Design and Development of Solar Chimney

Ishan Upadhyay[1], Honey Kumar G. Vishwakarma[2], Dr. A. G. Bhave[3]

[1]Student, M.E Energy Engineering, K. J. Somaiya College of Engineering, Vidyavihar, Mumbai - 400077, India

[2] Research Intern, Renewable Energy Laboratory, K. J. Somaiya College of Engineering, Vidyavihar, Mumbai - 400077, India

[3]Professor, Department of Mechanical Engineering, K. J. Somaiya College of Engineering, Vidyavihar, Mumbai - 400077, India

Abstract: ***The solar chimney, also known as solar updraft tower, is a proposed type of renewable-energy power plant that combines a solar air collector and a central high tube (chimney) to generate a solar induced convective flow which is used to generate electrical power using turbo-generator set. Natural convective air flow obtained can be used to drive the passive ventilation system. In this paper, the functional principle of the solar chimney has been described. Design of solar chimney is done by the energy balance and force balance of various components. Mathematical modelling of solar chimney is done through thermal analysis. Solar chimney is designed to provide ventilation for the room of two occupants. To get the accurate results absorber plate is divided into number of parts and thermal analysis is performed for each elements of the absorber plate. Solar chimney is designed to provide the mass flow rate for the room of dimensions 10m*5m*3m having two occupants. To validate the mathematical modelling developed, a small scale solar chimney is developed and two sets of experiments are performed to check the experimental results obtained against the theoretical value obtained.***

Keywords: Solar chimney, Passive ventilation, solar updraft tower, solar energy, passive cooling

1. Introduction

A solar chimney is basically a non-concentrating solar thermal technology. It combines three well known principles to convert solar energy into electrical energy [1]. It is a power generating facility which mainly consists of three components;

1) solar air collector
2) chimney and
3) Turbine [2]

The collector whose main function is to produce greenhouse effect is covered by a transparent glazing to trap the solar radiation. This produces greenhouse effect to increase the internal energy of the air mass inside the collector. Buoyancy drives the warmer air into the chimney, which is located at the center of the collector. This causes the collector to draw more air from the atmosphere, producing the air current flowing through the system. In this way solar chimney converts solar energy into kinetic energy of the air mass. A turbo-gen set is placed in the path of the air flow to convert kinetic energy of the flowing air into the electrical energy.

Available kinetic energy can be used to assist the room ventilation system i.e. solar chimney assisted natural ventilation system. Solar chimney used for natural ventilation system consists of two main components,

1) Solar collector
2) Chimney [3]

The whole setup, including the collector and chimney can be mounted on terrace away from the house to be ventilated, located at any floor. The collector, mounted either on the roof of the house or the terrace of the building, is covered by a transparent glazing. The main objective of the collector and chimney remains same here. Collector draws air from the house through the ducts.

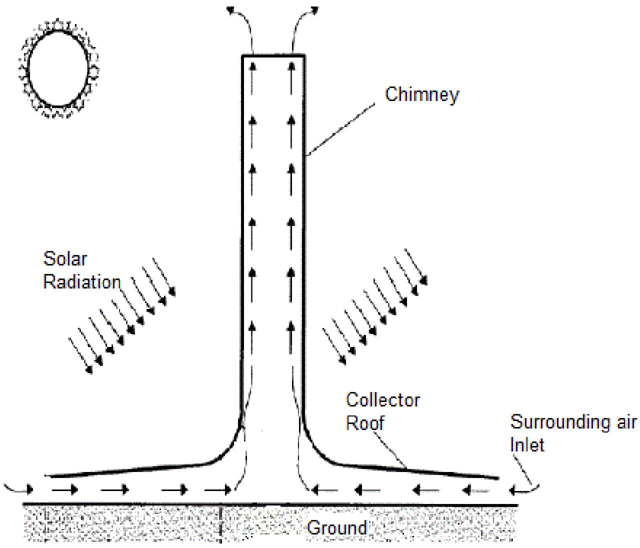

Figure 1: Solar chimney

1.1 Motivation

About 40-60% of the energy consumed in a commercial building is for space cooling and ventilation [4]. This relies on the electricity which is generated by combustion of fossil fuels mainly. At present, numbers of energy sources are utilized to generate electricity such as- coal, oil, gas and nuclear energy. Continuation of the use of these fossil fuels is set to face multiple challenges namely; depletion of the fossil fuel reserves, global warming and other environmental concerns and continuing fuel price rise. For these reasons, the existing source of convectional energy may not be adequate to meet the ever increasing energy demands.

