

Numerical Study of a Natural Ventilation System in Hot Climate Regions

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Abstract: In order to make the best use of solar energy and for an adequate dimensioning of bioclimatic dwellings at reduced cost, we will develop in this study, an economical process of natural ventilation. The model is considered as a room of dimension (1m x 1m x 1m) equipped with a solar chimney inclined at 45° to the horizontal to predict the performance of the proposed system. Then, we present the effect of temperature variation at the entrance of the room on the air renewal rate. We modeled the different flows produced by the fluent calculation code. The equations of conservation of mass, continuity of motion and energy are solved by the finite volume method. The validation of the results was done by data extracted from the literature. The interest of our work focuses on the notions of natural convection due to the thermal transfer of heat which have taken on particular importance in recent years due to the high cost of energy and the resulting imperatives of economy, hence the need to learn about thermal transfers.

Keywords: Solar energy, Solar chimney, Natural ventilation, Numerical simulation.

1. Introduction

Due to its geographical location, Algeria has one of the largest solar deposits in the world. The use of passive solar energy is generally considered the easiest and most cost-effective way for natural ventilation. Ventilation can be part of a global strategy as a determining means to ensure air quality and an adequate comfort zone for occupants. Renewing the air is not the only objective of ventilation; it is also used in hot and arid regions to modify the indoor temperature and to create a feeling of freshness for buildings. Natural ventilation also occurs due to the control of openings, doors and windows or by a passive solar means such as the solar chimney. Solar chimneys are a kind of renewable energy technologies, which increase natural ventilation in buildings. It usually consists of a window, a cavity, and a solid wall (the absorber). The air in the chimney is heated by solar energy, and flows upwards due to the Archimedes force.

2. Solar Chimney

Solar chimney is an attractive idea for many researchers. In order to improve natural ventilation, several configurations of the chimney have been studied. Some of the researchers are interested in analyzing the vertical chimney, and others had studied the effect of inclination on the performance of the solar chimney. While other studied the effect of the solar

chimney associated with other ventilation techniques. J. Mathur et al. [1] studied the effect of inclination on the flow rate out of the chimney. The results showed that the absorption is optimal, corresponds to an inclination angle varying from 40° to 60° depending on latitude. E.P. Sakonidou [2] and Gan [3] developed mathematical models solved by CFD, in order to predict the inclination and size that maximize the ventilation rate. A. Zoltan [4] presents a detailed mathematical simulation and an experimental study on solar chimneys. The results obtained show that the air velocity in the chimney depends on the distance between the heated plane and the glazing, and the maximum flow rate reaches at an inclination of 45 degrees. D.J. Harris [5] evaluated the impacts of the inclination angle, and double glazing on the ventilation rate. He found that for a chimney integrated into the south face, and an inclination angle of 67.5° has an efficiency of 11% higher than the vertical chimney. A comparison between four types of chimneys is presented by Mathur et al [6]. Where they find that the air flow rate increases when the solar chimney is covered. While the highest flow rate is given for an angle of 45° of inclination compared with the rate obtained by vertical chimneys. Evangellos Bacharoudis et al. [7] studied the phenomena of thermo-fluid produced inside solar chimneys.

In this study, we are interested in natural ventilation by the inclined solar chimney.

A. Geometry and the physical model

The studied configuration is shown in Figure 1. It is a cubic-shaped room with dimensions (1m x 1m x 1m).

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The upper part of this room is equipped with a solar chimney inclined at an angle of 45°, and with dimensions 1m x 0.35m. All sides of the latter are

adiabatic, to eliminate heat transfer with the ambient environment. The room has an opening of 0.35m x 1m on one of the vertical walls.

