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NUMERICAL STUDIES ON LAMINAR, TRANSITIONAL AND TURBULENT CONVECTIVE AIRFLOWS IN CHANNELS WITH GENERALISED GEOMETRY, INCLUDING APPLICATIONS TO THERMAL-VENTILATION PASSIVE SYSTEMS

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INTRODUCTION

The flows induced by natural convection appear in many engineering problems. Configurations formed by heated plates where these processes occur, were the topic of intense study in past years. However, new systems with a different constructive disposition and applications in several fields (bioclimatic architecture, electronic cooling, nuclear energy cooling systems) are at the moment of great interest. Since typical applications of buoyancy-driven airflows in smooth vertical channels are usually in small-scale devices (i.e. in electronic cooling equipment), most investigations were carried out for laminar flows. As a consequence of the great scale of certain passive ventilation systems, as solar chimneys, Trombe walls, or roof collectors, the flow established becomes transitional or even fully turbulent.

The regarded geometries frequently involve structures based on converging and sloped channels formed by heated plates, where buoyancy-driven flows take place. Therefore, the study of problems such as the transition to turbulent regime or flows with walled-channel geometries including sloped and converging walls are key to assertively find out the real heating transmission existing in these new systems in a more realistic manner.

Nowadays, the need to achieve human comfort by passive heating and ventilation techniques is greater as is the requirement for energy saving. *Passive solar systems* are the basic elements of bioclimatic design and they do not involve the use of mechanical or electrical devices. The *Trombe Wall* is the primary example of the technique called *indirect gain*, whose typical configuration is usually formed by a thick, darkened, masonry wall and a glazed wall. In ventilation applications, other passive systems, called *thermosyphons*, *heat syphon*s or *solar chimneys*, can yield natural motions of air due to the induced temperature differences by solar heating.

Although several reported works provided useful results for the analysis and design of passive solar devices in buildings, these works cannot determine the necessary details of convection for numerical simulations. Furthermore, as an important lack of design correlations is detected, it is necessary to carry out a systematic study that supplied the heat transfer coefficient and the mass-flow rate as a function of relevant parameters, for several configurations.

MATHEMATICAL AND NUMERICAL MODELLING DETAILS

Two-dimensional, laminar, transitional and turbulent simulations are obtained by solving the fully-elliptic governing equations of the established motion of air. Since the expected temperature variations are not too high, the *Boussinesq approximation* can be employed, assuming constant the thermophysical properties of the fluid, except for density variations in the buoyancy term in the vertical momentum equation. Both *uniform wall temperature* and *uniform heat flux* heating conditions at heated walls are considered.

The results are obtained numerically by means the finite-volume *Fluent* and *Phoenics* general-purpose codes. The $k\text{-}\omega$ turbulence model is employed, including a low-Reynolds number extension for near-wall turbulence, with low enough values of the dimensionless sub-layer scaled distance to wall y^+ and several grid lines included in the viscous sub-layer. This model allows treating naturally the transition of laminar to turbulent regimes. The obtained results are validated successfully with numerical and experimental results taken from literature. As a competitive advantage, the $k\text{-}\omega$ turbulence model revealed to be convergent enough, for the wide range of Rayleigh number studied. Since ω values computed at the first grid node close to the wall are very high, strong relaxation factors for turbulent variables are employed to get enough accurate solutions.

The following configurations are outlined. Figure 1 shows the basic scheme for the numerical simulation of the flow established in vertical, convergent and inclined channels. The inlet section is AB and the outlet section is CD. In the Figs. 2a) and b) it can be observed two experimental prototypes which contain in their configuration convergent and sloping channels formed by heated plates; the prototypes are installed outdoors in two building ceiling placed in Murcia (Spain). Figure 3 shows the considered schemes for the simulation of the flow in Trombe Walls coupled to a room (Fig. 3a) or with truncated geometry (Fig. 3b). Finally, Fig. 4 shows the regarded schemes for the study of solar chimneys with

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truncated geometry (Fig. 4a), or with an added computational domain to include the effects of the atmospheric wind (Fig. 4b).