The implementation of this project is of great significance in terms of energy saving opportunities. Centralized solar assisted space ventilation system could reduce the conventional energy sources dependency in considerable amount.

Solar passive cooling systems are well developed, requires south facing wall to accumulate maximum possible solar energy which is the major hurdle for making it popular in denser region. In a dense city like Mumbai it is difficult to obtain shade less south facing wall. Solar chimney on the other hand doesn't require south facing wall and can be more conveniently used.

1.2 Working Principle

A solar updraft tower works on following two well-known principles,
1) Greenhouse effect and
2) Buoyance effect.

Direct and diffused solar radiation strikes the glass roof where specific fraction of energy gets reflected, absorbed and transmitted. The quantities of these fraction depends on the solar incident angle and the optical characteristics of the glass such as; refractive index, thickness and extinction coefficient. The transparent glazed surface of the collector provides transparency for the short wave solar radiation. The transmitted solar radiation strikes the absorber plate surface where the part of energy is absorbed while remaining part is reflected back to the roof. Transparent collector glazed surface acts as an opaque surface for the long wave radiation reflected back from the absorber plate, producing greenhouse effect. The multiple reflection of the radiation continues resulting in the higher fraction of energy absorbed by the absorber plate to heat up the air mass underneath. The warm ground surface heats the adjacent air, causing it to rise. The buoyant air rises up into the chimney of the plant, there by drawing in more air from the collector perimeter and thus initiating forced convection which heats up the collector air more rapidly. As the air flows from the collector perimeter towards the chimney its temperature increases while the velocity of air stays approximately constant because of increasing collector height. The heated air travels up the chimney, where it cools through the chimney walls.

The pressure difference between the air at the chimney base and the ambient air at the outlet because of density difference which in turn depends on the temperature difference between the air at the base of the chimney and air at the top of the chimney causes motion of air through the chimney.

2. Design Methodology

Solar chimney is designed to ventilate the room of dimension 10m*5m*3m. Design is based on trial and error method as step-wise described below,

2.1 Solar Radiation Calculations

Radiation can be taken on the basis of monthly average hourly global radiation [5].

2.2 Required mass flow rate

ASHRAE suggested that ventilation rate (cfm) required per person in ordinary condition i.e. in house is 10 cfm. In this paper room with occupancy level of 2 is taken in calculations. Hence, required mass flow rate is given as [6,7],

$$Q_T = Q_c + Q_i + Q_f \quad \dots (1)$$

Where,

$Q_c = Q_{c\,N\text{-}E\text{-}W} + Q_s$

$Q_s = A_s * I_{bv}$

$Q_{c_{N-E-W}} = K\,A\,\frac{T_a - T_3}{dX}$

$Q_i = N * 100$

$Q_f = A_f\,(\tau\, I_{gv} + n\,\alpha\, I_{gv})$

$$m_{req} = \frac{(Q_T * 1.005 * 3024)}{H_{in} - H_{out}} \quad \dots (2)$$

Hin and Hout can be calculated from the inlet and outlet conditions and psychrometric chart.

