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Experimental investigation of natural convection in a vertical rib-roughened channel with asymmetric heating

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ABSTRACT

An experimental study in an open-ended vertical channel is carried out in order to describe the fluid dynamics and heat transfer of transient free convection inside a vertical rib-roughened channel asymmetrically heated at various uniform heat fluxes (650, 700, and 780 W/m^2) corresponding to various modified Rayleigh numbers (3.65×10^6, 3.93×10^6 and 4.4×10^6). Two ribs are symmetrically located on each wall. The investigations focused more specifically on the influence of the ribs positions inside the channel and the modified Rayleigh number (Ra^*) both in steady-state regime and during the transitional phase occurring just after the start of the heating on the flow structure and the heat transfer performance. The results showed the appearance of large-scale flow instabilities which will develop and propagate until the development of the pocket-like vortex (reversed flow). Also, the formation and breakup of recirculation eddies, vortex banishment, besides that a separation and shifting of the boundary layer from one wall to another are identified. The best position of the ribs for heat extraction depends on the magnitude of the Rayleigh number. In that case, the top position is the optimal position for the small and the moderate modified Rayleigh numbers.

1. Introduction

Since the pioneering work of Elenbaas [1] natural convection in open channels has been extensively studied over the last past decades, both experimentally [2–11] and numerically [12] for vertical or inclined configurations. Great interest was raised by this subject and it is still receiving significant interest from the researchers due to its wide range of practical applications such as solar chimneys, solar energy collectors, trombe walls, double-skin photovoltaic (PV) façades or the cooling of electronic components and many others [13–16].

A large number of numerical and experimental works are dealt with natural convection phenomenon in vertical plane channels among the ones cited above. It should also be noted that there are situations in which roughness or obstacles occur naturally or added in the channel in order to modify the aerodynamic characteristics of the flow and heat transfer performance or to satisfy design constraints. This includes among others, to induce an increase in the flow rate or to produce physical disturbances in the laminar boundary layer, thereby causing an earlier transition to turbulence and an enhancement of the chimney effect. This may be the case in electronic circuit boards or even surfaces of buildings. In all cases the understanding of the flow behavior of these systems is essential for their design. Among these works, the numerical works of Habchi and Acharya [17] of laminar mixed convection of air in a vertical channel with a single rectangular rib for a symmetrically or asymmetrically heated channel. They found that the mean Nusselt numbers of smooth channel are greater than those for ribbed channel for both symmetrically and asymmetrically heated channel. Hung and Shiau [18] performed an experimental study in a vertical channel heated asymmetrically with a single rectangular rib. Their results demonstrated that for a constant heat flux the channel spacing has insignificant influence on mean heat transfer parameters. It is observed in their results that for UWT boundary conditions the location of the obstruction affects greatly the heat transfer. Also, the presence of obstruction reduces the heat transfer. Said and Krane [19] studied numerically and experimentally the

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Nomenclature

A	Heated length, m
b	Channel wall spacing, m
C_p	Specific heat capacity, J/kg K
g	Acceleration of gravity, m/s^2
h, h_{ave}	Local and average heat transfer coefficient, W/m^2 K
k	Thermal conductivity, W/m K
Pr	Prandtl number($Pr = \frac{\nu}{\alpha}$)
Ra	Rayleigh number ($Ra = \frac{g\beta\varphi b^4}{k\nu^2} Pr$)
Ra*	Modified Rayleigh number ($Ra^* = \frac{Ra}{R_f}$)
R_f	Channel aspect ratio($R_f = \frac{A}{b}$)
T	Temperature, K
Vs	Sedimentation velocity, m/s
V	Vertical velocity component, m/s
x,y	Vertical and transversal coordinates, m

Greek symbols

β	Volume expansion coefficient, 1/K
Δ	Thermal to dynamical layer thickness ratio (Δ = 0.653 for Pr = 7)
φ	Heat flux density, W/m^2
ρ	Density, kg/m^3
ν	Kinematic viscosity, m^2/s
μ	Dynamic viscosity, Pa s
α	Thermal diffusivity, m^2/s

