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Enhancement of Natural Ventilation using Solar Chimney: A Numerical Investigation

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Abstract**—** *Rural areas have shortage of electricity, so natural ventilation becomes necessary. Ventilation through solar chimney harnesses solar energy as energy source and can be installed in rural buildings for improvement of air circulation. Rate of ventilation of a solar chimney for natural ventilation was investigated for both Horizontal type and Vertical type. Ventilation rate greatly depends on the temperature gradient of the room. The current work presents the comparative analysis of a room apartment with solar chimney of both types attached to them. In this study, a reduced scale Chimney of Horizontal and Vertical design is modelled through CFD to investigate the improvement of Natural Ventilation. Two different parameters have been considered for current study viz. Outlet Velocity and Temperature of Absorber plate.*

Keywords— Solar Chimney, Natural Ventilation, Enhancement, Flow Velocity.

Nomenclature

L	*Length of Duct (m)*
W	*Width of Duct (m)*
H	*Height of Duct (m)*
m	*Mass flow rate (kg/s)*
T_{in}	*Inlet Temperature (K)*
T_{out}	*Outlet Temperature (K)*
V_{in}	*Inlet Velocity (m/s)*
V_{out}	*Outlet Velocity(m/s)*
R	*Room*
SC	*Solar Chimney*
R-100	*Height of 100 mm in Room*
R-300	*Height of 300 mm in Room*
R-500	*Height of 500 mm in Room*
R-700	*Height of 700 mm in Room*
R-900	*Height of 900 mm in Room*
SC-100	*Height of 100 mm in Solar Chimney*
SC-300	*Height of 300 mm in Solar Chimney*
SC-500	*Height of 500 mm in Solar Chimney*
SC-700	*Height of 700 mm in Solar Chimney*
SC-900	*Height of 900 mm in Solar Chimney*

I. INTRODUCTION

Most of the energy derived from the various system found on earth originate from sun. Sun emits massive amount of electromagnetic radiation into space. The mean distance between Sun and Earth is 1.50×10^8 km. At surface of the sun the intensity of solar radiation is 6.33×10^7 W/m^2. It subtends an angle of only 32 minutes at the earth's surface. Solar radiation that reaches at surface of the earth is quite differs in both amount and character from the radiation at the top of atmosphere. Some amount of the radiation is reflected back into the atmosphere by clouds. Then the radiation entering the atmosphere is absorbed by molecules and dust particle present in air. U.V. rays are absorbed by oxygen (O_3) Ozone and some of the infrared energy is absorbed by water vapour and CO_2. Some of the radiations is scattered by dust particle molecule and droplet in clouds and atmosphere. Solar radiation that reaches the ground directly from sun without being absorbed or scattered is called Direct Radiation or Beam Radiation. Solar radiation obtained from sun after its direction has been hanged by reflection and scattering is diffuse radiation.

The total solar radiation energy received on horizontal surface of unit area on the ground in unit time. Position of Sun directly overhead is Zenith Position. Zenith angle is the angle between the beam from the sun and vertical. Solar altitude is the angle between the beam from sun and horizontal.

1.1 ROLE OF SOLAR ENERGY IN WIND FORMATION

The radiation continuously showered on earth by sun represents the most basic and inexhaustible source of all forms of energy- conventional and non-conventional, renewable and non-renewable the only exception is nuclear energy. The heat from sun causes continuous evaporation of water from oceans, lakes, rivers, plant and soil. The sun also heats up the air due to difference in nature of terrains, altitudes and distances from the sun, this heating is not uniform. The air acquires different temperature horizontally as well as vertically. This leads to wind- slow fast, providing wind energy. Wind also plays important role in solar chimney and is also considered as an important parameter in natural ventilation with solar

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chimney. The wind flows over the earth surface is broadly classified as Global winds and Local Winds.

Global Winds- the forces which determines the global wind are in two form.

i. Primary Force: These forces are developed because of differential heating of earth's surface at equator and polar region. There is net heat gain in tropical region due to solar radiation whereas in polar region there is net heat loss. This causes transportation of air from tropic region towards pole.

ii. Secondly, the causes of wind is spinning of earth about its axis.

