Experimental Thermal and Fluid Science 74 (2016) 324–338

Contents lists available at ScienceDirect

Experimental Thermal and Fluid Science

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

Effects of buoyancy and inclination for opposing mixed convection in a symmetrical heated duct with a plane symmetric sudden contraction–expansion

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ARTICLE INFO

Article history:
Received 9 July 2015
Received in revised form 3 December 2015
Accepted 11 December 2015
Available online 30 December 2015

Keywords:
Mixed convection
Forward–backward facing step
Constricted flow
Three-dimensional heat transfer
Electronics cooling
Wall effects

ABSTRACT

In this work, transient laminar opposing mixed convection is studied experimentally in an open vertical rectangular channel configuration with plane symmetric forward–backward facing steps located at the middle of the test section with uniform heat flux imposed to the lateral walls of each step while the other bounding walls are treated as adiabatic surfaces. The effect of opposing buoyancy and the geometrical configuration of partial blockage on the heat transfer behavior for the double stepped wall is analyzed for a Reynolds number of $300 \leqslant Re \leqslant 900$, channel inclination of $0^\circ \leqslant \gamma \leqslant 90^\circ$, and different values of buoyancy strength or modified Richardson number. From experimental measurements, space-averaged surface temperatures and overall Nusselt number of each simulated electronic chip are obtained for a wide range in the parametric space. Also, phase-space plots of the self-oscillatory system, characteristic times of temperature oscillations and spectral distribution of the fluctuating energy are presented. Results show that for relatively large values of buoyancy strength, strong three-dimensional secondary flow oscillations develop in the axial and spanwise directions. The temperature measurements show that for a fixed value of the modified Richardson number, there is not a linear dependence between the duct orientation and the heat transfer rates achieved. Also, when the duct is inclined with respect to the horizontal, the right (upper) and left (lower) oscillating vortical structures present large and small amplitude thermal fluctuations, respectively. In addition, it is pointed out that the highest flow reversal takes place at the channel corners of the upper heater block, and that higher surface temperatures are reached at the centerline of the latter. The analysis brings out the significance of the three-dimensional configuration of the vortical structure and how the buoyancy induced secondary flow is affected by the partial blockage.

1. Introduction

Mixed convection heat transfer in the presence of finite-size heat sources has become a subject of increased interest because of advances in the electronics industry and heat exchanger technology. As higher flux densities are obtained due to advances in electronic systems miniaturization and because of the presence of protruding heaters, the flow features around partially blocked geometries are of fundamental interest in the implementation of passive thermal control mechanisms aimed towards increasing the capability of these electronic devices to dissipate excessive heating. As a result, a considerable amount of literature work has been devoted to evaluate the thermal performance of rectangular channels with various forms of partially blocked geometries. One of the most frequently investigated configurations on laminar mixed convection in flow passages with an abrupt change in geometry are backward and forward-facing steps [1–7], as these geometries generate detachment and reattachment of flows and develop recirculation regions which result in a higher heat transfer performance. Abu-Mulaweh [8] presented an extensive review on the topic along with a detailed summary of the effects of several parameters such as step height, expansion ratio, inclination angle, Reynolds and Prandtl numbers, and buoyancy force (Richardson number) on the flow and thermal fields. There have also been considerable numerical and experimental investigations of incompressible laminar flow in ducts with plane symmetric sudden contractions [9–14] and plane sudden expansions [15–21] in flow

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http://dx.doi.org/10.1016/j.expthermflusci.2015.12.013
0894-1777/