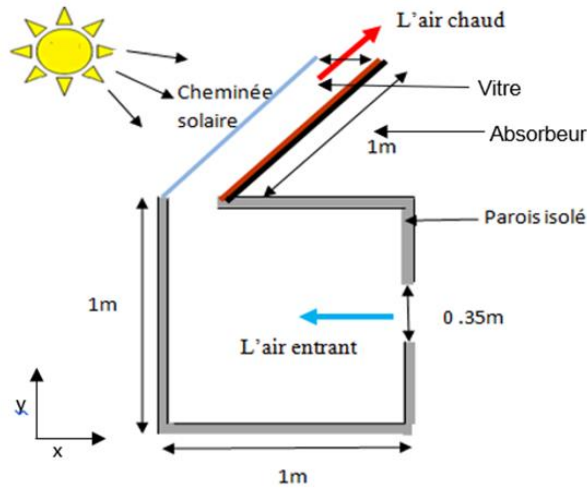


Fig. 1 : Physical model diagram

The hypotheses

- The physical description quickly becomes very complicated. It is therefore appropriate to make a number of assumptions. The choice is made on a two-dimensional domain, and the assumptions used in this work are:
- The flow is two-dimensional.
- Steady flow.
- The air flow is turbulent.

- The fluid is Newtonian and incompressible.
- The absorber and the glass are always parallel.
- The air temperature at the inlet of the flow channel is equal to the ambient temperature.
- Boussinesq approximation is considered.

B. The governing equations

The flow inside the cavity is governed by the averaged Navier Stokes equations

$$\frac{\partial \bar{u}_j}{\partial x_j} = 0 \quad (1)$$

$$\bar{u}_j \frac{\partial \bar{u}_i}{\partial x_j} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\nu \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) - \rho \overline{u'_i u'_j} \right] + \bar{F} \quad (2)$$

$$\bar{u}_j \frac{\partial \bar{T}}{\partial x_j} = k \frac{\partial^2 \bar{T}}{\partial x_j^2} - \frac{\partial}{\partial x_j} \left(\overline{u'_j T} \right) + \bar{\varphi} \quad (3)$$

With $\bar{F}$ Archimedes' thrust and $\bar{\varphi}$ the source term of energy

$$\bar{F} = -g\beta(T - T_0) \quad (4)$$

The correlations of velocity and temperature fluctuations ($\overline{u'_i u'_j}$ and $\overline{u'_j T}$), given by:

$$\overline{u'_i u'_j} = \nu_t \left(\frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) + \frac{2}{3} k \delta_{ij} \quad (5)$$

$$\overline{u'_j \cdot T} = -K_t \frac{\partial \overline{T}}{\partial x_j} \quad (6)$$

The turbulence model used in this study is the standard k-ε model. The equations that express the variation of

the turbulent kinetic energy k and its dissipation rate ε are respectively [8]:

$$\overline{u}_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\frac{\nu_t}{\sigma_k} \frac{\partial \varepsilon}{\partial x_j} \right] + P + G - \varepsilon \quad (7)$$

$$\overline{u}_j \frac{\partial \varepsilon}{\partial x_j} = \frac{\partial}{\partial x_j} \left[\frac{\nu_t}{\sigma_\varepsilon} \frac{\partial \varepsilon}{\partial x_j} \right] + \frac{\varepsilon}{k} (C_{\varepsilon 1} P + C_{\varepsilon 3} G - C_{\varepsilon 2} \varepsilon) \quad (8)$$

With : $P = -\overline{u'_i u'_j} \frac{\partial \overline{u}_i}{\partial x_j}$,

Production term which corresponds to a transfer from the average movement to the fluctuating movement.

- $\varepsilon = \nu \frac{\partial^2 \overline{u'_i}}{\partial x_j^2}$, viscous dissipation.

$G = -\beta \cdot g_i \cdot \overline{u'_i T'}$, work of gravity forces during turbulent fluctuations:

The other constants of the turbulence model are listed in the table below:

Table 1: Constants of the k-ε model [9]

$C_{1\varepsilon}$	$C_{2\varepsilon}$	C_μ	σ_k	σ_ε
1.44	1.92	0.09	1.0	1.3

C. Boundary conditions

The boundary conditions for the model studied are: at the inlet and outlet of the system, the condition is fixed and it is of the Dirichlet type. Then this condition is equal to atmospheric pressure. The condition at the inlet is imposed at the window level which is assumed to be the entrance to the calculation domain and the condition at the outlet is imposed at the chimney outlet. On solid walls, the conditions are of the Dirichlet type. Regarding the dynamic field, we impose the adhesion condition and which is translated by a zero speed on the walls. For the thermal field, a constant temperature on

the window and the absorber must be fixed. The other walls of the room are considered adiabatic.

D. Mesh used

The mesh used is characterized by: 118500 cells, 237955 faces, and 119456 nodes. This is the mesh that gave the most satisfaction in terms of results.