RESULTS OBTAINED IN SLOPING AND CONVERGENT CHANNELS

Based on the generalised geometry of Fig. 1, the study of the induced mass-flow rate was carried out in Zamora *et al*. (2008), whereas the behaviour of the heat transfer coefficient (Nusselt number) at heated walls was analyzed in Kaiser *et al*. (2009).

Firstly, the effects of the Rayleigh number and the inlet turbulence intensity upon the buoyancy-induced mass flow rate in sloping and convergent channels were studied in Zamora *et al*. (2008). In this work, the obtained results for turbulent flow were linked with the laminar ones obtained in previous research. As a relevant conclusion, it should be noted that for sloping and convergent channels, the results for the dimensionless mass flow rate could be fitted to those obtained for vertical channels by modification of the Rayleigh number through a given geometric factor, concerned with the slope and convergence angles. In addition, a generalized correlation for the dimensionless mass flow rate was reported, valid for the wide range of modified Rayleigh number outlined, involving laminar and turbulent regimes. The effects of turbulence intensity at inlet of the channel were analyzed. High values of initial turbulence intensity yielded an advance on the transitional Rayleigh number.

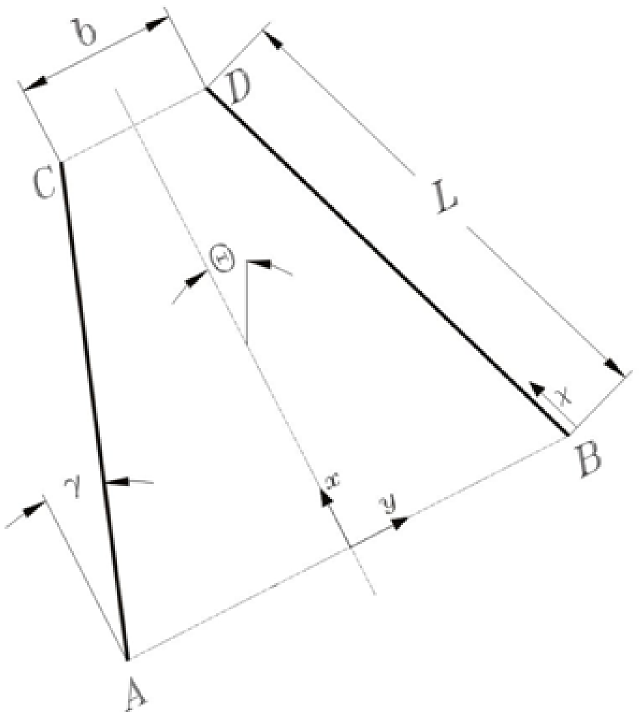

Fig. 1: Scheme of a converging sloped channel formed by walls AC and BD. The convergence angle is g, and the slope angle Q.

Secondly, in Kaiser *et al*. (2009), a numerical correlation for the average Nusselt number in isothermal heated, inclined and convergent channels, for high Rayleigh numbers, was reported. It is remarkable that there was a full continuity between the correlation for laminar regime previously proposed and those obtained for turbulent regime in this study. In this work, the conditions for which the transition laminar-turbulent appeared was analyzed in detail, as well as the effects of the slope and convergence angles on the average Nusselt number. The numerical correlation proposed in this work was validated successfully with experimental results obtained in the *hydro-solar chimneys* prototypes that can be observed in Fig. 2.

