EXPERIMENTAL STUDY AND SIMULATION OF AIRFLOW IN SOLAR CHIMNEYS

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Abstract

A detailed mathematical simulation and experimental investigation of airflow in solar chimneys is studied in this paper. Several experimental studies were carried out on the solar chimney; their choice depends on the parameter of the design and the thermal performances for different geometrical configurations. The experimental tests show that the field speeds in the chimney is influenced by the width of the channel and also of the angle of inclination of the chimney. Therefore, investigations have been carried out in this paper to find the effect of inclination on the performance of solar chimney in Ouargla Province, Algeria. The simulation of this problem is implemented into the commercial CFD code Fluent 6.3. 26. The conservation equations of mass, continuity and energy are solved by the Finite Volume Method. The validation of the results is presented. An good agreement between the experimental results and simulation ones is observed.

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Keywords: Solar energy - Transfer of heat - natural ventilation - solar chimney - FVM, Simulation.

1. INTRODUCTION

The natural ventilation is a passive strategy for cooling building. Efficient air ventilation and thermal comfort are of great importance in rural areas and hot climate. Natural ventilation may result from air penetration through a variety of unintentional openings in the building envelope, like openings doors, windows. Natural ventilation is one of the techniques used for conditioning buildings, and solar chimneys are systems which can contribute to improve the energy efficiency of building.
Solar chimneys are more interesting in applications requiring low and moderately temperatures, such as drying building heating. Solar chimney is renewable energy technology, which enhance natural building ventilation. It usually consists of glazing, cavity, and metallic wall that absorb solar energy.

Many researches were employed and studied the different configurations of solar chimney; some researchers have been interested in analyzing the vertical chimney, while others have been studying the inclined solar chimney. The different theoretical and experimental studies were carried out. Z. Adam et al [1] proposed a mathematical model of heat transfer in solar chimney and carried out experimental investigation of air flow in the chimney, with different inclinations and distance between heated plate and the glazing. J. Mathur et al [2] the major part of these studies relates to the determination of velocity profiles and temperature in the chimney according to air blade thickness, inclination angle. Theoretical results of the proposed model are in good agreement with the experimental ones. N.K and Bansal et al [3] developed a mathematical model for steady state flow in solar chimney consisting of conventional chimney connected to solar air collector.. J. Marti Herrero and M.R. Heras Célemin [4], proposed mathematical dynamical model to evaluate chimney energy performance with 24 cm concrete wall as storage surface for solar radiation. The results show that for 2 m height and 14.5 cm width of air channel 0.011kg/s air mass flow rate is obtained for 450W/m2. J. Mathur et all [5] studied the effect of the slope on the outgoing flow of solar chimney. The results showed that heat pulling is optimal, if the angle of inclination varies between 40° to 60° according to latitude. They carried out experimental study on small size chimney, which shows that ventilation rate increases with the increase of the ratio between absorber size and the distance between glass and absorber.

### Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>e (cm)</td>
<td>thickness (cm)</td>
</tr>
<tr>
<td>Su</td>
<td>Dynamic source terms in X directions</td>
</tr>
<tr>
<td>Sv</td>
<td>Dynamic source terms in Y directions</td>
</tr>
<tr>
<td>T\text{glazing}</td>
<td>Mean glass temperature (K)</td>
</tr>
<tr>
<td>T\text{absorber}</td>
<td>Absorber temperature (K)</td>
</tr>
<tr>
<td>T\text{ambient}</td>
<td>Ambient temperature (K)</td>
</tr>
<tr>
<td>T\text{mediums}</td>
<td>Temperature of air in channel l (K)</td>
</tr>
<tr>
<td>U, v</td>
<td>Velocity (m/s)</td>
</tr>
<tr>
<td>ρ</td>
<td>Air density (kg/m3)</td>
</tr>
<tr>
<td>μ</td>
<td>Air viscosity (m2/s)</td>
</tr>
<tr>
<td>Γ\text{T}</td>
<td>Fluid exchange coefficient of general transport</td>
</tr>
<tr>
<td>α (°)</td>
<td>Angle of inclination with respect to horizontal</td>
</tr>
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</table>
2. Experimental Part

Chimney prototype is schematized in figure 1. We summarize its main components as follows:
- A case made of iron sheet, dimensions 2 x 1 m, opened on the side exposed to solar radiation. On the lateral sides, there are openings for the entry and the exit of air flow.
- Only one transparent glass cover with 5 mm thickness.
- A thin absorber plate made of galvanized steel painted in black with 0.4 mm thickness.
- A thin back galvanized steel plate placed on insulator with 0.4 mm thickness.
- The distance between transparent cover and absorber plate is: 10 mm, 20 mm, and 30 mm.
- The back insulation is ensured thanks to two polystyrene sheets, 40 mm and 20 mm thickness.