2.3 Heat transfer coefficient between absorber plate and cover plate

Heat transfer coefficient between cover plate and absorber plate can be calculated as,

$$h_{p-c} = \frac{Nu_l\, K}{h} \dots (6)$$

Where, $Nu_l = 0.157 * (Ra_l * \cos\beta)$

$$Ra_l = \frac{\left(g\,(T_{pm} - T_c) * h^3 * P_r\right)}{T_{p-c_{avg}} * r^2}$$

2.4 Mean plate temperature and cover plate temperature

Losses due to convection and radiation between absorber plate and collector with convective loss due to wind and re-radiation can be given as,

$$\frac{q_l}{A_p} = h_{p-c_1}(T_{pm} - T_c) + \sigma\left(\frac{(T_{pm}^4 - T_c^4)}{\left(\frac{1}{\varepsilon_p}\right) + \left(\frac{1}{\varepsilon_c}\right) - 1}\right) = h_w(T_c - T_a) + \sigma\,\varepsilon_c(T_c^4 - T_{sky}^4) \quad \dots (3)$$

Equation for useful energy can be given as,

$$m\,C_p(T_4 - T_3) = \left((I_{gh}\,\tau\alpha_{avg}) - \left(U_t(T_{pm} - T_a)\right)\right)A_p \quad \dots (4)$$

Using above two equations by trial and error method T_{pm} and Tc can be calculated.

2.5 Height of the chimney

The pressure difference available between the ambient air and hot air at the base of the chimney is used to ventilate the room. The total pressure draught available by chimney is used to overcome following friction losses,

Total pressure drop developed across chimney = Friction loss in the chimney + Friction loss in collector + Lossesdue to acceleration of air in collector + Pressure loss in room + Minor losses (Neglected).

$$\Delta P_{chimney} = \Delta P_{Chimney_{loss}} + \Delta P_{Collector_{loss}} + \Delta P_{acceleration} + \Delta P_{room_{loss}}$$

$$\rho\,\beta\,\Delta T\,g\,H = f_X \frac{R}{2h}\,\rho\left(\frac{m}{2\rho\pi RH}\right)^2 + f_Y \frac{2H}{D}\,\rho\left(\frac{4m}{\rho\pi D^2}\right)^2 + 2\rho\left(\frac{2m}{\rho\pi D^2}\right)^2 + \Delta P_{room_{loss}} \dots (5)$$

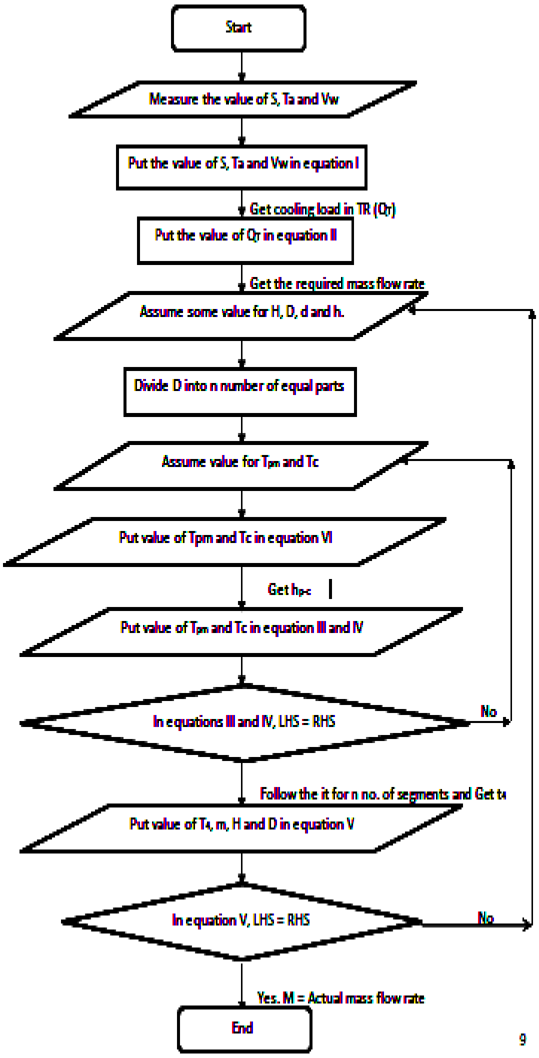

Chart -1: Design methodology of solar chimney

Solar chimney was designed to ventilate the room of 10 m * 5 m * 3 m dimensions and the following data were taken for calculations,