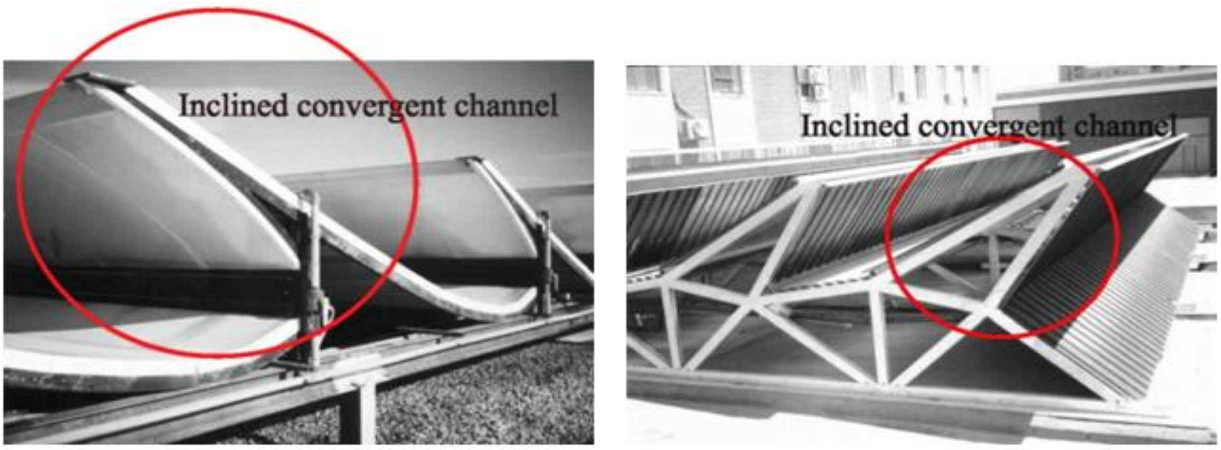

Fig. 2: Two experimental prototypes of the hydro-solar chimney that includes an inclined convergent channel.

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RESULTS OBTAINED IN TROMBE WALLS

In Zamora and Kaiser (2009a), thermal and dynamic optimization of the convective flow in Trombe Wall shaped channels were carried out. The regarded configurations can be observed in Fig. 3. Depending on the requirements of the real design, the results proposed in this work provide the inter-plate spacing that maximizes the induced mass-flow rate or heat transfer (or even the total energy flow) within C-shaped channels with Trombe Wall configuration, for given conditions that assume isothermal heated walls.

Correlations were obtained for the optimum aspect ratio that maximizes the average Nusselt number at walls, and for the optimum aspect ratio that maximizes the dimensionless mass-flow rate, in Trombe Walls shaped channels for a wide range of Rayleigh numbers. In addition, the results obtained for the blended-optimum that maximize the total energy flow are situated between the obtained thermal and dynamic (mass-flow) values, for each value of the Rayleigh number.

As a relevant conclusion, it should be remarked that for given geometrical configurations, the effects of including intermediate, discrete heat sources produces an appreciable increase in the Nusselt number, as well as in the mass flow-rate. This can be explained by the behaviour of the discrete obstacles tested as turbulence generators.

