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IMPACT OF EXTERNAL SURROUNDINGS ON NATURAL CONVECTION IN A VERTICAL CHANNEL ASYMMETRICALLY HEATED (ECCOMAS CONGRESS 2016)

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Abstract. *This paper reports a numerical study of natural convection problem between vertical plates with asymmetric heating. Influence of perturbation conditions outside of the channel on flow structure and on the heat transfer rate are investigated. The effect of temperature consists of considering a gradient of temperature between the bottom and top of the channel in order to obtain a thermal stratification. The effect of surface radiation on the laminar air flow with a thermal stratification is investigated by considering temperature of grey bodies. Results show that these weak perturbations outside the channel are a real influence on flow and that the influence of thermal stratification is more important than surface radiation. Numerical simulations have been carried out at modified Rayleigh number Ra=5.10*^{5} *(laminar regime) and with Prandtl number Pr=0.71.*

Nomenclature

A	surface of the heated wall	d_w	width of the downward flow
q_{r_i}	net radiative heat flux	l_w	length of the downward flow
Ra	Rayleigh number	H	height hot plate of channel
Ra_b	modified Rayleigh number	$\tilde{J}_i$	radiosity linear system
$\dot{m}_{in}$	mass flow rate entering through bottom-end	Nu_1	Nusselt number on the heated plate
$\dot{m}_{out}$	mass flow rate exiting through top-end	$\overline{Nu_1}$	Mean Nusselt number on the heated plate
$\dot{m}_{es}$	mass flow rate entering through top-end	p	pressure
T	temperature	Pr	Prandtl number
T_0	reference temperature	**Greek Symbols**	
$T_{bottom\ body}$	temperature of grey surface bottom-end	ΔT	temperature difference scale
$T_{top\ body}$	temperature of grey surface top-end	ϵ	emissivity
b	width of the channel	κ	thermal conductivity
u, v	velocity components	ν	kinematic viscosity
t	time	Φ	heat flux
U_{CN}	characteristic velocity	Ψ	stream function
$\vec{e_y}$	coordinates axes	σ	Stefan-Boltzmann constant
$\vec{v}$	velocity vector	θ	dimensionless temperature

1 INTRODUCTION

The heated vertical open-ended channel is representative of practical interest such as the chimney, the solar panel, or the Trombe wall. The problem of natural convection in vertical channels has been the focus of extensive investigations [10]. Authors studied free convection between vertical flat plates with symmetric or asymmetric heating, with uniform heat fluxes or constant temperatures[4]. There are several ways to take into account the surrounding conditions. The channel can have adiabatic extensions, be closed in cavities or open domain [7, 1, 2, 17, 16]. These different strategies lead to an increase in size of the computational domain which proves to be expensive, both in memory and in computational time [19]. Moreover, interactions between the channel and surroundings are not correctly estimated by these strategies [3, 12, 13, 14]. Indeed, thermal stratifications are often not considered although experimental studies show its existence. As the same, except some studies in literature [6, 15], major of numerical investigations overlooked surface radiation in natural convection case. Moreover, several studies [6, 20, 21] confirmed that radiation transfer represent significant percent in heat transfer global.

The influence of thermal stratification on the laminar air flow induced by natural convection in vertical, asymetrically-heated channels is discussed. Studies conducted by the French Research Group AMETh [9] on natural convection in open-ended channels are taken as the base case for carrying out the computations. The thermal stratification is created by setting a constant bottom temperature different from the top temperature, in order to obtain a weak gradient of temperature between the entrance and the exit of the channel. The influence of external surface radiation is also investigated and temperature of grey bodies (bottom and top channel) are set to values in agreement with thermal stratification outside the channel.

2 DESCRIPTION OF TEST CASE

A vertical parallel plate channel of width b and height H is formed by two walls, one partially heated at a constant and uniform heatflux Φ on its half middle section and the remaining walls are adiabatic (see Figure 1).

