International Journal of Heat and Mass Transfer 52 (2009) 1138–1148

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer enhancement in self-sustained oscillatory flow in a grooved channel with oblique plates

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ARTICLE INFO

Article history:
Received 4 February 2008
Received in revised form 18 September 2008
Available online 14 November 2008

Keywords:
Heated obstacle
Heat transfer enhancement
Oscillatory flow
Oblique plate

ABSTRACT

The aim of this work is to investigate the conjugate heat transfer in periodic mounted obstacles channel with oblique plates as vortex generators installed at the rear obstacles on the opposite wall. Special attention will be paid to the analysis of flow evolution and heat transfer enhancement in the intermediate and low Reynolds number range without recourse to turbulent flow. Various physical arrangements are considered as plate length, tilt angle and Reynolds number in order to investigate their influence on the thermal and flow characteristics in the steady state as well as in the self-sustained oscillatory flow.

1. Introduction

Transitional flow regimes in channel with geometrical inhomogeneities, are of great importance in numerous engineering fields, such as compact heat exchangers, oxygenators and, dialysers and electronic cooling systems of electronic equipment. A significant research effort has been devoted to finding the best ways to study these flow regimes and many techniques based on both active and passive methods have been proposed to enhance heat transfer in these applications. Among these methods one can find systems involving vortex generators such as fins, ribs and other cylinders. The geometrical characteristics of vortex generators play a significant role in the rate of heat transfer. Disturbance promoters increase fluid mixing and interrupt the development of the thermal boundary layer, leading to enhancement of heat transfer. However, the complex flow characterized by the appearance of successive separations, recirculation, reattachment and deflection make the understanding of the flow behaviour and the evolution of heat transfer in such systems more difficult.

Wu and Perng [1] investigated the effect of installing an oblique plate on heat transfer over an array of five obstacles mounted in a horizontal channel and they observed an enhancement of heat transfer of up to 39.5% in the value of *Nusselt* number.

Garimella and Eibeck [2] experimentally investigated the effect of prostration of a vortex generator on heat transfer from an array of discrete heat sources. A maximum heat transfer enhancement of about 40% was reported.

In a study by Herman and Kang [3], the effect of setting curved vanes in a grooved channel was investigated. Enhancement of heat transfer was then reached with rates similar to those obtained in turbulent flow although at low Reynolds numbers. This enhancement of heat transfer was mainly the result of fluid flow acceleration between the vane and the heated block and the elimination of large recirculation regions within the grooves. Yang [4] proposed an oscillating bar as a vortex generator in a channel with heated obstacles. His results showed that the vortices induced by the oscillating bar allowed an increase in heat transfer from the heated obstacles. Fu and Tong [5] carried out a numerical simulation on the effect of an oscillating cylinder on the heat transfer from heated blocks in a channel flow. Their results proved that heat transfer was remarkably enhanced as the oscillating frequency of the cylinder was in the lock-in region. Ko and Anand [6] reported an experimental investigation about heat transfer and pressure drop in a uniformly heated rectangular channel with wall-mounted porous baffles. Their findings showed that the use of such material could enhance heat transfer rates by up to 300% when compared to smooth heated channels. However, this heat transfer enhancement was accompanied by a significant increase in

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doi:10.1016/j.ijheatmasstransfer.2008.09.013

Nomenclature

A	dimensionless surface area
d	plate length
h	dimensionless obstacle height ($=h^*/H$)
H	channel height
k	thermal conductivity
L	dimensionless obstacle spacing ($=L^*/H$)
Nu	*Nusselt* number
$Nu_{\text{face i}}$	mean face *Nusselt* number
Nu_{overall}	overall obstacle *Nusselt* number
Nu_x	local *Nusselt* number
p	dimensionless pressure
Pe	*Peclet* number
Pr	*Prandtl* number
Re	*Reynolds* number
T	temperature
t	time
u and v	dimensionless velocity components
w	dimensionless obstacle width ($=w^*/H$)
x and y	dimensionless coordinates

Greek symbols

α	thermal diffusivity
β	linear part in pressure function of Eq. (10)
γ	plate angle
Δ	difference
θ	dimensionless temperature
ν	kinematic viscosity
ρ	density
τ	dimensionless time