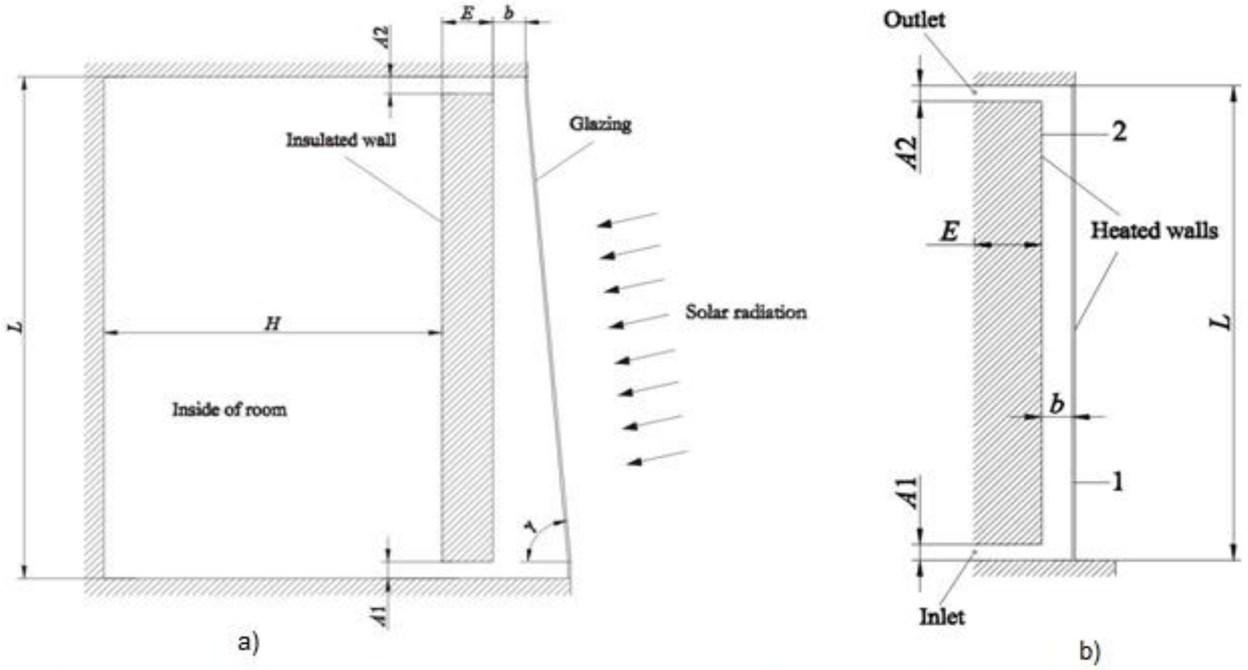

Fig. 3: a) Scheme of a two-dimensional Trombe Wall coupled to a room. b) Scheme of a two-dimensional truncated Trombe Wall.

RESULTS OBTAINED IN SOLAR CHIMNEYS

In Zamora and Kaiser (2009b), the optimum wall-to-wall spacing in solar chimney shaped channels was determined. Depending on the requirements of the real design, the correlations and the results proposed in this work let us to optimize the inter-plate spacing that maximize the induced mass flow rate or the heat transfer within the chimney for a given conditions (weather conditions, walls temperature and height of the chimney).

For the regarded configuration of Fig. 4a), the behaviour of the wall-to-wall spacing that maximized the mass-flow rate was clearly different to the thermal one. This fact can be explained by the sudden change of the flow pattern due to the development of reversed flow regions, which was detected for given ranges of parameters.

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In summary, the relevant discrepancies encountered between the behaviour of the airflow established respectively in Trombe walls systems and in solar chimneys systems can be analyzed by comparing the concluding remarks reported respectively in Zamora and Kaiser (2009a), and Zamora and Kaiser (2009b).

RESULTS OBTAINED FOR BUOYANCY-WIND DRIVING FLOW IN SOLAR CHIMNEYS

In Zamora and Kaiser (2010), a numerical study on mixed buoyancy-wind driving induced flow in a solar chimney for building ventilation was carried out (Fig. 4b). Note that this is a typical application of the convective airflow inside passive solar systems. The knowledge acquired in previous work was applied to assess a detailed analysis of the chimney performance for different conditions.

Numerical results for pressure coefficients, average Nusselt number and the induced mass flow-rate were obtained, assuming as free the outlet section of chimney. The conditions for which the wind driving forces revealed as dominant were determined, obtaining for positive wind velocities (wind from left in Fig. 4b), sizeable higher values of the induced mass-flow rate than those reached considering only buoyancy forces. Against that, for a negative wind velocity (wind from right in Fig. 4b), the mass flow rate becomes negative through the chimney (i.e., the air comes into its upper part), for given conditions. Finally, for positive wind speeds, a global correlation for the induced mass-flow rate was obtained, being valid for the complete range of considered relevant parameters.

