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Review

Influence of the dynamic boundary conditions on natural convection in an asymmetrically heated channel

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A B S T R A C T

The present paper is concerned with the results of the numerical investigation of unpermanent laminar, natural convection in an asymmetrically heated inclined open channel ($i = 0{,}45{,}60$ and 75°) with walls at uniform heat flux ($q_w = 10{,}50{,}75$ and $100\ \mathrm{W\ m^{-2}}$). Two methodological approaches have been adopted to investigate the air flow in these configurations: 2D and 3D description, and four sets of inlet-outlet velocity-pressure boundary conditions have been considered. Significant differences are observed in the flow dynamics between 2D and 3D results. The numerical results are compared with the experimental data and a good agreement is obtained when a local pressure boundary condition is applied at the inlet/outlet sections in the 3D case. A generalized correlation for the average Nusselt number is then obtained from numerical results. This correlation covers a wide range of the modified Rayleigh number and aspect ratio values ($Ra_m\cos(i)$ varying from 1.71×10^4 to 3.60×10^6 and $6.5 < H/b < 12.8$).

1. Introduction

A new generation of computational tools for building and community energy systems will be developed in the near future (Wetter et al. [1], Jin et al. [2]). Their validation will involve comparisons between simulations, analytical solutions and real-scale experiments and inter-model comparisons using existing standards such as ASHRAE Standard. This investigation provides theoretical foundations for buoyant flow analysis in passive systems. Passive systems based on buoyant flows developing in heated vertical or inclined channels are used in many engineering applications such as solar chimneys, photovoltaic cooling systems, or devices for air conditioning and natural ventilation in buildings. Recent papers can be found in the literature for such configurations, as well from an experimental point of view (Chami and Zoughaib [3], Popa et al. [4], Daverat et al. [5]) than for an analytical or numerical point of view (Bassiouny and Korah [6], Suárez et al. [7]), in continuation of numerous previous works during the last decades. Elenbaas [8] pioneered the experimental investigation of natural convection of air within a vertical parallel-plate channels and identified the different types of flows regimes, according to the definition of a modified Rayleigh number. Bar-Cohen and Rohsenow [9] derived a set of correlations for the Nusselt number in an asymmetrically heated channel. Sparrow et al. [10] highlighted on their wall the possibility of a reversal flow at the upper end of a channel heated at a constant temperature on one side. More recently, the domain of existence of reversal flow was deeply experimentally investigated by Dupont et al. [11,12] for a constant flux wall heated channel.

From a numerical point of view, imposition of coherent boundary conditions at the geometrical limits of the computational domain is not obvious because velocity and pressure values are not known *a priori* at the inlet and outlet sections of the channel. Different strategies are then available to improve theoretical aspects of building performance modelling and the open geometries. One is to consider extended spatial domains at the entrance and at the exit of the channel where free stress or non rotational flow conditions can reasonably be applied. Naylor et al. [13] considered as an example a semi-circular virtual extension at the entrance of the channel with a Jeffery [14] or Hamel [15] flow

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Nomenclature

Dimensionless terms
- θ dimensionless temperature
- A surface area
- G dimensionless flow rate
- $Nu_{1/2}$ local Nusselt number at mid-height of the channel $\left(\frac{1}{\theta}\right)$
- P dimensionless modified pressure
- Pr Prandtl number (ν/κ)
- Ra_H height-based Rayleigh number $\left(Ra_m\left(\frac{H}{b}\right)^5\right)$
- Ra_m modified Rayleigh number $\left(\frac{g\beta q_w b^4}{\lambda\nu^2}\frac{b}{H}Pr\right)$
- Re Reynolds number $\left(\frac{u\Delta x}{\nu}\right)$
- t dimensionless time
- u,w dimensionless fluid velocity components
- x,y,z dimensionless cartesian coordinates

Greek letters
- β volumetric coefficient of thermal expansion $[K^{-1}]$
- δ Kronecker symbol
- ε wall emissivity
- κ thermal diffusity $[m^2\ s^{-1}]$
- λ thermal conductivity $[W\ m^{-1}\ K^{-1}]$
- ν kinematic viscosity $[m^2\ s^{-1}]$