The fluid flow is assumed laminar and two-dimensional. Accounting for the small relative temperature difference occurring between the heated wall and the aperture, the Navier-Stokes and energy equations are expressed with the Boussinesq approximation. The viscous dissipation term in the energy equation is neglected. The energy equation and the one dealing with radiant interchanges amongst surfaces is coupled through the thermal boundary conditions.

2.1 Heat and fluid flow equations

The governing flow and heat transfer equations, written in dimensionless and conservative form, read:

$$\nabla \cdot \vec{v} = 0 \tag{1}$$

$$\frac{\partial \vec{v}}{\partial t} + \nabla \cdot (\vec{v} \otimes \vec{v}) = -\nabla p + Pr Ra_b^{-1/2} \nabla^2 \vec{v} + Pr \theta \overrightarrow{e_y} \tag{2}$$

$$\frac{\partial \theta}{\partial t} + \nabla \cdot (\vec{v}\theta) = Ra_b^{-1/2} \nabla^2 \theta \tag{3}$$

with the reduced dimensionless temperature $\theta = \frac{T-T_0}{\Delta T}$. The reference temperature T_0 is set to 298.15 K. The dimensionless parameters governing the fluid flow and heat transfer are the Prandtl number $Pr = \frac{\nu}{\kappa}$ set to 0.71, the Rayleigh number $Ra_b = \frac{g\beta\Delta T b^3}{\nu\kappa}$ set to $Ra_b = 5 \cdot 10^5$ and characteristic velocity $U_{CN} = \kappa \frac{Ra_b^{1/2}}{b}$.

2.2 Surface radiation

For a given temperature distribution on the channel internal surfaces, the surface radiation problem is fully described by the linear system for radiosity $\tilde{J}_i$ (W/m^2). The net radiative heat flux resulting from surface radiation, which is defined in the hemisphere of a surface element, can be calculated by:

$$q_{r_i} = \frac{\epsilon_i}{1-\epsilon_i}(\sigma T_i^4 - \tilde{J}_j) \ (i = 1, 2, ..., m) \tag{4}$$

where σ is the Stefan-Boltzmann constant, m is the total number of surface elements, ϵ_i is the emissivity of the surface element i and $\tilde{J}_i$ (W/m^2), the linear system for the radiosity.

In this paper, we consider that the emissivity of internal walls is equal to 0.1 and the emissivity of the surfaces corresponding to the bottom-end and top-end, are set to 0.9. The originality of this study is temperature of bottom body and top body which are different to reference temperature. Indeed, surface radiation is only considered in thermal stratification case. As a consequence, bottom and top body can have a temperature as if they are located at a distance from the aperture of the channel, in a stratified ambient air.

2.3 Boundary Conditions

Boundary conditions have been the focus of several studies [5], [9] [22] [14]. According to latest results produced by [5], pressure boundary conditions at the top and bottom sections improved results when they are based on Local Bernoulli relation.

Three configuration cases are referenced in this paper. In each case, the conditions at the solid walls are the same as those in [9]; only the thermal boundary conditions are modified.

- Reference case: it's the case of AMETh [9] with Local Bernoulli (LB-LB) type of pressure boundary conditions at bottom and top of the channel. Thermal boundary conditions at bottom/top are:
  $\theta(x, 0) = 0$ and $\theta(x, 2H) = 0$
- Thermal stratification case: it consists of setting a low dimensionless temperature at the bottom, set to -0.01, in order to obtain a gradient of temperature at the outside of the channel. Thermal boundary conditions at the bottom/top are:
  $\theta(x, 0) = -0.01$ and $\theta(x, 2H) = 0$.
- Radiation surface and thermal stratification: the channel consists of 4 gray-diffuse, vertical surfaces (the three parts of left-hand side wall and the adiabatic right-hand side wall) and two horizontal surfaces regarded as grey radiators at an effective temperature of $T_{rad} = -0.03$ and $T_{rad} = 0.03$, respectively.
  The emissivity of vertical surfaces are set to $\epsilon = 0.1$ and emissivity of horizontal surfaces are setted to $\epsilon = 0.9$. Thermal boundary conditions at the bottom/top:
  $\theta(x, 0) = -0.01$ and $\theta(x, 2H) = 0$
  and horizontal surface temperature are set to:
  $T_{bottom\ body} = -0.03$ and $T_{top\ body} = 0.03$