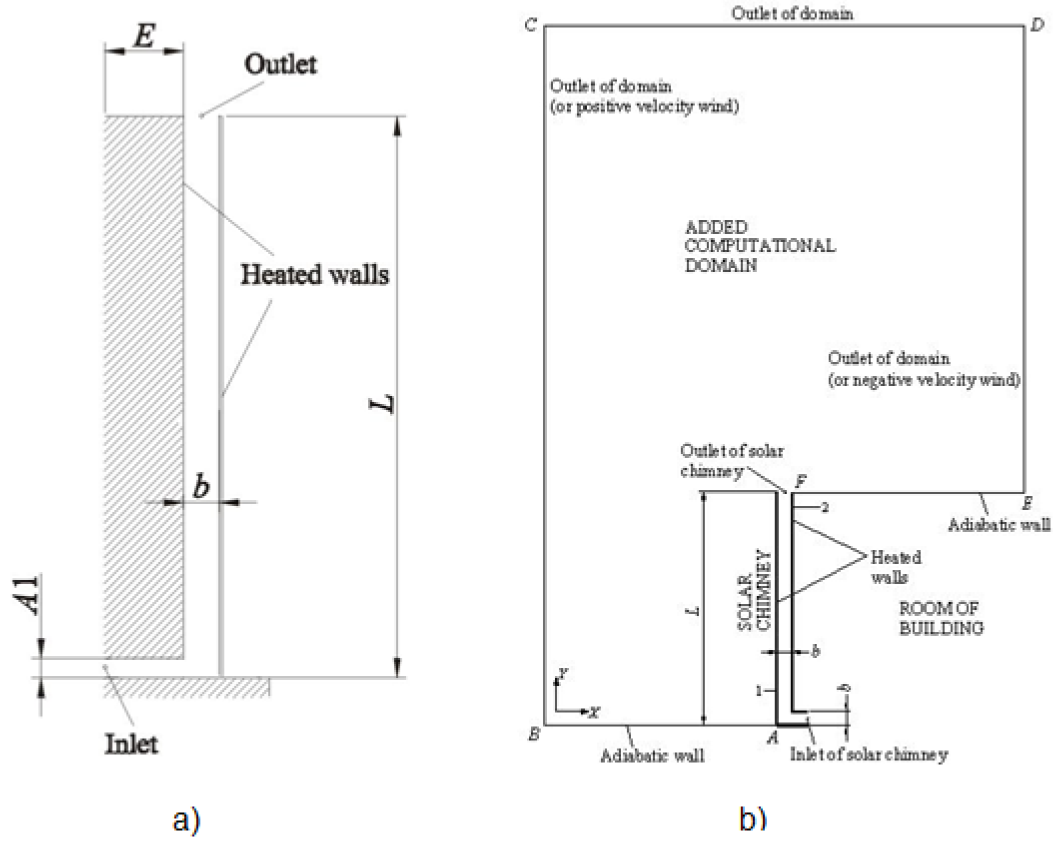

Fig. 4: a) Scheme of a two-dimensional L-shaped channel with solar chimney geometry. b) Scheme of the complete computational domain to simulate the atmospheric wind.

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LITERATURE CITED

ZAMORA, B., KAISER, A.S. and VIEDMA, A. (2008). On the effects of Rayleigh number and inlet turbulence intensity upon the buoyancy-induced mass flow rate in sloping and convergent channels. *International Journal of Heat and Mass Transfer*, 51: 4985–5000.

KAISER, A.S., ZAMORA, B. and VIEDMA, A. (2009). Numerical correlation for natural convective flows in isothermal heated, inclined and convergent channels, for high Rayleigh numbers, *Computers and Fluids*, 38: 1–15.

ZAMORA, B. and KAISER, A.S. (2009a). Thermal and dynamic optimization of the convective flow in Trombe Wall shaped channels by numerical investigation. *Heat and Mass Transfer*, 45: 1393–1407.

ZAMORA, B. and KAISER, A.S. (2009b). Optimum wall-to-wall spacing in solar chimney shaped channels in natural convection by numerical investigation, *Applied Thermal Engineering*, 29: 762–769.

ZAMORA, B. and KAISER, A.S. (2010). Numerical study on mixed buoyancy-wind driving induced flow in a solar chimney for building ventilation. *Renewable Energy*, 35: 2080–2088.

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