Nomenclature

A_c	cross-sectional area of the channel, m^2
A_{heater}	surface area of each heater exposed to the water flow, m^2
D_H	hydraulic diameter (characteristic length), m
f	frequency, Hz
g	gravity acceleration, m s^{-2}
Gr^*	modified Grashof number, $Gr^* = g\beta\dot{q}D_H^4/k\nu^2$
h	heat transfer coefficient, W m^{-2} K^{-1}
H	channel width, m
I	measured current, A
k	thermal conductivity, W m^{-1} K^{-1}
l_2	length of the discrete heat sources, m
L_i	nondimensional length of the discrete heat sources, $L_i = l_i/D_H$
$\overline{Nu}$	space-averaged Nusselt number based on the hydraulic diameter
$\widetilde{Nu}$	time-and-space averaged Nusselt number
P	channel perimeter, m
Pr	Prandtl number, $Pr = \nu/\alpha$
$\dot{Q}$	net convective heat flux transferred to the fluid, W
$\dot{q}$	net convective heat flux per unit surface transferred to the fluid, W m^{-2}
$\dot{q}_{cond}$	calculated conduction losses to the ambient, W m^{-2}
$\dot{q}_{el}$	measured input power per unit surface supplied to each heater, W m^{-2}
$\dot{q}_{rad}$	calculated radiation losses to the ambient, W m^{-2}
Re	Reynolds number based on the hydraulic diameter, $Re = u_0 D_H/\nu$
Ri^*	modified Richardson number, $Ri^* = Gr^*/Re^2$
St	Strouhal number based on the hydraulic diameter, $St = fD_H/u_0$
t	time, s
T_{amb}	ambient temperature, K
T_0	fluid temperature at the channel inlet, K
T_w	local surface temperature, K
$\overline{T}_w$	mean surface temperature of each heater, K
u_0	fluid velocity at the channel inlet, m s^{-1}
V	measured voltage, V
x, y, z	rectangular Cartesian coordinates
X	nondimensional axial coordinate, $X = x/D_H$
Y	nondimensional transverse coordinate, $Y = y/D_H$
Z	nondimensional spanwise coordinate, $Z = z/D_H$

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	thermal volumetric expansion coefficient, K^{-1}
ΔT	temperature difference, $\Delta T = T_{wj} - T_0$, K
ε	surface emissivity of aluminum
γ	inclination angle with respect to the horizontal
ν	kinematic viscosity, m^2 s^{-1}
ρ	fluid density, kg m^{-3}
σ	Stefan–Boltzmann constant, 5.670373(21)10^{-8} W/m^2 K^4
τ	nondimensional time

Subscripts

$j = R, L$	indicates left and right heated slabs, respectively

geometry. In addition, it is well established that without introducing buoyancy force in these configurations, the flow is symmetric at low Reynolds numbers. However, at higher Reynolds numbers, transition from symmetric to an nonsymmetric flow occurs at a critical Reynolds number above which the flow bifurcates and is no longer symmetric about the centerline of the channel [22–34]. Therefore, the exploration of the three-dimensional (3D) aspects during mixed convection heat transfer is yet to achieve adequate attention. Also, in the above mentioned studies, researchers have focused on describing the global steady heat transfer characteristics, and relatively few studies have been reported on the transient local and overall heat transfer characteristics for the protruding components. Nonetheless, complex flow phenomena in ducts with abrupt changes in geometry during mixed convection have features in common, such as the presence of transition from steady to a periodic flow occurring through a Hopf bifurcation when the buoyancy parameter exceeds a threshold value.

The above review shows that mixed convection heat transfer in channels with complex geometries has received great interest in recent years. However, a particularly interesting geometry of modified channel configuration that has received little attention in the literature is that of an open vertical rectangular channel with sudden symmetric contraction–expansions that have localized heat sources subjected to a constant heat-flux boundary condition. In particular, studies that address the effects of wall confinement on the 3D flow and thermal behavior of the vortical structure and its corresponding temperature fluctuations due to flow oscillation have been practically overlooked. This is the motivation for the present paper. In this work, a systematic and thorough investigation of transient laminar mixed convective cooling is studied experimentally. Attention is given to the effect of opposing buoyancy and channel orientation on the overall thermal performance of these complex flows. The aim of the present investigation is to provide information which adds to the knowledge of the time-dependent and 3D aspects of laminar opposing mixed convection heat transfer in ducts with an abrupt change in geometry. The overall goal from the present study is to develop advanced thermal management schemes that are capable of removing very large heat fluxes from advanced electronic devices, thus increasing their reliability and durability by means of a more accurate thermal control. In this paper, the experimental set-up used to obtain the experimental data is described. The calculation procedure established to determine the mixed convection heat transfer coefficients and the dimensionless data analysis is explained. Finally, the results of the experimental data are presented and discussed in detail.

2. Materials and methods

In this section, information about the experimental apparatus, devices used and procedures followed for the processing of experimental data are provided.

2.1. Experimental arrangement

Fig. 1 shows a schematic diagram of the experimental setup. Water enters through the upper opening of a square duct with a uniform velocity u_0 and temperature T_0. A constant-head tank that's filled from a reservoir tank using a centrifugal pump is used to maintain a steady inflow condition during the experiment. Prior to the channel inlet, a nozzle with honeycomb and mesh structures