CFD Analysis of Solar Chimney using Perforated Plates

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Abstract— The solar chimney is a natural ventilation technique that has the potential to save energy use in buildings as well as maintain comfortable indoor quality. This research aims to study inclined and vertical solar chimney by incorporating perforated plates using CFD technique. The location of perforated plates and wall is varied and its effect on air flow is studied for natural ventilation. A two-dimensional symmetric model using the RNG (Re-Normalization Group) k–ε turbulence closure is simulated. The discrete ordinates non-grey radiation model is used to implement the radiative-transfer equation. To simulate solar irradiation, the solar ray-tracing algorithm is employed. The software used for modeling is Creo 2.0 and for analysis ANSYS CFX is used.

Key words: Solar Chimney, Perforated Plate, Ansys CFX

I. INTRODUCTION

The most potent, dependable, and sustainable source of energy in our solar system is the sun, for which there is great interest with harnessing its power both efficiently and economically. An innovative system that is receiving more and more attention is the solar updraft tower, or solar chimney. A solar chimney – often referred to as a thermal chimney – is a way of improving the natural ventilation of buildings by using convection of air heated by passive solar energy [1]. A simple description of a solar chimney is that of a vertical shaft utilizing solar energy to enhance the natural stack ventilation through a building.

Over the past couple of decades, computer simulation has become much more prevalent. Current CFD software’s are much more accurate than they once were and are is becoming more user-friendly, but still the mesh generation for a model can be difficult and requires a great deal of experience. These software’s can be used over and over again. Also, many different test cases can be run to determine flying qualities in various situations. There are also several different programs that are readily available that can produce highly reliable results. With the use of CFD, the cost and time required for prototyping has reduced drastically over the years, thereby accelerating the design and development of modern aircrafts.

The process of heating a space using a solar chimney is fairly simple. When the solar radiation hits the side of the chimney, the column of air inside the chimney is heated. If the top exterior vents of the chimney are closed, the heated air is forced back into the living space. This provides a type of convective air cooling. As the air cools in the room it is pulled back into the solar chimney, heating once again. When solar chimneys are used for heating, they operate similarly to Trombe walls. Cooling a space using a solar chimney is slightly different than cooling using a Trombe wall. Since a roof overhand cannot be installed in addition to a solar chimney, two additional vents are present. The first vent has been mentioned, the one at the top of the chimney. The second is at the opposite end of the building, providing an opening between the building and outside air to allow for ventilation. When solar radiation hits the side of the chimney, the column of air inside the chimney is again heated. The vent at the top of the chimney is kept open so this heated air is not trapped. This heated air is pulled up and out of the chimney, pulling new air in from the outside and creating a sort of “draft” that provides cool, fresh air into the building.

II. LITERATURE REVIEW

In general, there are various different configurations of solar chimney going by many names like thermal chimney and roof solar collector. However, to be considered a solar chimney, the basic principle is to employ the sun to produce an updraft of air along a channel. With increasing interests in solar chimney research, various theoretical, experimental and computational researches across different weather conditions were examined [2,3].

Ohanessian and Charters [4] examined the effects of glazing and wall thickness on the modified Trombe-Michel wall during the winter in Melbourne, Australia using finite difference simulation. Around the same period, Akbarzadeh et al. [5] conducted experiments with a modified Trombe wall at a building roof in the University of Melbourne, Australia. Similarly, Das and Kumar [6] experimented with a flat-plate solar chimney employed to dry agricultural products.

Awbi [7] gave an introduction of the various methods of natural ventilation and examined the effects of wind and solar-induced ventilation theoretically using vertical and inclined solar chimneys. Results showed that the influence of wind was greater than the stack effect while the inclined solar chimney performed better due to its greater exposed surface area.

Aboulnaga [8] carried out theoretical analysis on a common resident building in Al-Ain city, UAE. The solar chimney’s depth and inclination angles were varied. Results gave an optimum inclination angle of 35° and a solar chimney depth of 0.20 m.