Density of air, ρ_{air}	1.225	Kg/m
Acceleration due to gravity, g	9.81	m/s2
Expansion coefficient of air, βair	0.00309	/K
Specific heat of air, Cp	1007	J/kg
Pressure drop across room, P_{room}	3 m of H2O	
Kinematic Viscosity of air, μ	19*10-6	m2/s
Absorptivity of the absorber plate, α	0.85	
Transmissibility of cover plate, τ	0.85	
Emissivity of cover plate, ε	0.85	
Number of occupants, N	2	

Following dimensions of solar chimney were obtained for the same:

Table 1: Chimney Dimensions

Component	*Dimension*
Height of chimney (H)	5 m
Diameter of collector (D)	4 m
Diameter of chimney (d)	1 m
Space between collector plate and absorber plate (H)	1 m

3. Results

Solar chimney was analyzed to obtain mass flow rate of the chimney from morning 7.00 am to 5.00 pm.

Table 2: Results

Sr. No.	*Time*	*T4 (°C)*	*M (kg/s)*	*Mreq (kg/s)*
1	7.00 to 8.00 am	48.84	0.015	0.017
2	8.00 to 9.00 am	60.39	0.021	0.018
3	9.00 to 10.00 am	66.89	0.026	0.022
4	10.00 to 11.00 am	73.03	0.027	0.024
5	11.00 to 12.00 pm	76.14	0.029	0.026
6	12.00 to 1.00 pm	79.79	0.027	0.026
7	1.00 to 2.00 pm	78.59	0.026	0.022
8	2.00 to 3.00 pm	75.41	0.025	0.018
9	3.00 to 4.00 pm	69.14	0.022	0.014
10	4.00 to 5.00 pm	57.66	0.015	0.011

In the graph below mass flow rate is plotted against time and it is found that maximum mass flow rate 0.029 kg/s is obtained at 11.00 to 12.00 pm.

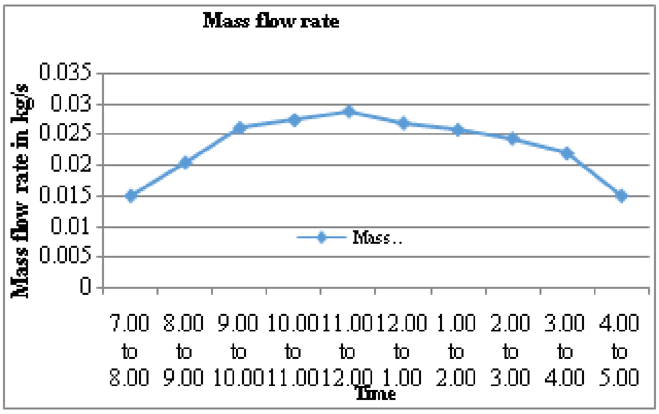

Figure 2: Mass flow rate vs. Time

Figure below shows variation of mean plate temperature over time,

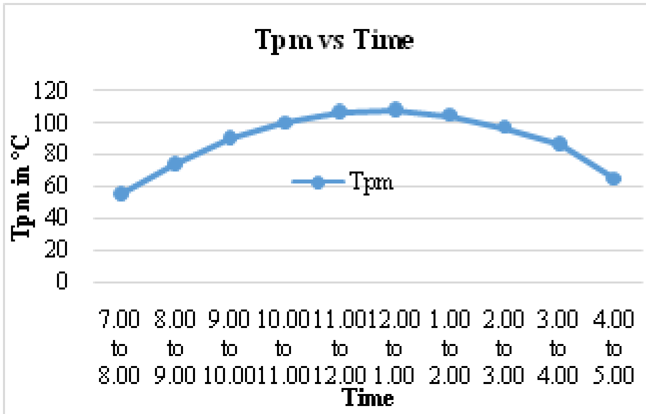

Figure 3: Mean plate temperature vs. Time

Mean plate temperature increases from morning and reaches maximum value 107°C at 12.00 pm.

