 0.15). It was observed that for *Re* in the range from 100 to 600, a decrease in *AR* leads to an increase in *Nu*, *f* and overall performance. Pehlivan et al. [16] carried out experimental investigations on flow and heat transfer characteristics of three different sharp edged converging-diverging wavy channels in the *Re* range of 1500–9000 and observed that *Nu* increases with increase in corrugation angle of the channel. Aslan et al. [17] carried out both experimental and numerical studies on sharp-edged and rounded peak wavy walls with *Re* in the range of 2000–11,000. They reported that for fixed channel height, a 100% increase of performance goodness factor takes place in rounded peak than for sharp peak wavy channel.

Ramgadia and Saha [8] considered various shapes of waviness, viz. triangular, arc and sinusoidal shapes in their numerical study. They reported that sinusoidal channels give best thermal performance followed by arc and then triangular channels. Hence, the general inference would be that smooth waviness is associated with better thermal performance than sharp-edged waviness. Ramgadia and Saha [4] studied numerically the effect of amplitude and wavelength on flow and heat transfer characteristics of a sinusoidal wavy channel in *Re* range of 100–600. They reported a decrease in pressure drop with decrease in amplitude of the wave for fixed wavelength to amplitude ratio. Lu et al. [18] introduced new wavy microchannel having porous fins with an objective to decrease thermal resistance and pressure penalty simultaneously. Detailed parametric study showed that new wavy microchannel showed superior performance on thermal as well as flow characteristics as compared to that of conventional wavy microchannels. Sarkar and Sharma [19] proposed a flow regime map for laminar to turbulent flow transition ($10 \leqslant Re \leqslant 2000$) to distinguish steady, two types of periodic, quasi-periodic and chaotic flows, for fully developed flow in sinusoidal wavy channels. The transitional map is obtained by using time signal analysis for various amplitudes and wavelengths. Increase in heat transfer enhancement is observed to be more than of pressure drop penalty for chaotic flows as compared to the steady, periodic and quasi-periodic cases. At higher flow rate in turbulent regime, there is enhanced mixing of core fluid with near wall fluid thereby considerable increase in heat transfer and reduction in friction factor takes place [20].

Heat transfer in wavy channels can be improved by generating secondary flows inside the channel which may be induced either by making the channel skewed or by keeping the top and bottom walls of the channel at different inclination angles. These strong secondary flows can acquire three-dimensional nature even at lower *Re* and result in better mixing of recirculated flow with the core flow. Flow and heat transfer characteristics in skewed channels have been experimentally studied by Chang et al. [20] over a wide range of *Re* (1000–30,000). They stated that macroscopic mixing between the core and near wall fluid due to shear layer instability leads to heat transfer enhancement in transverse wavy channels. Additional heat transfer enhancement is achieved in skewed wavy channels by the strong wave-wise secondary flows introduced in the transverse direction. Singh et al. [21] performed experiments on wavy channels by considering rotation of the top wall relative to bottom wall in a plane parallel to incoming flow. The angle of rotation is referred to as 'inclination angle' which is varied from 0° to 80°. They observed that relative inclination between the waves of two walls makes the flow three-dimensional giving rise to enhancement of heat transfer. Maximum heat transfer rate is reported for channels of relative inclination 20° followed by simple wavy channel (0°) and relatively lower