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Numerical study of fully developed unsteady flow and heat transfer in asymmetric wavy channels

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ABSTRACT

The present study aims at the numerical investigation of fully developed flow and heat transfer through asymmetric wavy-walled geometry. The flow characteristics and thermal performance of wavy-walled configuration is assessed for three different geometries generated using three phase shift angles (φ) between the two opposite heated walls. The function $y = 2a \cdot \sin^2(\pi x/L)$ is used to describe the walls of the wavy channel. For the symmetric geometry ($\varphi = 180°$) considered in the present study, the ratios $H_{\min}/H_{\max}$ and L/a are kept fixed to 0.4 and 8.0 respectively while the four asymmetric channels are created through a desired phase-shift of $\varphi = 0°, 45°, 90°$ and 135° between the two opposite sine-wave walls. The finite volume method on collocated grid has been employed to solve the time dependent Navier–Stokes and energy equation. The fully developed flow and heat transfer has been modeled using periodic boundary conditions. The critical Reynolds number of unsteadiness is found to be the highest for the symmetric ($\varphi = 180°$) wavy-walled channel. The flow in all three geometries has been found to be equally complex but the asymmetric geometry with 0° phase-shift reveals maximum flow asymmetry about the flow centreline. It has also been observed that the most asymmetric geometry having 0° phase-shift encourages best heat transfer over symmetric configuration with 180° phase-shift, but is accompanied by the highest friction penalty.

1. Introduction

A wavy-walled geometry is one of the classically used passive methods applied to achieve heat transfer augmentation in applications with stringent space restrictions. One of the advantages of a wavy-walled channel is that it can be fabricated with ease and provides enhanced thermal–hydraulic performance. For such geometries, higher heat transfer is ensured through the use of optimum geometrical and flow parameters. The instability of shear layer caused by the curved wall geometry triggers high mixing between the near wall fluid and the fluid from the core which along with the self-sustained oscillations due to the geometry augments heat transfer considerably. Thus, the corrugations act as turbulence promoter with an objective to accelerate heat transfer. Compared to classical channel flow the wavy surface structure adds a degree of complexity to the flow by inducing streamline curvature, flow separation and flow reattachment, leading to flow situations which are often present in relevant technical and geophysical applications.

The wavy-walled channels are type of corrugated plate heat exchangers which are widely used for different kinds of heat transfer operations found in process industries. The study of the heat transfer through wavy-walled channels or fins (Fig. 1(a)) as discussed in Dong et al. [1] is of interest for applications in the electronic industry where the cooling of electronic devices is carried out by forcing coolant fluid over the boards on which the devices are soldered. The dissipation of heat from the electronic circuit boards is of utmost important to augment the performance as well as reliability of the components which quite often strongly depends on the operating temperatures of the components itself. Another potential application of the wavy-walled channel is in the internal cooling of a gas turbine blade as shown in Fig. 1(b). Use of the wavy-walled channel is also deployed in other applications like systems biological transport processes, polymeric composite manufacturing, for modeling flow over waves important in geophysical flow dynamics and in medical applications that use wavy-walled channels to investigate extracorporeal blood oxygenation.

In one of the early studies concerning to wavy channel, Goldstein and Sparrow [2] performed experimental study of heat and mass transfer for laminar, transitional and low Reynolds number turbulent flow through a wavy-walled channel. It was observed

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Symbols

$2a$	amplitude of the sine function, $2a = 0.5(H_{\max} - H_{\min})$
C_f	Skin friction factor, $\tau_w/0.5\rho u^2_{\mathrm{avg}}$
C_p	specific heat
f	friction factor, $\Delta p/0.5\rho u^2_{\mathrm{avg}}$
f_l	Friction factor (with respect to length scale, H_{avg}), $\left(\frac{H_{\mathrm{avg}}}{L}\right)\Delta p/0.5\rho u^2_{\mathrm{avg}}$
fr	frequency of vortex shedding
$H_{\min}$	minimum height between two wavy-walls
$H_{\max}$	maximum height between two wavy-walls
H_{avg}	average height between two wavy-walls, $(H_{\min} + H_{\max})/2$
h_x	local heat transfer coefficient
L	characteristic length of single period
Nu_x	local Nusselt number, $h_xH_{\mathrm{avg}}/k = -((\partial\theta/\partial n)\|_{n=0})/(\theta_w(x, y) - \theta_b(x))$
Nu	wall averaged Nusselt number, $\frac{1}{L}\int_0^L Nu_x(1 + y'^2)^{1/2}dx$
P	periodic component of pressure
p	pressure
Pr	Prandtl number, $\mu C_p/k$ (0.7 for air)
Re	Reynolds number, $\rho u_{\mathrm{avg}}H_{\mathrm{avg}}/\mu$
St	Strouhal number, $fr{\cdot}H_{\mathrm{avg}}/u_{\mathrm{avg}}$
T	dimensional temperature
u and v	dimensionless Cartesian velocity components in x and y directions respectively
x and y	dimensionless distances along x-axis and y-axis