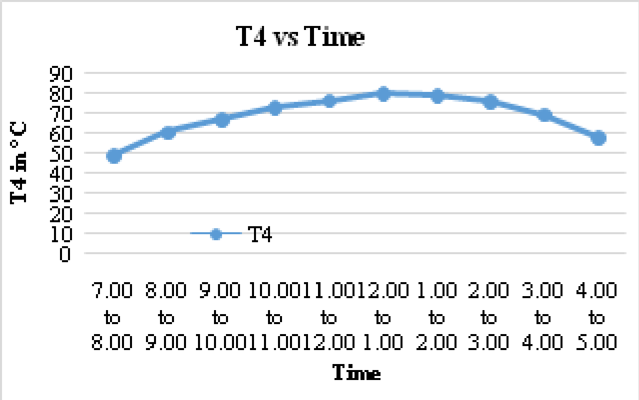

Figure 4: Air temperature at the base of the chimney vs. Time

Temperature of air at the base of the chimney increases from morning 7.00 am and reaches to maximum value of 71.66°C at 1.00 pm. After this it reduces to and at 5.00 pm air base temperature reduces to 52.79°C at 5.00 pm.

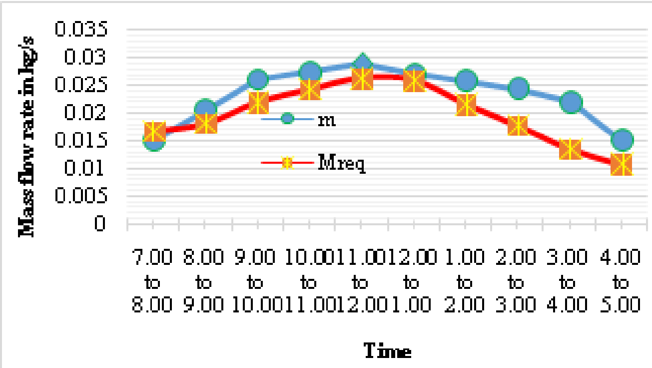

Figure 5: Actual mass flow rate vs. Theoretical mass flow rate

Figure above shows the required mass flow rate for the given hour and actual mass flow rate obtained from solar chimney.

4. Validation

4.1 Design of small scale solar chimney

Depending on manufacturing feasibility and cost for manufacturing of solar chimney, following dimensions were chosen and small scaled solar chimney was analyzed for its performance.

Dimensions of small scaled solar chimney:
H = 1.5 m
D = 1.2 m
h = 0.03 m
d = 0.1 m

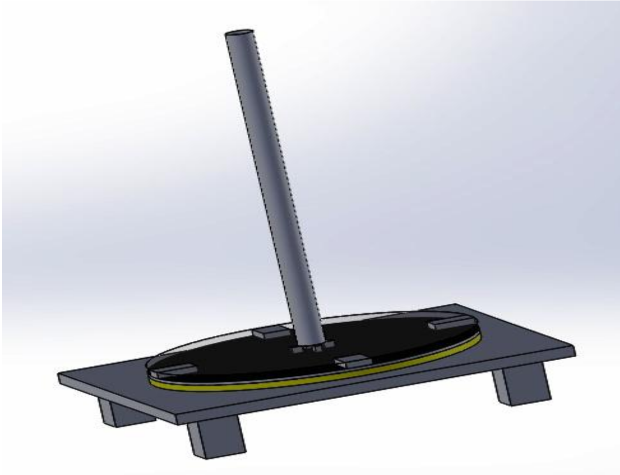

Figure 6: Small scale solar chimney – Design

4.2 Manufacturing of Solar Chimney

Following materials were used to fabricate the components of solar chimney,

Table 3: Small scale solar chimney - Components

Sr.No.	*Component*	*Material*	*Dimension*
1.	Absorber	Mild steel	Diameter = 1.2m Thickness = 5mm
2.	Collector	Transparent acrylic sheet	Outer Diameter = 1.2m Inner diameter = 0.1m Thickness = 4mm
3.	Chimney	PVC pipe	Diameter = 0.1m Height = 1.5m

4.3 Testing of solar chimney

Two sets of readings were taken while testing a solar chimney. Following instruments were used:
1) Thermo-electric Pyranometer with RN 2104 indicator - Dynalab,
2) RTD sensor PT-100 – Anadig system,
3) Thermometer
4) Hot wire anemometer – Kusam meco.