Coriolis force: Responsible for generation of wind current towards west. Between 30°N to 30°S heated air at equator rises and is replaced by cooler air coming from North to South. This flow of air pattern is Hadley circulation.

The western winds are found between 30°N to 70°S these winds form circulation transferring cool air southward and warm air northward. This pattern is Rossby calculation.

1.2 SOLAR CHIMNEY

Solar chimney employs convective current to draw air out of a building. Ventilation effect in the structure can be created by drawing air into the house due to the creation of warm or hot zone with an exhaust outlet.

Sun rooms can be utilized to achieve this function. Air can be drawn into the living space by connecting the north side windows with the lower vents of living space and any side operable windows must be closed and thermal mass wall in the sunroom must be shaded.

The construction of narrow configuration of thermal chimney can be done by using heated black metal absorber inside a glazing that can withstand high temperatures and can be isolated. The chimney must terminate above the roof level. Thermal chimney effects be integrated into the house with open stairwells.

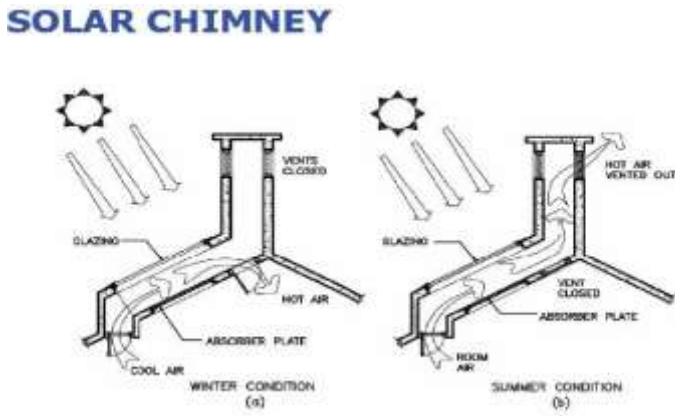

Fig.1.1 : Components of Solar Air Heater[6]

A solar chimney consists of a glazed solar collector inside which the air gets heated by the day solar energy, and with a vertical shaft as chimney to enhance the ventilation and cooling of the building.

A solar chimney is an example of natural passive method, which harnesses solar energy to create buoyancy effect which helps in generating air flow inside air channel. Solar chimney system is extensively utilized in drying of crops, wood or grains heating and cooling applications. Lots of works and studies have been done in the area of solar chimney which is evident from literature which is discussed in Chapter 2. The heating can be supplied by use of a fan to direct the heated air into the building. Thus, Outside temperature is the key factor in the efficiency of the chimney. Primary studies on the solar chimneys prove that even cloudy days are capable of creating chilling effect by warming the air. Also, the local climate conditions should be considered to optimize the thermal comfort since solar chimney might need another type of heating/cooling systems.

Principle of the solar chimney contains three essential elements as follows:

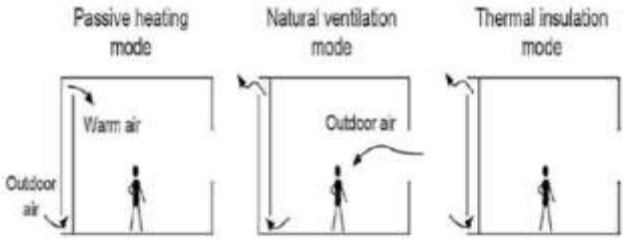

Fig.1.2 : Components of Solar Chimney

II. LITERATURE REVIEW

Wei et al [1] studied about the performance of ventilation when the solar chimney are connected in series and integrated with building. Both the physical and mathematical model were set up, and the effects of sizes on ventilation performance were analysed by RNG *k-e* model and enhanced wall unction method using a CFD software and concluded that performance of ventilation of solar chimney which are connected in consisting of an inclined section on roof and vertical section, the velocity decreased after the first increase with chimney channel width. The optimal ratio of length to width was found to be 12:1. The improvement of fluid flow as well as increase in flow rate can be achieved by decreasing the inclined angle of second floor chimney inlet. They found that the optimum angle of inclination was 4°. The ventilation rate is decreased inside the chimney increases with length ratio of the inclined section to vertical section. These are indicating that the vertical section height should be maximum to increase the flow rate inside the chimney as well as to optimize the chimney ventilation performance. The ventilation performance was enhanced with the increase of total chimney length.

