International Journal of Heat and Mass Transfer 55 (2012) 3576–3581

Contents lists available at SciVerse ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Technical Note

Determination of hot spots on a heated wavy wall in channel flow

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ARTICLE INFO

Article history:
Received 23 May 2011
Received in revised form 12 December 2011
Accepted 14 February 2012
Available online 14 April 2012

Keywords:
Channel
Wavy wall
Amplitude
Local heat transfer
Hot spot
Simulation

ABSTRACT

The present study deals with the effects of wall geometry on the fluid flow and heat transfer in a channel with a wavy wall heated with constant heat dissipation. The waviness is characterized by wave amplitude and period. A detailed parametric numerical investigation of the effect of waviness on the local heat transfer parameters is performed for different turbulent flow conditions and compared with the literature.

The effect of flow and geometry parameters is assessed quantitatively. Generalization is done based on the Reynolds number, Re_A, which uses doubled wave amplitude, or height, $A = 2a$, as the characteristic length, and on the geometry parameter, A/λ, which essentially is the amplitude-to-wavelength ratio. A dimensionless location of the hottest spot on the wavy wall is shown to be dependent on these two dimensionless parameters. A correlation which encompasses the hottest spot locations for all the cases studied in the work is suggested.

In order to obtain generalization for the hottest spot temperature, the Nusselt number is introduced based on the constant (uniform) heat flux and variable temperature difference, with wave amplitude as the characteristic length. It is shown that, for all cases studied herein, the hottest temperature is represented as $Nu_{A,min}(Re_A, A/\lambda)$. Accordingly, a correlation for the minimum Nusselt number is suggested. A further generalization for the hottest spot temperature is attempted for the conjugate problem with a conducting wall. It includes wall-to-fluid thermal conductivity ratio, k_s/k_l, as the additional dimensionless parameter which determines the Nusselt number.

1. Introduction

Heat transfer characteristics of turbulent flow in channels with structured wall roughness have been studied since Webb et al. [1] and Kader [2]. Heat transfer from a modified surface was extensively explored by Bergles [3,4]. At present, it is well known that single-phase convective heat transfer can be enhanced by various surface modifications, including structured roughness, as discussed by Ravigururajan and Bergles [5], Bergles [6] and Manglik [7].

Among other geometries, wavy surfaces have drawn the attention of various researchers, and the literature reports a number of empirical studies on the subject, e.g. Zilker et al. [8], Zilker and Hanratty [9], and Hudson [10]. The Reynolds numbers, based on the bulk velocity and channel half-width, varied between 7200 and 28,000. It was found, in particular, that reversed flows were possible for wave height-to-length ratios $2a/\lambda > 0.033$, and reverse flow rate increased with increasing this ratio.

Several common methods for numerical solution of the turbulent flow in channels with a roughened surface are presented in the literature. Chen and Patel [11], Richmond and Patel [12], and Patel et al. [13] proposed solution of the Reynolds-averaged Navier–Stokes equations coupled with two-layer wall treatment. It was shown that the standard wall functions are not applicable in regions of strong adverse and favorable pressure gradients. The method of Patel et al. [13] is quite successful in predicting separation and reattachment points, e.g. for $2a/\lambda = 0.2$ and $Re_W = 8160$, where W denotes the channel width. Cherukat et al. [14] reported DNS of a flow over a sinusoidal surface with amplitude-to-wavelength ratio of 0.05 ($\lambda = 50.8$ mm and $a = 2.54$ mm) and $Re = 3460$, reflecting the experimental work of Hudson [10]. Yoon et al. [15] performed DNS at a range of the wave amplitude-to-wavelength ratio, $0.01 \leqslant a/\lambda \leqslant 0.05$, for $Re_W = 6760$, where the wave length is fixed having the same value as the mean channel height, $\lambda = W$. The mean reverse flow appeared only from $a/\lambda = 0.03$, and the locations of separation and reattachment points depended strongly on the wave amplitude.

The available literature on heat transfer appears to be more limited. Dellil et al. [16] investigated the effect of geometric parameters by varying the wave amplitude from zero (flat plate) to $0.1W$, while the wave length was kept constant and equal to the channel height, W. The minimum and the maximum Nusselt numbers appeared to be located near the separation and the

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http://dx.doi.org/10.1016/j.ijheatmasstransfer.2012.02.049

Nomenclature

$A = 2a$	double wave amplitude (m)
a	wave amplitude (m)
b	constant
Gr	Grashof number
k	thermal conductivity (W/mK)
L	length (m)
Nu	Nusselt number
q''	heat flux (W/m^2)
Re	Reynolds number
T	temperature (°C)
t	foil thickness (m)
V	velocity (m/s)
W	nominal channel width (m)
x, y	coordinates (m)

Greek letters

ε	dissipation rate (m^2/s^3)
κ	turbulent kinetic energy (m^2/s^2)
λ	wave length (m)
μ	dynamic viscosity (m^2/s)
ρ	density (kg/m^3)