Experimental installation includes:
- Measurement of solar radiation
- Measurement of ambient air temperature, air temperature inside chimney, and temperatures of absorber and pane.
- Measurement of air velocity at chimney outlet.

![Figure 1: Experimental apparatus](image)

In this experimental study of solar chimney, we have carried out several tests. Measurements are carried out with Ouargla site (VPRS laboratory at Kasdi Merbah University in Ouargla city, Algeria). In order to estimate the effectiveness of the solar chimney, we schedule tests during clear climate period. At each day, the tests are taken between 9:00 h until 16:00 h with thirty minutes step (30 min).

Solar chimney is built so that the majority of variables can be modified during the experiments such as air blade thickness and chimney slope.

Measurements are taken when chimney reached thermal stability with their environment. Thermocouples are used to measure absorber temperature, air temperature, as well as room temperature. At chimney outlet, air velocities are measured with hot wire anemometer.

<table>
<thead>
<tr>
<th>(e) (cm)</th>
<th>10</th>
<th>20</th>
<th>30</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\alpha) (°)</td>
<td>30</td>
<td>•</td>
<td>•</td>
</tr>
<tr>
<td>45</td>
<td>•</td>
<td>•</td>
<td>•</td>
</tr>
</tbody>
</table>
3. Simulation Part

3.1 Governing equations

Figure 2 shows the scheme of solar chimney geometry. The chimney is titled to southern direction. Absorber and pane are maintained at constant temperature.

![Figure 2. Scheme of chimney geometry](image)

The analysis of thermo-aerodynamics phenomena requires great number of parameters such as chimney dimensions, material characteristics and flow physical parameters. So, in order to reduce computing time and model complexity, some assumptions are adopted:

- Two-dimensional model.
- Unsteady flow.
- Air flow is turbulent.
- Fluid is Newtonian and incompressible.
- Absorber and pane are parallel.
- Air temperature at drainage canal inlet is equal to room temperature.

Conservation equations are expressed by using Boussinesq approximation [8] which imposes constant values for all thermo physical properties except for the density in buoyancy force. It is also supposed that viscous dissipation is neglected. For constant flow, equations of continuity, energy and momentum are written in the following form [6, 7]:

Continuity:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho v)}{\partial y} = 0
\]

Momentum equation:

\[
\frac{\partial (\rho u)}{\partial x} + \frac{\partial (\rho u v)}{\partial y} = \frac{\partial}{\partial x} \left( \mu \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial u}{\partial y} \right) + S_u
\]

\[
\frac{\partial (\rho u v)}{\partial x} + \frac{\partial (\rho v v)}{\partial y} = \frac{\partial}{\partial x} \left( \mu \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu \frac{\partial v}{\partial y} \right) + S_v
\]

Energy equation:

\[
\frac{\partial (\rho u T)}{\partial x} + \frac{\partial (\rho v T)}{\partial y} = \frac{\partial}{\partial x} \left( \Gamma_r \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \Gamma_r \frac{\partial T}{\partial y} \right) + S_T
\]
Where X and Y are Cartesian coordinates, $\rho$ is air density (kg/m$^3$), $S_u$ and $S_v$ are dynamic source terms respectively in X and Y directions, $\mu$ is air viscosity, $\Gamma_r$ is fluid exchange coefficient of general transport at Ra above 109. In present study, two equations turbulent model is used. Governing equations become temporally averaged equations. The parameters $\mu$ and $\Gamma_r$ are replaced by their effective values $\mu_{\text{eff}}$ and $\Gamma_{r\text{eff}}$ given by turbulence model.

3.2 Boundary conditions

Pressure at inlet and outlet solar chimney (Dirichlet conditions) is equal to atmospheric pressure. Temperatures on pane and absorber (Dirichlet conditions) are fixed at constant values $T_{\text{glazing}}$ and $T_{\text{absorber}}$.

3.3 Numerical procedures

The governing equations are solved by using a general-purpose computational fluid dynamic code which is based on finite volumes method. For mesh, irregular grid numbers (300×50) are used.

The $K$-$\varepsilon$ standard model implies the solution of two additional partial derivative equations for the turbulent kinetic energy ($K$) and its dissipation rate $\varepsilon$ [9].

Constants values $C_1$, $C_2$, $C_\mu$, $\sigma$ are respectively 0.09, 1.44, 1.92 and 1.0 [9].

4. Results and Discussions

4.1. Experimental results

Figure 3 shows the variation of daily solar radiation according to time. Solar radiation curve takes bell cheap curve; it passes from 584 W/m$^2$ at 9:00 h until 789 W/m$^2$ between 12:00 h and 13:00 h.