Indices

W	Wall
∝	Ambient
0	Reference value

natural convection in a vertical channel with a single semi-circular obstacle. Bhavnani and Bergles [20] conducted an experimental study of natural convection from a vertical isothermal surface with repeated ribs or steps. Their results showed that the stepped surface helped improve the heat transfer until 23.2% corresponds to an optimum step pitch-to-height ratio equal to 16, while all of the ribbed surfaces decrease the heat transfer performance. Tanda [21,22]; Ambrosini and Tanda [23] analyzed experimentally the natural convection inside a vertical channel formed with a ribbed wall and an opposing adiabatic smooth wall. The natural convection from a grooved plate with different sizes of the grooves has been studied experimentally and numerically by Kwak and Song [24]. A numerical study was carried out by Desrayaud and Fichera [25] to detail the effects of the location of two rectangular ribs on the flow structure and an isotherm pattern in a vertical isothermal channel. The influence of the rib conductivity is also considered. Their results showed only for high values of the channel Rayleigh number, the mean Nusselt number increases as the distance of the ribs from the inlet increases. The best position for the ribs depends on the magnitude of the Ra. Recently, Dihmani et al. [26] analyzed numerically the effect of the rib width and the Rayleigh number on combined natural convection and thermal radiation heat transfer in a vertical vented channel, with a rectangular rib placed on the left wall. Also, Dihmani et al. [27] performed numerical analysis focusing on the effect of the size and location of the vent opening on combined natural-radiative convection in the same geometry as in [26].

On the one hand, all experimental and numerical studies previously cited on the vertical rib-roughened channel were limited to thermal measurements (flow and wall temperature) both for uniform heat flux (UHF) and for uniform wall temperature (UWT) problems using air as working fluid. However, despite these efforts, the prediction remains an open problem. There is a persistent need to deepen the knowledge and understanding of the related phenomena especially dynamic behaviors of such problems and that infers useful engineering information for controlling the energy transfers. Also, in the author's knowledge this is the first study that analyzes and details experimentally the transient natural convective flows in a vertical channel asymmetrically heated with surface-mounted square ribs using water as working fluid.

On the other hand, at the level of knowledge and current thinking, it seems clear that numerical simulations of free convection in an open-ended channel with the influences of parametric changes in the obstacles geometry require further developments before being usable for design. This can only be made possible by the contribution of new experiments necessary to understand the physical phenomena that drives and alters the flow behavior, to generate reference measurements and the necessary thermal and dynamic data. Since these data are essential data for validation of numerical simulation tools, in order to find out reliable ways to enhance heat transfer.

For the purpose to get access to these data and to show the effect of the position of a pair of square ribs on flow dynamics and heat transfer enhancement, an experimental investigation has been presented in this paper. It deals with the study of flow dynamics and heat transfer induced by natural convection in a vertical rib-roughened channel heated asymmetrically with two square adiabatic ribs attached symmetrically on each wall. Three positions of the two ribs are considered: near the inlet and the outlet of the heated zone and at the middle of the channel. It should be mentioned that the use of water as working fluid allows to neglect the effect of radiation.

2. Experimental set up

2.1. Design

This paper presents the experimental study of heat transfer and flow dynamics induced by natural convection in a vertical asymmetrically heated channel with two symmetrical surface-mounted adiabatic square ribs. The channel is immerged inside a 200 l water vertical tank of inner dimensions 460 × 460 × 960 mm^3 and made of 20 mm thick Plexiglas ®. The detailed geometry scheme is shown in Fig. 1. The channel is composed of two vertical parallel plane walls (height: 2A = 376 mm, width: L = 300 mm) separated by an adjustable distance (b) (width b is fixed to 36 mm). One wall is heated in its central part (height A = 188 mm) and two unheated extensions (height A/2) are respectively located upstream and downstream open-ends of the channel while the opposite wall remains entirely unheated throughout the duration of all the experiments. Two adiabatic square ribs are mounted symmetrically on each wall of fixed dimension 12 × 12 mm made up of Plexiglas ®; leading to a reduction in the cross-sectional area of the channel of 60%, giving a free flow spacing of 12 mm (Fig. 2) and located in three different positions in the inlet and the outlet of the heated zone and in the center of the channel. Because the ribs have poor conductivity (k = 0.23 W/m K), the part of local heat flux delivered to water by the rib surfaces can be neglected. The channel is laterally bounded with two transparent PMMA vertical plates with10 mm of thickness (parallel to plane xOy), as well as, for a better control of the flow conditions at the channel entrance, a quarter of a circle (R = 36 mm) was added at the bottom of each wall. The heating of the central half part of the heated wall is provided by a fabric heater which delivers a heat flux uniformly distributed throughout the heating zone. This thermal system consists of a vertical plane thermofoil heater, covered by a 3 mm-thick aluminum plate on the