3. Results and discussions

From the data presented in Table 2, we carried out a two-dimensional numerical simulation; using the Fluent calculation code version 6.3.26.

Table 2: Temperatures for different intensities of solar radiation [1].

Solar radiation (W/m ²)	Glass temperature (K)	Absorber temperature (K)
500	314.3	329.04
550	317.36	340.65
600	326.02	346.28
650	330.18	354.66
700	333.51	358.49
750	337.29	361.38

The figure below presents the theoretical and experimental results obtained by Mathur et al [1], as

well as those obtained by the Fluent calculation code, and this for different intensities of solar radiation.

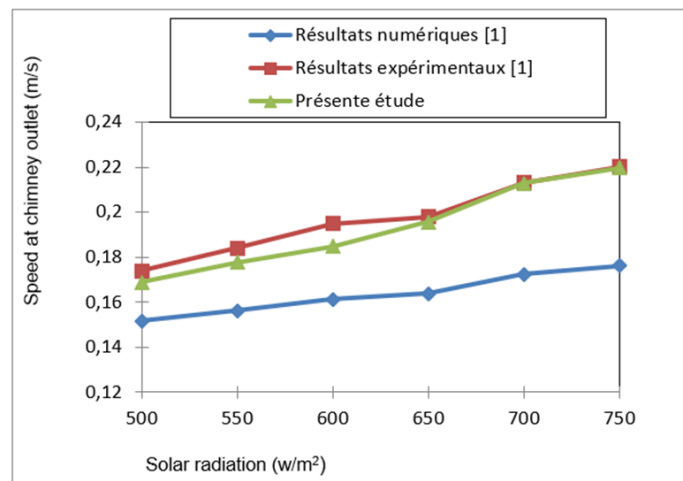


Fig.2: Velocity at the chimney outlet as a function of solar radiation

The figure shows that the air velocity at the chimney outlet is proportional to the intensity of solar radiation.

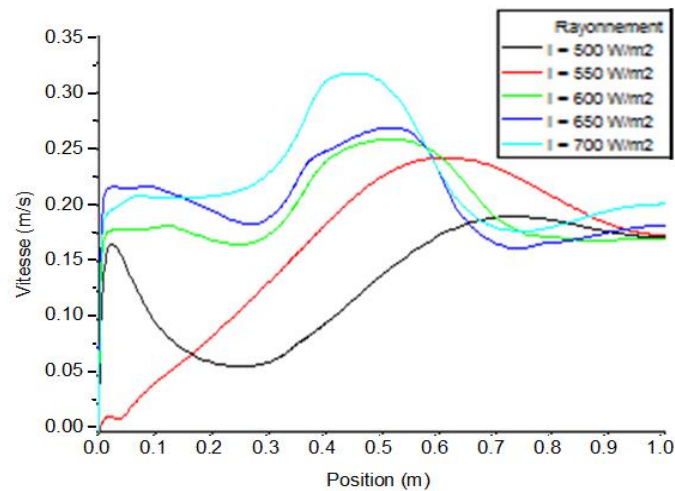


Fig. 3: Velocity profiles at mid-height of the part.

Fig. 3 shows that the maximum values are proportional to the solar radiation, and that its positions are in the middle zone of the room when the radiation intensity increases. This is due to the direction of the flow, and the attractive forces generated by the Archimedes thrust at the chimney.

a. Effect of temperature decrease at the system inlet

Fig. 4 shows the variation of the volume flow rate as a function of temperature and this for fixed solar radiation intensity equal to 700 W/m².