Greek symbols

φ	phase-shift angle
$\beta(t)$	mean periodic pressure gradient in the x-direction
θ	non dimensional temperature, $(T - T_w)/(T_{b1} - T_w)$
μ	dynamic viscosity
ρ	mass density
τ	cycle time
ω_z	z-component of vorticity, $\frac{\partial u}{\partial y} - \frac{\partial v}{\partial x}$

List of subscripts

min	minimum value
max	maximum value
avg	average value
w	value at the wall
b	bulk value
1	quantities evaluated at domain inlet

that higher heat and mass transfer was achieved in a wavy channel in comparison to a parallel-plate channel for the same Reynolds number range. For an operating Reynolds number range of 6000–8000, the heat transfer of wavy channel was found to be three times higher than for that of parallel-plate geometry. Nishimura et al. [3] have carried out experimental study of flow and heat transfer in a symmetric wavy-walled channel. The performance of two geometries namely, sine-shaped and arc-shaped channels was compared for Reynolds number range of 20–300. Higher heat transfer was observed when the devices were operated in unsteady regime. The experimental study performed by Saidi et al. [4] on a wavy-walled channel was aimed at the characteristics of vortex development and its influence on the heat and mass transfer properties.

Instabilities noticed near the exit of the wavy channel with three different phase-shifts in the experiments performed by Rush et al. [5] were found to move toward the entrance of the channel with increasing Reynolds numbers. Additionally, enhancement of heat transfer was found with increasing flow instability. The transition to unsteadiness of fluid flow through the geometry was related to the induced instability in shear layers developed between the trapped vortices and the core fluid. The laser Doppler velocimetry study conducted by Hudson et al. [6] reported Reynolds shear stresses for wavy channel geometry. The flow was delineated into an inner region affected by the presence of wavy wall and an outer region, where the wave induced variations in flow were found to be small and Reynolds shear stress was approximately constant.

Patankar et al. [7] conducted a numerical study to achieve fully developed flow and heat transfer in ducts of varying cross-section. For this particular study, periodic boundary condition was used along the flow direction. Necessary precaution to be taken for the boundary condition of a single isolated module of the periodic geometry was discussed in detail in their study. To simulate fully developed flow through a sinusoidal channel Wang and Vanka [8] utilized the concept of periodic domains as discussed by

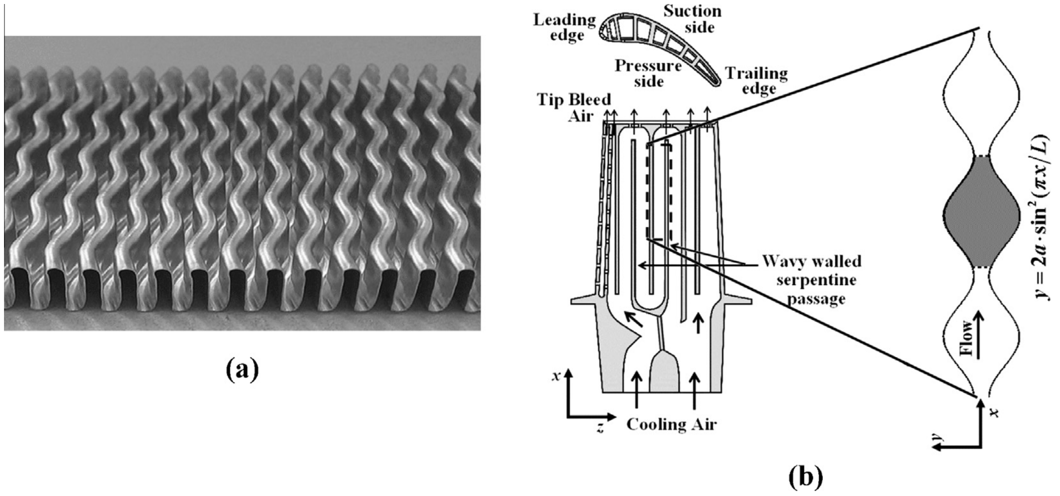

Fig. 1. (a) Photograph of wavy-walled fins (Dong et al. [1]); (b) conceptual cooling strategy of turbine blade cooling.