Khedari et al. [9] examined the effects of the modified Trombe wall in a room. Results showed that a

![Fig. 1: Solar Chimney](image-url)
bigger air gap or a darker colour on the wall induced more airflow.

Hirunlabh et al. [10] studied a south-facing metallic solar wall (MSW) incorporated in a house. Six experimental points were placed within the house at 1.00 m above the ground. Results showed that temperature within the MSW increased with wall height and decreased with the air gap’s depth. In addition, mass flowrate increased with increasing stack height and solar chimney’s depth.

Afonso and Oliveira [11] compared the differences in air change rate and volume flowrate between conventional and solar chimneys under weather conditions in Lisbon, Portugal. Measurement showed that a higher and wider chimney improved volume flowrate although the width is more significant.

Khedari et al. [12] conducted experiments on a school building installed with two roof solar chimneys, a modified Trombe wall, a Trombe wall and a metallic solar wall to determine their combined effects. 27 different positions were used to obtain the interior air temperatures and speeds.

Spencer et al. [13] performed scaled experiments with a solar chimney model using a 4 wt % aqueous saline solution and hydrogen bubbles to simulate the thermal stack due to solar irradiance. Results showed that the solar chimney’s optimal width is independent from solar irradiance but increased with stack height and the opening area. Furthermore, increasing the opening area of the interior’s inlet and solar chimney’s inlet increased the volume flow rate although the influence of the solar chimney’s inlet area is more significant.

III. ANALYSIS OF SOLAR CHIMNEY

The present work is concerned with carrying out two-dimensional simulations on a solar roof chimney, through which air flows. The inlet and outlet is defined of length.
The domain is defined as fluid. Reference pressure is set to 1 atm. Two variable k-epsilon turbulence model is set for analysis and inlet velocity is varied. Fluid is taken as air. Radiation model is set. Different domains i.e. absorber plate, glass, insulation is defined. For air domain air inlet, air outlet and symmetry boundary condition is defined similarly for glass domain heat flux and symmetry is defined. Interface wall between air absorber and air glass interface is generated with conservative interface flux as heat transfer. RMS residual values are set to 1e-4 and maximum iterations are set to 200 as.

The upwind scheme “second order upwind scheme” was selected for momentum and energy equations. In order to couple velocity and pressure, the SIMPLE algorithm was applied. Temporal discretization was achieved using the solution method “Implicit integration”. Standard scheme was utilized to interpolate pressure and the relaxation factors for pressure, density, body forces, momentum and energy were maintained at 0.3, 1, 1, 0.7 and 1 respectively. A low convergence criteria of 10^-4 was chosen for energy equation and 10^-3 was chosen for continuity and velocity equation for the residuals in order to accurately predict different parameters. The solution was initialized by computing from the inlet using “Standard Initialization” option. After the completion of these settings, the iteration procedure was initiated by clicking on “Run Calculation” button.

IV. RESULTS & DISCUSSION
The analysis has been carried out using ANSYS 14 for inclined solar chimney and vertical solar chimney without using perforated plate and with perforated plate. The inclination angle is set to 60° for 1° case of analysis.
Fig. 12: Velocity Vectors For 60 Degree Inclined Chimney with Perforated Plate

Fig. 13: Eddy Viscosity for 60 Degree Inclined Chimney with Perforated Plate

The temperatures contours, velocity vectors and eddy viscosity contours are plotted in figure 11, figure 12 and figure 13 respectively. Maximum temperature in room is near periphery of walls which minimum is across air flow zone shown by dark blue colour.