2.4 Monitored variables

2.4.1 Dynamic quantities

- Mass flow rate entering into the channel at $y = 0$:

$$\dot{m}_{in} = \int_0^1 v(x, 0)\,\mathrm{d}x \tag{5}$$

- Mass flow rate entering into the top section of the channel $y = 2H$:

$$\dot{m}_{es} = \int_0^1 \frac{|v(x, 2H)|v(x, 2H)}{2}\,\mathrm{d}x \tag{6}$$

- Mass flow rate exiting the channel at $y = 0$:

$$\dot{m}_{out} = \int_0^1 v(x, 2H)\,\mathrm{d}x \tag{7}$$

2.4.2 Thermal quantities

- Local nusselt number corresponds to the inverse of temperature at the left wall:

$$Nu_1(y) = \frac{1}{\theta(0, y)} \tag{8}$$

- Average of Nusselt number on the heated wall:

$$\overline{Nu_1} = \frac{2}{A}\int_{\frac{H}{2}}^{\frac{3H}{2}} Nu_1(y)\,\mathrm{d}y \tag{9}$$

  where A is the surface of the heated wall.

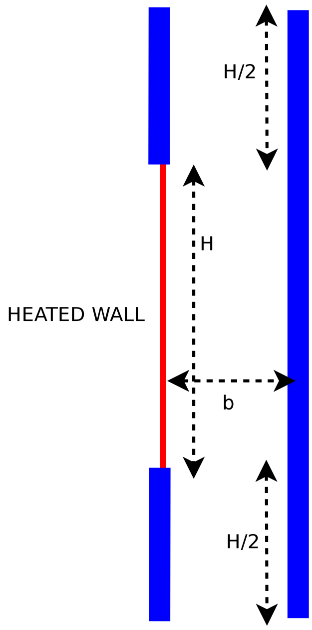

Figure 1: Geometry of the parallel-plate channel

2.4.3 Characterization of flow patterns

- The width of downward flow at the top-end of the channel ($y = 2H$) is calculated from :

$$d_w = b - x_1 \text{ with } \Psi(x_1, 2H) = \Psi_w \tag{10}$$

  Ψ_w the value of the stream function along the right plate arbitrary set to zero.

- The length of downward flow in top-end section is also deduced from the stream function set to zero: $l_w = 2H - y_1$ where y_1 is the such that $v(y_1) = 0$ along the right plate.

2.5 The channel geometry

3 RESULTS

3.1 Impact on dynamic quantities and on flow field

Thermal stratification has a more significant influence on dynamic quantities than surface radiation. Figure 3 displays the vertical component of the velocity in different horizontal sections of the channel. Major differences are shown in the entrance section at $y = 0$. Indeed, in thermal stratification case, the velocity at $y = 0$ consists essentially of a flat profile and it turns out to be parabolic without thermal stratification. The taking account of surface radiation do not modify the profile of vertical component of the velocity. This flat velocity profile at the entrance makes the mass flow rate in the channel decline. As reported in Table 1, the mass flow rate at the bottom of channel significantly decrease of 73% in thermal stratification case, and 65% with surface radiation. As a consequence, a plug-flow in the channel is produced. This result is in good agreement with the experimental studies realized by [8] and [14]. Therefore, thermal stratification and surface radiation reduces the mass flow rate at the bottom.