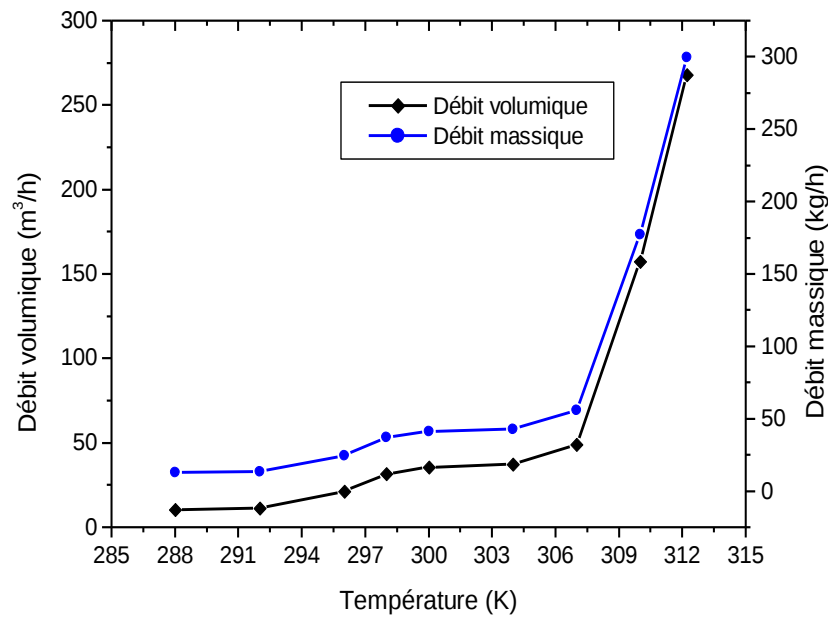
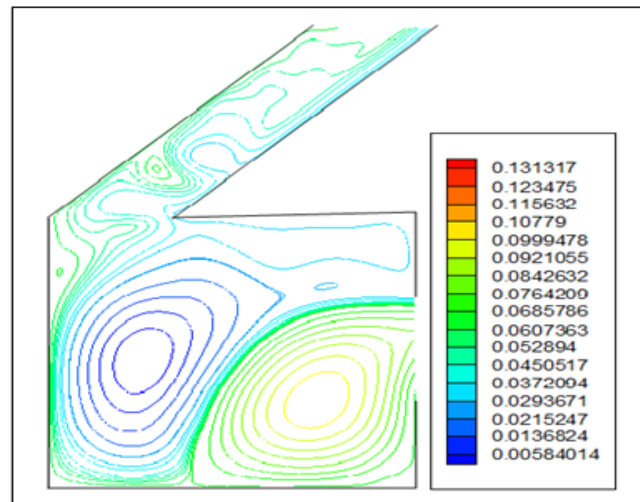


Fig. 4: Effect of reducing the room inlet temperature on the outgoing flow rate

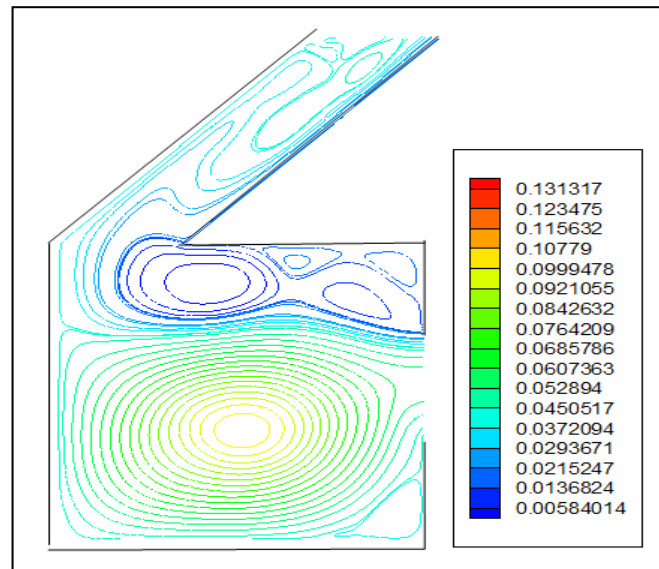
The curve presented in Fig. 4 shows the effect of the variation of the temperature at the room inlet on the air flow rate entering the room. The exhaust air flow rate decreases with the reduction of the temperature. The variation of the density is presented in the figure as the difference between the two curves.