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Christine Walker et.al [2] examined on a building model of reduced scale in which air is used as working fluid for natural ventilation through buoyancy effect analysed and it is experimentally found using the scaled model for common natural ventilation building, which is connected to central atrium of open office floor plans. The parameters of the scaled building model's experiments thus were used as inputs into CFD (computational Fluid Dynamics) simulation model to compare predicted and measured airflow patterns, temperatures and velocity distribution in scale building model.

Shiv Lal et.al. [3] Studied about solar chimney performance which are used in Power generation in warm and steppe climate of Kota, Rajasthan. The study was based on Computational Fluid Dynamics (CFD) and mathematical formulas. The specific parameters energetic and exegetic efficiencies are calculated by CFD modelling. They concluded that the high rise chimney and a lot of collector area required for MW power generation and it is feasible solution for sustainable development. They observed that the velocity of air is 12.2m/s and the temperature of air is 42.4 ^{0}C at 1200h and recorded maximum solar radiation of 820W/m^2 at 1400h. They found that the temperature of absorber plate is 4^{0}C to 6^{0}C higher than the atmospheric temperature of air. At 1200h the high energy is calculated by 3.5% and it is reduced in morning and evening time. The exergy efficiency is also observed about low of 8%. The aim of this study was based on the power generation so the turbine is installed at the point where maximum velocity is obtained by the simulation software. The performance of the chimney was based on the parameters height of chimney, inlet temperature and solar radiations. The diameter of the opening of chimney is taken very low as 0.20 m and generated low velocity so it produced small power and it can be used as small power plant.

Mathur et al [4] conducted an experiment to investigate the increment in ventilation rate increased with the ratio of absorber height to gap between glass and absorber. They setup a small size solar chimney to conduct the experiment and their calculations are based on mathematical approach. The parameters are taken of nine different combination of air gap between glass and absorber plate and the height of the absorber. It was found that the highest rate of ventilation of 5.6 Air Changes per hour in the room of 27 m^3 at solar radiation of 700 W/m^2 with the ratio between absorber height and air gap of 2.83 for a 1 m chimney height. So on the basis of experiment they finally concluded that in hot climatic conditions, when windows are kept closed /covered for preventing direct entry of solar heat, concept of solar chimney can be utilized by making minor modification to existing windows.

Rakesh Khanal et al. [5] performed an experiment with an inclined solar chimney model of passive wall with constant heat flux on absorber plate. The performance of the design has been evaluated for the range of 100 W/m^2 to 500 W/m^2 of heat flux with a constant air gap of 10 cm and the inclination angle of the passive wall was varying between 0 to 6 degrees. They found that the angle of inclination is not provide an influenced effect on the distribution of temperature across the gap width and along the height of chimney. The experimental results show that the inclined passive wall solar chimney provide the sufficient ventilation for a room of 27m^3 volume with absorber height of 70 cm and 10 cm air gap at an angle of 6^0 at an input heat flux of 500 W/m^2 based on ASHREA standard. The present design of inclined passive wall solar chimney has influenced improvement to achieve the maximum ventilation rate in comparison with other conventional chimney design.

Somaye Asadi et al [6] studied on a solar chimney to investigate the performance of solar chimney which are based on its layout in southern, west-southern and east southern part of the building. The performance of seven models are examined by simulated models which are performed on energy plus simulation software. These seven models are installed in different part of a seven story building. Their results are based on the only two parameters which are building layout and the materials of the walls and glasses. They found that the chimney which was installed in east southern part has maximum ventilation rate with compare to others and every solar chimney provides the necessary ventilation for space which are attached to it. The results was based on the 24 hours model and solar radiation through simulation.

De Carli et.al [7] context a numerical model able to perform the detailed simulation of the dynamic behaviour of water based surface embedded heating and cooling systems developed by authors is presented. To perform validation the test room was subjected to heating/cooling load profiles aimed to simulate different climatic conditions.

The conclusion made was when comfort conditions are achieved, the indoor parameters are close to each other and therefore small differences between the surface temperatures and air and operative temperatures are present. This explains why the calculations based on fixed or variable heat exchange coefficients do not differ in terms of calculated operative temperatures compared to the measured values.