![Graph showing solar radiation variation](image)

Figure 3. Variation of solar radiation with time at inclination $\alpha=45^\circ$ and air blade thickness $e=20$ cm.

Between pane and absorber, solar radiations create a temperature gradient which is the driving force in solar chimney. Figure 4 shows the difference in significant temperature corresponding to solar intensity.

There is a linear increase in the whole temperature values, the maximum absorber temperature varies as $T_{\text{absorber}}=134,381.0.1376$ while the average temperature which correspond to pane maximum temperature varies like $T_{\text{glazing}}=18410.1811$ due to absorber nature which absorb and store thermal energy. This energy absorption increases the absorber temperature; the major part of this energy is consumed by air acceleration in solar chimney.
Fig. 4. Variation of solar radiation with time at inclination $\alpha = 45^\circ$ and air gap thickness $e = 20$ cm.

Figure 5. Variation of the solar radiation with time (traced by software PVSYS'T4_37).

Figure 6 shows a temperature increase during the morning until 13:00 h. The increase is due to great density of incident solar flow in this period. After midday, there is progressive reduction in the absorber temperature and radiation intensity. It is also noticed that pane temperature and air in solar chimney ($T_{\text{medium}}$) remains almost constant between 12:00 h and 14:00 h and decreases more slowly after 14:00. In spite of solar radiation intensity decreases and this phenomenon appears thanks to heat released by absorber.
Figure 6. Variation of different temperatures and solar radiation intensity according to time for clear day.

Figure 7 and 8 show the variation of air flow (m$^3$/h) according to change in absorber slope. We note that as distance between absorber and pane increases air flow increases in solar chimney. It is noticed that air flow corresponding to angle 45° is higher than those to angle 30°. For optimal effectiveness, sun rays must be perpendicular to solar chimney. In hot season, the Sun does not go up very high in the sky; the chimneys must be tilted at optimal slope (45°). The slope of solar chimney is high for a maximum flow value and there is more effective natural ventilation.

Figure 7. Variation of air flow with time inclination angle $\alpha=45^\circ$ and air blade thickness $e=30$, $e=20$ cm and $e=10$ cm.
Figure.8. Variation of air flow with time for inclination angle $\alpha=30^\circ$ and air blade thickness $e=30$, $e=20$ cm and $e=10$ cm.

4.2 Validation of numerical results

The first step consists in validating our numerical results by comparing them with those obtained by the experimentation. Figure IV.9 shows the variation of air flow according to the solar radiation. We observe a good agreement between the two curves.

Figure.9. Experimental and simulation results of air flow according to solar intensity for inclination angle $\alpha=30^\circ$ and air blade thickness $e=20$ cm
4.3. Velocity profile

Velocity profile is presented in figure (10), is mainly generated and preserved by buoyancy forces. It is observed that velocity is higher along hot walls (the absorber), but far away from the wall velocity decreases. We can also note that maximum velocity (in red) is increasingly close to vertical walls when increasing Rayleigh number \((Ra = 2.85 \times 10^9)\). Also, when chimney width increases air velocity decreases.

Figure 10. Dynamic velocity profile for inclination angle \(\alpha=45^\circ\) and air blade thickness \(e=30\text{cm}\), \(e=20\text{cm}\) and \(e=10\text{cm}\).

4.5. Temperature contours

Temperature contours with different inclination angle and air blade thickness are presented in figure (11). Heat produced by solar radiation and located in solar chimney is transferred by convection upwards in the middle of the chimney. It is what explains that temperature is relatively high at absorber neighboring.

We note that temperature values lay between high value corresponding to absorber temperature and low value corresponding to pane temperature.

Figure 11. Dynamic temperature contours for inclination angle \(\alpha=45^\circ\) and air blade thickness \(e=30\text{cm}\), \(e=20\text{cm}\), \(e=10\text{cm}\).
5. Conclusion

An experimental and numerical study is undertaken for a tilted solar chimney. Experimental study under various chimney slopes (30° and 45°) and air thickness located between absorber and pane (e=10cm, 20cm and 30cm), leads to the following conclusions:
- The variation in temperature between the absorber and the pane varies according to incident solar flow.
- Adopted design allows to obtain rather high air flow at chimney outlet, which is interesting to exploit them in natural ventilation
- Numerical simulation allows determining temperature contours and velocity profile inside solar chimney for various chimney inclination with Rayleigh number Ra=10^9. By using Boussinesq approximations, main results are summarized as:
  - Variation of air blade thickness plays a very important effect to increases significantly air flow.
  - Optimal thermal pulling is reached at chimney inclination angle 45°.

6. References