Table 1: Various Parameters of Inclined Chimney with Perforated Plate

<table>
<thead>
<tr>
<th>LOCATION (MM)</th>
<th>AVERAGE TEMP(°K)</th>
<th>EXIT AIR VELOCITY (M/SEC)</th>
<th>RADIATION INTENSITY [W m^-2 sr^-1]</th>
<th>PRESSURE (Pa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>210</td>
<td>300.89</td>
<td>.112369</td>
<td>169.29</td>
<td>.01195</td>
</tr>
<tr>
<td>185</td>
<td>300.84</td>
<td>.113576</td>
<td>167.99</td>
<td>.01186</td>
</tr>
<tr>
<td>160</td>
<td>300.81</td>
<td>.112735</td>
<td>167.40</td>
<td>.01187</td>
</tr>
<tr>
<td>133</td>
<td>300.74</td>
<td>.115387</td>
<td>164.63</td>
<td>.01188</td>
</tr>
</tbody>
</table>

Table 1 above shows the variation in exit air velocity, average radiation intensity and average temperature for different locations of perforated plate. The same is depicted by bar graphs as shown in fig 14 for average temperature. As perforated plate moves towards right average temperature decreases though the variation is less.

Fig. 14: Temperature Graph For 60 Degree Inclined Chimney with Perforated Plate

Fig. 15: Radiation Intensity of 60 Degree Inclined Chimney with Perforated Plate

The second design is analyzed with vertical chimney design with varying wall location from left face as discussed in further section. The wall location taken as 150mm from left, 200mm from left and 250mm from left face.

Fig. 16: Velocity Vector for Vertical Chimney without Perforated Plate

The velocity vectors as shown in fig 16 above shows the higher magnitude towards exit section as shown by red and yellow color contours. The velocity on other zone is lower shown by dark blue color while velocity is high across flow zone.
After conducting CFD simulation on vertical chimney without perforated plates with varying wall location, average temperature of room, air exit velocity and radiation intensity are found.

The temperature contour above in fig 18 shows higher magnitude of temperature near walls shown by light blue color, red and yellow color near wall absorbing direct sunlight. The remaining portion shows lower temperature as shown by dark blue color.

<table>
<thead>
<tr>
<th>WALL LOCATION (m)</th>
<th>AVERAGE TEMP (K)</th>
<th>AIR EXIT VELOCITY (m/sec)</th>
<th>RADIATION INTENSITY [W m²-2 sr⁻¹]</th>
</tr>
</thead>
<tbody>
<tr>
<td>150</td>
<td>301.98</td>
<td>.235</td>
<td>198.97</td>
</tr>
<tr>
<td>200</td>
<td>302.14</td>
<td>.174</td>
<td>204.13</td>
</tr>
<tr>
<td>250</td>
<td>302.22</td>
<td>.140</td>
<td>206.55</td>
</tr>
</tbody>
</table>

Table 2: Vertical Chimney without Perforated Plate & Varying Wall Location

Further analysis were conducted using CFD technique on vertical chimney with perforated plates as discussed in next section. The perforated plate location was kept at 50mm from left face and 75mm from left face.
As it can be noticed from air velocity contour in fig 22 highest air velocity is achieved on regions between perforated wall and absorber wall.

With inclusion of perforated plates the velocity vector shows the magnitude is higher between wall and perforated plate shown by red and yellow color contours in fig 23 above.

From average temperature and radiation intensity graph it can be observed that perforated plate placed at 50mm from left face shows higher temperature and intensity which justifies the use of perforated plate.

V. CONCLUSION

The CFD analysis of solar chimney is conducted using ANSYS CFX for 600 chimney inclinations initially without using perforated plates and with perforated plates. The average room temperature and air flow rate along with radiation intensity is examined. All the analysis were conducted at 650 W/m² heat flux. The average temperature of room dropped to about 130°C by using perforated plate and hence can justify the application of perforated plate to achieve better cooling and significant improvement in airflow rate is also achieved. The average radiation intensity in room decreases on changing location of perforated plate from right to left. For vertical chimneys without perforated plates shows lower average temperature of room compared with perforated plates. Radiation intensity changes by changing wall location which gradually increases as the wall moves from left to right. Air flow rate is found to be maximum when wall location is 150mm from left face and maintaining the average temperature of room to lowest at 301K. The use of perforated plates in vertical chimney leads to higher average temperature compared to without perforated and flow rate is also less as compared to design without perforated plate.

REFERENCES