III. NUMERICAL MODELLING

A reduced scale air model is developed for solar chimney model analysis. All major investigations are done using commercial CFD software ANSYS FLUENT. The reason behind the CFD application is the cost effective for analysis. In present study, Two designs viz. Horizontal and

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Vertical Chimney have been fabricated to investigate the enhancement of Natural Ventilation.

3.1. COMPUTATIONAL MODEL

Ansys fluent software is selected for simulation of solar chimney model. The main reason is recent published research paper on solar chimney power plant[3]. Ansys Fluent is most widely accepted commercial software for natural ventilation or buoyancy driven modelling.

Thickness of wooden walls is neglected in computational model due to virtual thickness option available in Ansys fluent software.

Simulations are carried out under unsteady state conditions as the ambient solar irradiance as well as the air temperature and air speed within the solar chimney model from experiments data recorded in test facility are found to be fairly proper for whole day, only morning data is have more error than afternoon data. These equations are converted into their integral forms and solved using the finite volume method. In addition, the evaluation of the gradients and derivatives are carried out using the least square cell-based evaluation method since the flow solution is solved on unstructured meshes.

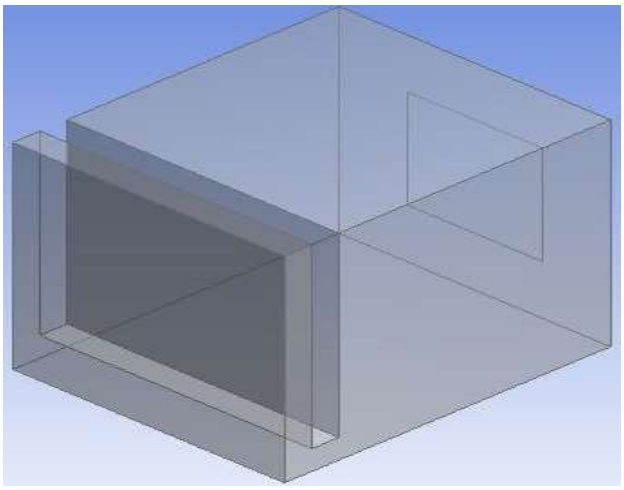

Fig.3.1 : CAD Geometry of Vertical Solar Chimney

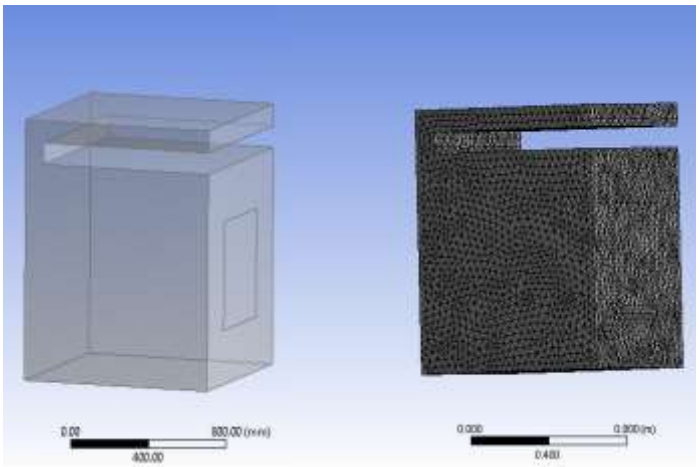

Fig.3.2 : CAD Geometry & Meshing of Horizontal Solar Chimney

3.2. SOLVER SETTING

The buoyancy of air is modelled using the Boussinesq approximation as the solar chimney stack effect is natural convection under small change in air temperature. The computational model considers density to be constant except for the buoyancy term in the momentum equation. From Equation 4-3, the gravitational acceleration is defined as 9.81m/s in the negative y-direction while the density is specified as 1.177Kg/m^3 at an operating temperature of 27^{o}C.

$$(\rho - \rho_o)g = -\rho_o.\beta(T - T_O).g$$

Where $T = 300k$

$\rho_0 = 1.177\ kgm^{-2}$

$\beta = 3.1 * 10^{-3}k^{-1}$

Equation of Boussinesq Model

In Solver, Inlet and Outlet was taken as Pressure Inlet and Outlet. Glass was taken as Semi Transparent Wall. Solar Load Calculator was used to specify the value of Solar Radiation at Absorber Plate.