However, flow penetrates deeper into the channel in thermal stratification case and also with surface radiation. The development of the dynamic layer along the left plate wall at the entrance

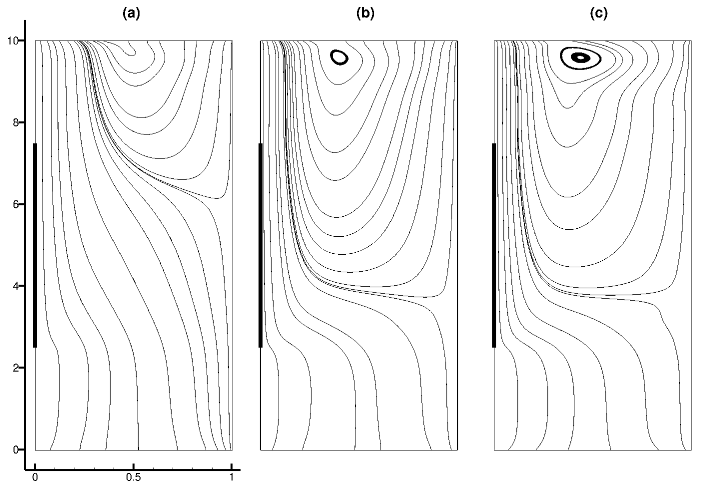

Figure 2: Streamtraces for (a) Reference case, (b) Thermal stratification case and (c) Thermal stratification with radiation

of the heated region at $y = \frac{H}{4}$ is visible in Figure 3. The return flow penetrating through the top section at $y = H$ is also visible with a negative value of vertical component of velocity. This observation is confirmed by the accurate measurements of d_w and l_w which are reported in Table 1. The depth of the pocket of recirculation increases of 67%. As the same, the mass flow rate in entrance at the top of the channel significantly increases: +144% in thermal stratification case and +207% when considering surface radiation. Figure 2 shows the pocket-like streamlines.The taking account of surface radiation modifies the flow structure much at the top section than in the remainder of the channel. This recirculation, fed by fluid drawn into the top section of the channel adjacent to the adiabatic wall, creates a vortex at the top section of the channel. Moreover, the size of the vortex increases by considering surface radiation and setting a temperature to grey bodies surface. Observation of vortex at the exit of channel has been already made by [11] and [18]. So, thermal stratification produces a vortex-like structure at the top region of the channel. The taking account of surface radiation alters significantly the structure of the flow at the top region of the channel. This can be explained by the influence of the temperature of the surface body of the top aperture of the channel.

Although all these effects, the flow stays in steady-state in thermal stratification case and with surface radiation.

Dynamic quantities	$\dot{m}_{in}$	$\dot{m}_{out}$	$\dot{m}_{es}$	d_w	l_w
Reference Case	5.91	5.91	1.61	0.61	4.05
Thermal stratification Case	1.58	1.58	3.93	0.68	6.78
Radiation and thermal stratification case	2.05	2.05	4.94	0.90	6.22

Table 1: Dynamic quantities

3.2 Impact on thermal quantities

Temperature field is not significantly altered by thermal stratification and surface radiation. Figure 4 shows the effect of thermal stratification on the temperature distributions along the two vertical walls. As it can be seen, dimensionless temperature of right plate increases range from -0.01 below the channel bottom-end to 0.002 above the channel top-end when a low thermal stratification. Right wall temperature remains low and close to that of the fluid entering at the bottom of the channel. The taking into account of surface radiation slows down its heating. In the reference case, the maximum temperature is reached at the upper region of the channel instead of the mid-height in other configuration cases. So, as observed by [8] in their experimentation, thermal stratification increases slightly plates temperature. However local and mean Nusselt indicated in Table 2 decrease up to -2.5% in presence of thermal stratification and surface radiation. As a consequence, heat thermal transfer is reduced. This result is in good agreement with [8].