Subscripts

b	bulk
f	fluid
m	mean
p	refers to one period
s	solid
w	wall
0	at inlet conditions

Superscript

$*$	dimensional

Other

–	time average

pressure drop. Self-sustained oscillatory flow has been widely investigated by Amon et al. [7] and Nigen and Amon [8]. They determined that the laminar flow undergoes a flow bifurcation at a critical Reynolds number which is significantly lower than the one related to a Poiseuille plane channel flow. These investigations indicated that the heat transfer rate increases when the flow passes from a laminar to a transitional regime, which is due to better flow mixing after flow bifurcation, and also that this enhancement is usually accompanied by an increase in the pressure drop.

Nishimura et al. [9] experimentally investigated the influence of the imposed oscillatory frequency on mass transfer enhancement of grooved channels with different cavity lengths, for an external pulsatile flow. It was found that the mass transfer enhancement by means of fluid oscillations is higher in laminar than in turbulent flow and there is noticeable enhancement at intermediate Strouhal numbers, depending on the cavity length and Reynolds number. Adachi and Uehera [10] performed numerical investigations of flow and temperature fields for steady state and self-sustained oscillatory flows in periodically grooved channels for various channel geometrical configurations. They determined correlations existing between heat transfer and pressure drops and they found that heat transfer is significantly enhanced, and pressure drop increases after the first flow bifurcation. They found that the bifurcation occurs at *Reynolds* number in the range of 1000–1100. They also determined that expanded grooved channels perform more efficiently than contracted grooved ones. Recently, Guzmán and Del Valle [11] performed numerical investigations of the transition scenarios and heat transfer characteristics in grooved channels as the flow regime evolves from a laminar to a transitional regime. They found that the mean heat transfer rate remains mostly constant in the laminar steady regime but it continuously increases in the case of transitional regime. The rate of increase of this heat transfer is higher when the flow regime is quasi-periodic rather than periodic. This enhancement is twice more important in the periodic flow regime and it can be twice and half higher for the quasi-periodic regime. Wang and Jaluria [12] numerically studied heat transfer enhancement by using a square cylinder as vortex generator in the upstream obstacles channel at low Reynolds number. They found that heat transfer can enhance up 95% for Reynolds number of 1000. Self-sustained oscillatory flow in a grooved channel was also studied in heat transfer and fluid mixing by several researchers [13,14].

This study lies within the scope of previous works and focuses the way to investigate the conjugate heat transfer in periodic mounted obstacles channel with oblique plate as vortex generator installed at the rear obstacles on the opposite wall. This way to improve heat transfer by modifying the direction of the flow towards the obstacle faces and by activating the self-oscillations using oblique plates placed periodically can be considered as a new approach and be used in the cooling air of electronic systems. Special attention will be paid to the analysis of flow evolution and heat transfer enhancement in the intermediate and low Reynolds number range without recourse to turbulent flow. The study is limited to Re = 1000 because methods of cooling electronic components in laminar forced convection usually concern velocities ranging from 0.3 to 5 m/s (Anderson and Moffat [15]). This corresponds to a Reynolds number based on the hydraulic diameter ($d_H = 2H$) varying from 200 to 2000 or Re_H = 100–1000. Various physical arrangements are considered as plate length, plate tilt angle and Reynolds number in order to investigate their influence on the thermal and flow characteristics in the steady state as well as in the self-sustained oscillatory flow.

2. Mathematical formulation

Fig. 1 shows the physical geometry considered in this study. It consists of a two-dimensional horizontal channel containing heating blocks regularly distributed on its lower wall and insulated oblique plates of low thickness (thickness/H = 0.01) at the upper wall. Each block base is maintained at a constant temperature. The flow is assumed to be laminar and incompressible, the fluid viscous Newtonian. Buoyancy induced effects are negligible based on typical experimental and numerical calculation in similar configurations [11]. All the physical properties of the fluid and of the solid are considered as constant. The formulation adopted here is that of a constant flow rate in time with a fluctuating pressure gradient between the inlet and the outlet of each module. The imposed nondimensional flow rate value is given by $u_{0m}{\cdot}H = 8/3$.