IV. RESULTS AND DISCUSSION

In present study only vertical solar chimney is fabricated but in CFD simulation one special case is also designed for vertical solar chimney. In present section comparison is made between these two chimneys for one day full simulation basis for whole year. Figure 4.3 and figure 4.2 show line diagram of both designs used for CFD simulation.

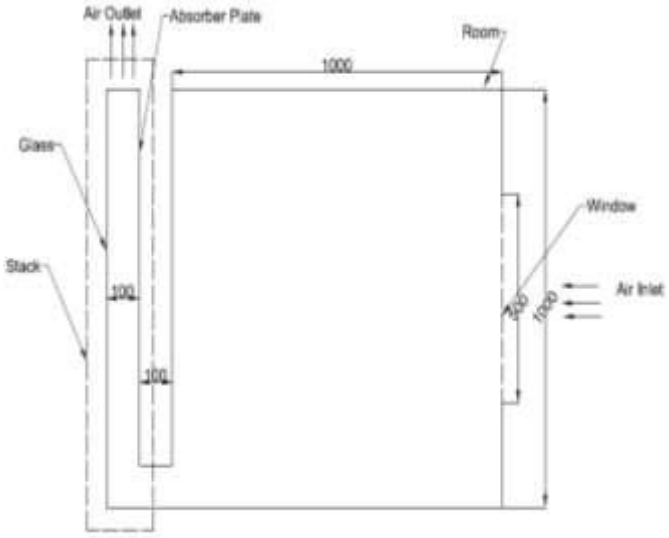

Fig.4.1: Line Diagram of Vertical Solar Chimney

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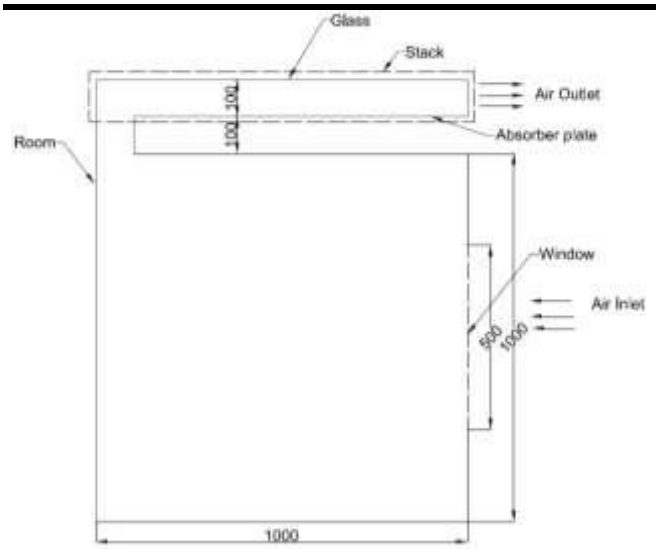