Subscripts

in	inlet
l	liquid
max	maximum
min	minimum
s	surface
w	wall

reattachment points, respectively. It was found that the location of the maximum local Nusselt number moves downstream with an increase in wave amplitude, whereas the reattachment point moves upstream. Park et al. [17] studied turbulent flow and heat transfer in a channel with one wavy wall using a nonlinear κ–ε–f_μ model. Constant temperature boundary conditions were used at the walls. Wave amplitude varied from zero (flat wall) to 0.15W. Flow Reynolds number based on the streamwise average velocity and the channel width, W, was kept constant at 6760. The Nusselt number distribution along the wave was found to be periodical in the streamwise direction, approaching its minimum and maximum values in the vicinity of flow separation and close to the reattachment point, respectively. Choi and Suzuki [18] used large-eddy simulation (LES) to study the geometry similar to that of Park et al. [17]. While the wave length was kept constant, the amplitude-to-wavelength ratios were 0.01, 0.05 and 0.1. Flow separation and near-wavy-wall streamwise vortices were found to play an important role in both heat and momentum transfer.

In all studies mentioned above, a constant (uniform) temperature was used as the boundary condition. In many cases, however, a constant wall heat flux or, more generally, constant heat dissipation in a conducting wall must be applied to reflect the real situation. As the overall heat transfer may be enhanced by a wavy wall, at some spots the local heat transfer coefficient can be comparatively low. For a gaseous medium, this would result in no more than some increase in the local wall temperature. If, however, liquid cooling is used, undesirable boiling can occur at the locations that essentially are time-average "hot spots" on the surface.

This paper presents a numerical investigation of time-average fluid flow and heat transfer in a two-dimensional channel with uniform heat dissipation at a wavy wall. In the next section, the physical and numerical models are introduced and discussed. Further, the results for various flow conditions and wall geometry parameters, including inlet temperatures, flow rates, wave amplitudes, wave lengths (unlike the previous works) and wall thermal conductivity are presented, and their dimensional analysis is done. Correlations which encompass the hottest spot locations and maximum wall temperatures for all the cases studied in the work are suggested and then expanded for a conducting wall.

2. Numerical study

The physical model is a two-dimensional, 100 mm long and 10 mm nominally wide, channel with one wavy and one flat wall, as shown in Fig. 1. The parameters include the wavy wall thickness, t, the wave height, $A = 2a$, and wavelength, λ. The wave heights are 0.25, 0.5, 0.75 and 1.0 mm, whereas three different wavelengths used are 3, 4 and 5 mm. Accordingly, the ratio A/λ varies from 0.05 to 0.25, whereas $A << W$ in all cases.

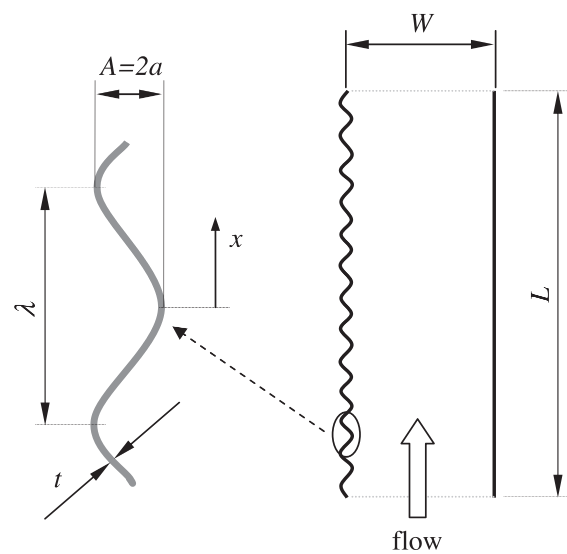

Fig. 1. Two-dimensional vertical channel with a wavy surface on the left-hand side and a flat wall on the right-hand side.

The flow and heat transfer characteristics are based on the experimental works by Bachar [19] and Netz et al. [20]. Three different inlet mean flow velocities are explored, namely 0.23, 0.5 and 1.17 m/s – for the 10 mm by 10 mm cross-section channel used in the experiments these correspond to the Reynolds number range of $4500 < Re < 32{,}000$, where Re is based on the hydraulic diameter. Water flow is considered. The heat input level is also chosen based on the experiments.

Steady state conservation equations are solved. The boundary conditions are fully developed flow at the entrance and "pressure outlet" at the exit of the domain. For the energy, the inlet bulk fluid temperature is assigned, whereas at the wavy wall, a foil heated with a uniformly distributed constant heat source, insulated from the opposite side, is used. The flat wall is insulated, as well. Thus, once the fluid enters the domain, both the flow field and temperature distribution are developing, the former because of the wall waviness and the latter because of heating.

The numerical method is essentially the same as used by Rashkovan et al. [21]. The κ–ε and Reynolds Stress Model (RSM) were considered. Two-layer modeling was compared to the wall-function approach. In the two-layer model, the boundary layer is