Thermal quantities	$Nu_1(\frac{H}{2})$	$\overline{Nu_1}$
Reference case	6.27	6.74
Thermal stratification case	6.16	6.62
Radiation and thermal stratification case	6.16	6.56

Table 2: Thermal quantities

4 CONCLUSIONS

In presence of a small thermal stratification outside of the channel, the flow structure at the top end of the channel is strongly impacted : the depth of the recirculation flow and the mass flow in entrance at the top section increase. The principal influence is the creation of a vortex penetrating the channel at the top end. The impact of surface radiation is essentially observed at the top section of the channel, where the dimensionless temperature of grey body has been set to 0.03. The vortex observed is larger and streamlines are tighter near the left wall.

Thermal quantities are slightly altered by thermal stratification and surface radiation. Temperature of the right wall increases but remains low and close to the temperature of the fluid entering at the bottom of the channel.

In conclusion, thermal stratification outside the channel has a significant effect on the flow structure and on dynamic quantities. In present study, thermal stratification has been investigated with a weak constant variation at the bottom of the channel. It could be interesting to more quantify the thermal stratification effect on flow and identify others sensible parameters like pressure or aspect ratio.

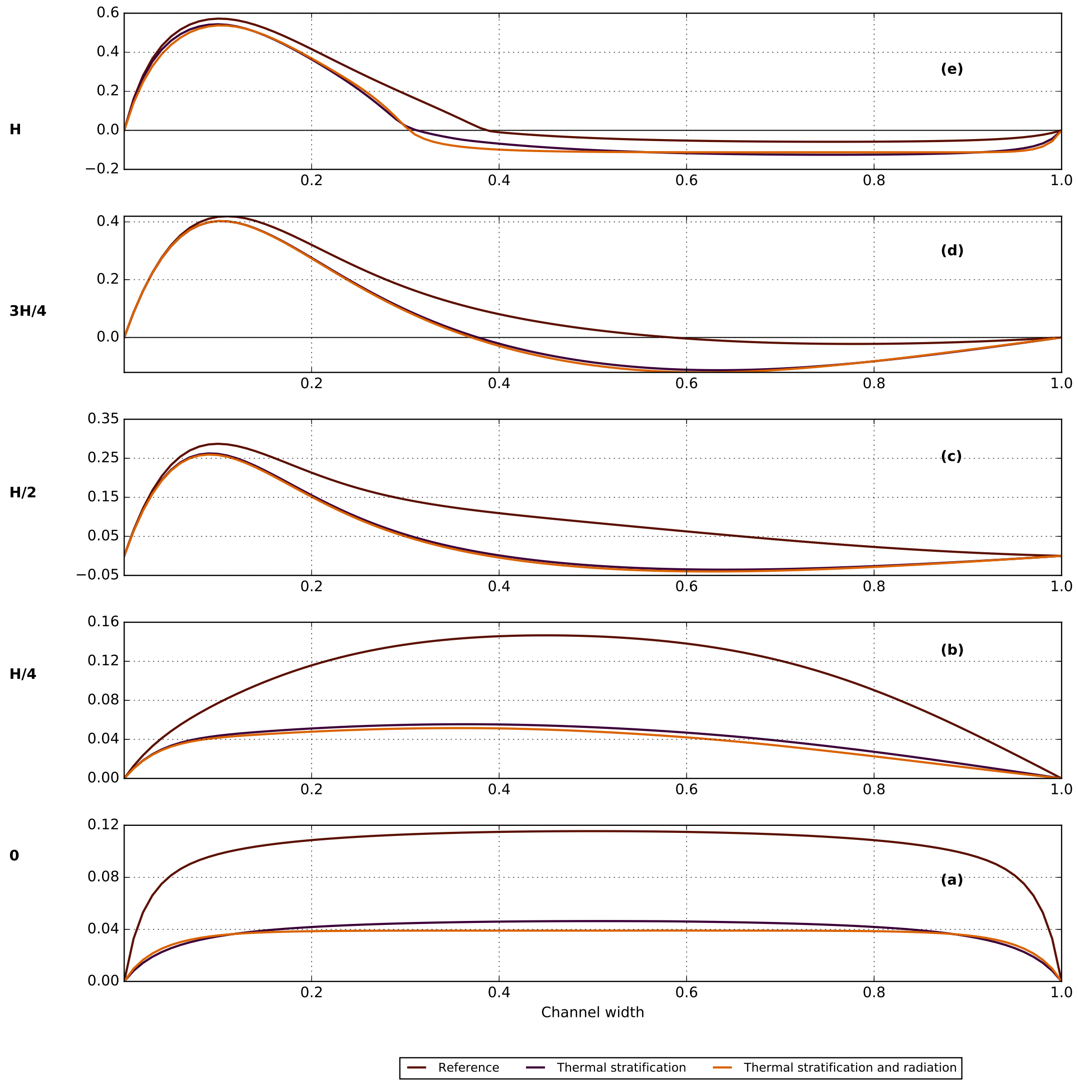

Figure 3: Vertical velocity profiles (a) at the bottom of the channel(y=0), (b) at the inlet of heated wall section (y=H/4), (c) at the mid-height of the channel (y=H/2), (d) at the end of the heated wall section (3H/4), (e) at the top section of the channel (y=H)

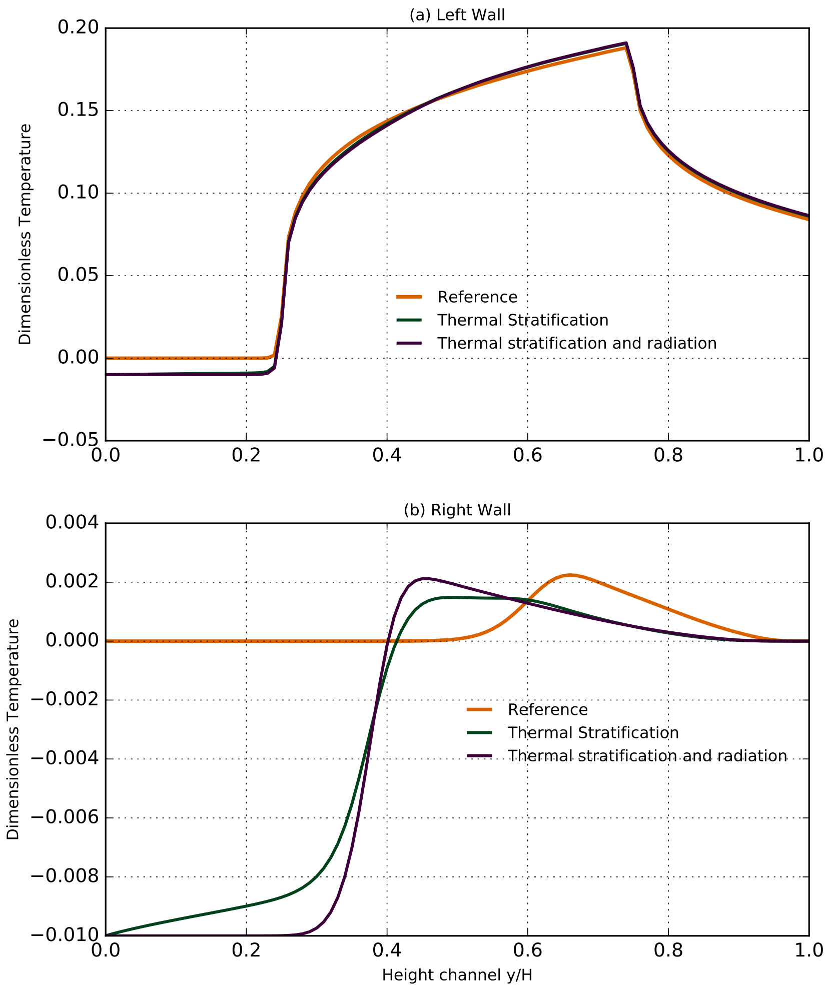

Figure 4: Dimensionless temperature distribution along the vertical channel walls: (a) Adiabatic wall, (b) Heated wall

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