Fig.4.2: Line Diagram of Horizontal Solar Chimney

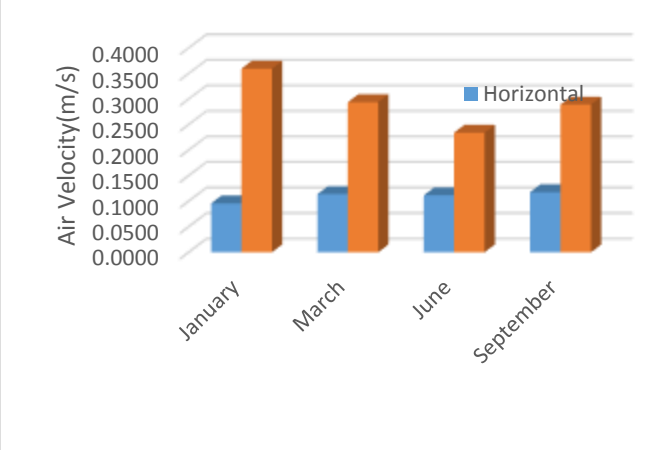

Fig.4.3: Design comparisons for solar chimney at R-500 measuring location

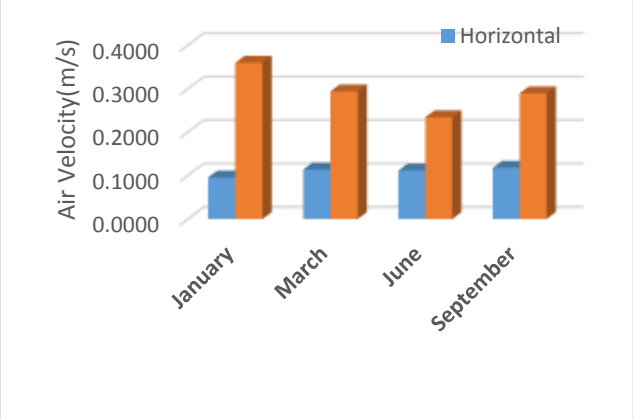

Fig.4.4: Design comparisons for solar chimney at SC-500 measuring location

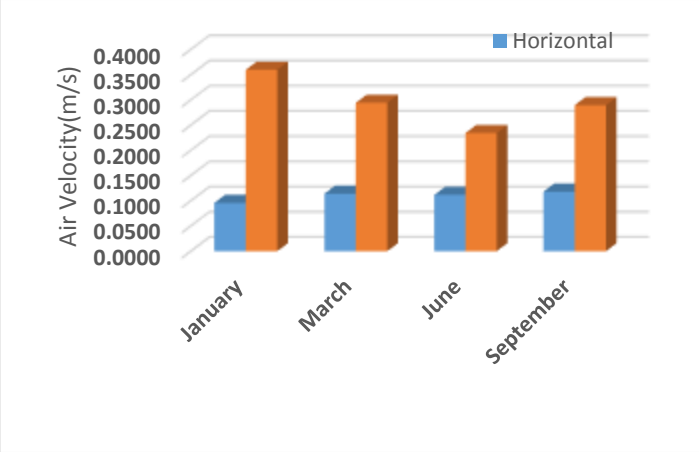

Fig.4.5: Design comparisons for solar chimney at SC-700 measuring location

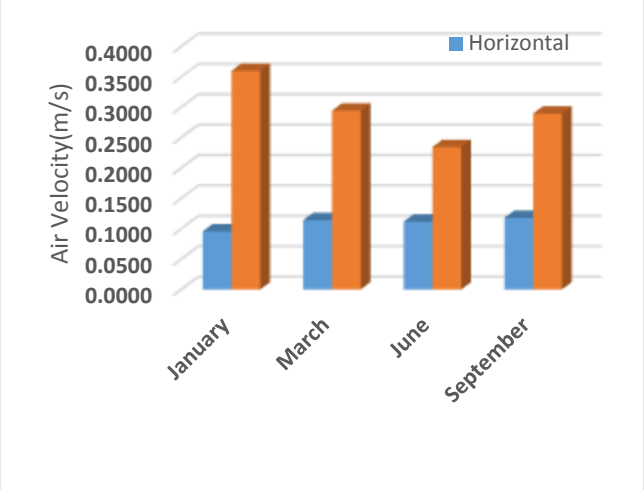

Fig.4.6: Design comparisons for solar chimney at SC-out measuring location

Fig. 4.3 Show that effect of solar chimney position in horizontal and vertical direction, R-500 shows the mid-point of solar chimney, at this point, vertical direction air velocity is maximum.

Fig. 4.4, 4.5, 4.6 shows the effect of solar chimney position in horizontal and vertical direction with respect to chimney height, SC-500 and SC-700 are the points at 500 mm and 700mm height of solar chimney respectively. SC-Out is the point at the outlet of solar chimney.

V. CONCLUSION

In this study, a reduced scale Chimney of Horizontal and Vertical design is modelled through CFD to investigate the improvement of Natural Ventilation. Two different parameters have been considered for current study viz. Outlet Velocity and Temperature of Absorber plate. Comparison between Horizontal and Vertical designs has been done. Following Conclusions can be drawn:

i) Both designs viz. Vertical and Horizontal have been compared and it was found that Vertical Chimney

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enhanced ventilation rate much better in comparison to Horizontal chimney as much as 275% enhancement.

ii) It was found that Vertical Solar Chimney enhanced air flow stream velocity up to 22 times.

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