b. Flow structure

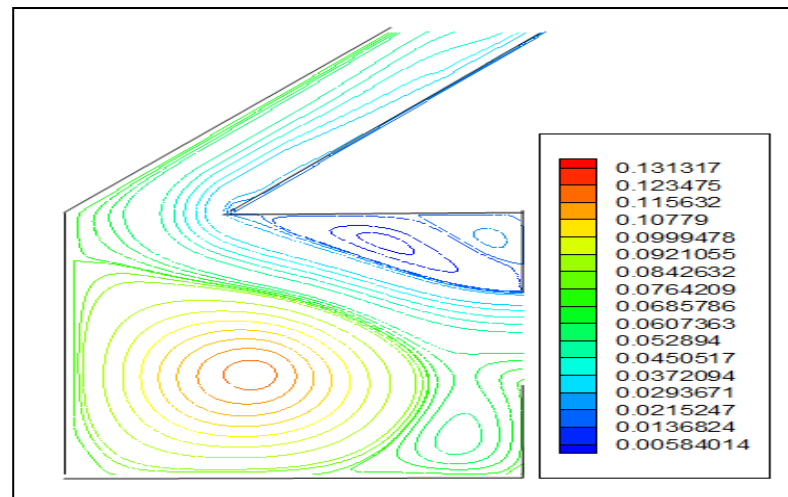
The streamlines are shown in the following figures for different room inlet temperatures.



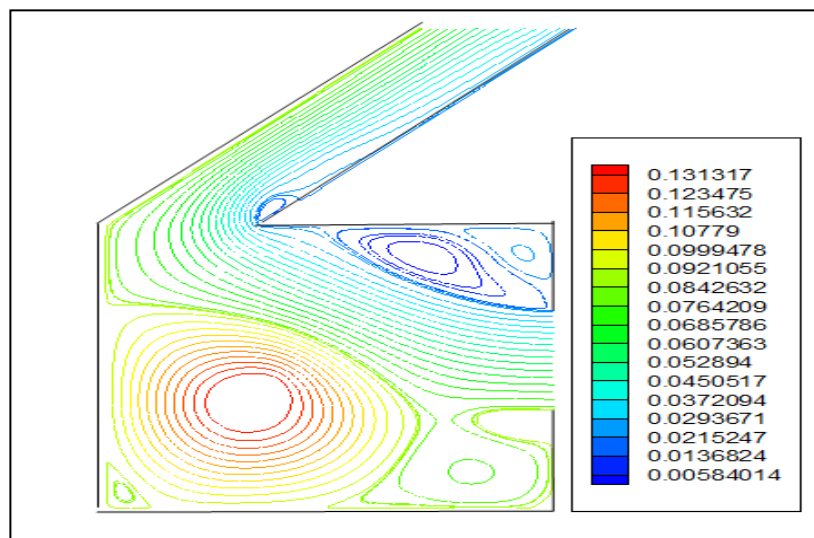
(1) T= 298 K



(1) $T = 310\text{ K}$



(2) $T = 307\text{ K}$



(4) $T = 312.2\text{ K}$

Fig. 5: Streamlines for different inlet temperatures.

For an inlet temperature of 298 K, we observe the presence of two juxtaposed vortices located in the lower part of the part, these vortices group together and cause the fluid to lose energy and consequently the air flow rate decreases.

When the inlet temperature reaches 307 K, the size of the vortex placed near the opening becomes larger. This vortex moves towards the center of the room, when the inlet temperature reaches 310 K. As for the second vortex, its size is reduced considerably and settles at the base of the chimney when the inlet temperature equals 307 K, the latter disappears in the form of parallel lines starting from the inlet of the room to the outlet of the chimney from 310 K. This reflects the increase in the flow rate of the air leaving the chimney.

Nomenclature

T :	Temperature	K
P :	Pressure	atm
Q :	Volumetric flow	m ³ /h
U :	Flow velocity	m/s
I :	Solar radiation intensity	W/m ²
K :	Turbulent kinetic energy	
a :	Thermal diffusivity	m ² /s
β:	Volumetric thermal expansion coefficient of air	K ⁻¹
ρ:	Density	kg/m ³
μ:	Dynamic viscosity	kg/s.m
ν:	Kinematic viscosity	m ² /s
α :	Tilt angle	°
ε :	Turbulent energy dissipation	
λ:	Thermal conductivity	W/m. K

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Conclusion

Natural ventilation by solar chimney has multiple advantages. It does not require fossil energy or electrical energy to operate and allows high flow rates. The flow of air in the room is linked to solar radiation. According to our study we can also conclude that:

The air speed at the outlet of the solar chimney increases as the intensity of solar radiation increases. This reflects the efficiency of the system.

The reduction in temperature when entering the room results in a reduction in the flow of air evacuated by the solar chimney.

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