Latin letters
- $\vec{V}$ velocity vector $[m\ s^{-1}]$
- b characteristic width [m]
- g gravitational acceleration $[9.81\ m\ s^{-2}]$
- H channel height [m]
- i inclination angle[°]
- l depth [m]
- q_w heat flux at the wall $[W\ m^{-2}]$
- ΔT temperature difference $(q_w b/\lambda)$ [K]
- T_0 inlet temperature [K]
- V_b bulk velocity $[m\ s^{-1}]$
- V_{ref} reference velocity $\left(\frac{\kappa}{H}Ra_H^{1/2}\right)$ $[m\ s^{-1}]$

Subscripts
- 0 reference
- *in* channel inlet
- BC boundary condition
- GB global Bernoulli condition
- LB local Bernoulli condition

approximation at the perimeter of this domain. Andreozzi et al. [16] and Campo et al. [17] considered inlet and outlet rectangular extensions at both ends of the channel. The problem of such extensions is that the natural convection flow that develops in the channel is very sensitive to the size of the extensions, and boundary conditions must be rejected far from the inlet/outlet of the channel. Suárez et al. [7] found in that way that the computational domain including the whole channel they consider must be 200 times larger and higher than the channel itself for assuming independence of the flow and heat transfer in the channel from the external surrounding domain.

The problem then turns into the choice of realistic inlet boundary conditions and their numerical implementation (Le Quéré [18], Desrayaud et al. [19]). Hence, it follows that two and three dimensional natural convection in inclined channels with open boundaries has been rarely investigated using inlet-outlet boundary conditions. In order to investigate the influence of the boundary conditions imposed at the ends of a heated vertical or inclined channel on the natural convection flow inside the channel, an in-house numerical code has been developed. The configurations we consider are similar to those experimentally investigated by Webb and Hill [20] and Dupont et al. [11,12]. We defined different sets of pressure–velocity boundary conditions, either for 2D and 3D computations. The experimental data available from the experiments provide relevant information for comparison with the numerical simulations in terms of heat transfer at the heated wall, mass flow rate in the channel, but also for velocity and temperature profiles.

In the first part of the paper, the numerical approach is introduced and different sets of pressure–velocity boundary conditions are discussed in 2D and 3D for a vertical channel. Then numerical results are compared with experimental data, particularly for the existence of a reversal flow for height-based Rayleigh number Ra_H, ranging from 5.89×10^9 to 5.89×10^{10}, for aspect ratio $6.5 < H/b < 12.8$ and tilt angle of the channel $0 < i < 75^\circ$.

Finally, a generalized correlation for the Nusselt number is proposed from the 2D numerical results and compared to existing ones.

2. Problem description

2.1. Geometry

In order to focus on the flow and heat transfer in the channel, we consider in this study a computational domain restricted to the channel geometry. This raises the question of defining a physically coherent set for the boundary conditions at the inlet and outlet of the channel, that enables in particular recirculation of the fluid inside the channel.

First, we consider a two-dimensional open channel asymmetrically heated by a constant parietal heat flux imposed on its left side (see Fig. 1, Dupont et al. [12]). The experimental channel consists in two parallel rectangular plates of dimension $H \times l$ with $H = 0.64$ m made of epoxy resin with copper cover of low emissivity ($\varepsilon = 0.26$) to limit the radiative effects. The front and rear faces are made of glass for measurement facility, and the entrance and exit borders are completed with a convergent, consisting of a quarter-cylinder shape of radius 50 mm. Measurements are achieved with a two-component Dantec Laser Doppler Anemometer (LDA) system for velocity. Wall temperatures were measured by 34 type K, 100 μ m thermocouples. The calibration of the temperature measurement system showed an accuracy of ± 0.1 K. In the present investigation, different heat fluxes and channel widths are studied, namely: $q_w = 10$, 50, 75 and 100 $W\ m^{-2}$ and $b = 0.05$, 0.06 and 0.1 m, resulting in aspect ratios (H/b) of the channel equal to 12.8; 10.67 and 6.5 respectively. For three-dimensional numerical investigation the depth $l = 0.304$ m is considered. Thirty two cases were considered, which are summarized in Table 4.

2.2. Governing equations

Computational fluid dynamics (CFD) approach is employed to simulate the airflow and heat transfer in the inclined channel system. The continuity (1a), momentum (1b) and energy (1c) equations for a two or three dimensional laminar flow of an incompressible Newtonian fluid under the Boussinesq