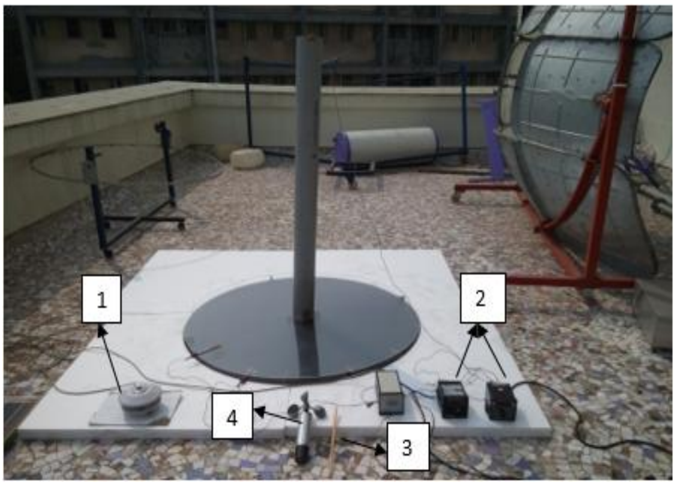

Fig -7: Solar chimney testing setup

Table 4: Result Table 1

Sr. No.	Time	T_a (°C)	V_{air} (m/S)	S (W/m^2)	T_{pm} (°C)		T_C (°C)		T_4 (°C)		$V_{chimney}$ (m/s)	
					T	E	T	E	T	E	T	E
1	12.00	39.6	0.6	725	87.72	78.2	58.2	61.5	52.1	57	0.83	1.2
2	1.00	42.5	0.3	646	85.19	75.2	59	62.4	56.3	54.4	0.64	0.93
3	2.00	44	0.5	549	79.19	65.9	56.3	50.5	54.8	49.9	0.57	0.89
4	3.00	41	0.3	378	66.44	59.3	49.4	49.6	49.5	50.2	0.49	0.55
5	4.00	39	0.2	260	56.89	54.7	44.3	47.3	45.1	47.0	0.43	0.55
6	5.00	38	0.4	217	52.8	51.4	41.8	44.6	43.3	44.7	0.4	0.65

Table 5: Result Table 2

Sr. No.	Time	T_a (°C)	V_{air} (m/S)	S (W/m^2)	T_{pm} (°C)		T_C (°C)		T_4 (°C)		$V_{chimney}$ (m/s)	
					T	E	T	E	T	E	T	E
1	2.45 pm	39.5	0.4	400	66.85	65.8	48.6	47.4	46.1	49.8	0.63	0.68
2	3.00 pm	36.3	0.5	340	60.52	62.1	43.8	44.9	42.9	45.5	0.63	0.53
3	3.15 pm	34	1.0	306	56.09	58.2	40.2	42.5	40.7	45.5	0.64	0.8
4	3.30 pm	36	0.3	259	54.75	55.8	41.5	42.2	41.1	42.2	0.56	0.68
5	3.45 pm	28.6	1.2	215	45.93	52.3	32.8	40.2	35.7	43.1	0.65	0.14

Figure 8 shows the different nodes of measurement. Temperatures of collector plate and absorber plate were taken at the outer most section of the plate. Velocity of air and air temperature at the base of the chimney is measured at the base of chimney.

To validate the mathematical model developed above, calculated theoretical results and experimental observations obtained for small scaled solar chimney are to be compared. In the table given above values of mean plate temperature (T_{pm}), Cover plate temperature (Tc), temperature of air at base of chimney (T4) and velocity of air inside chimney ($V_{chimney}$) obtained from mathematical modelling i.e. theoretical value (T) is compared against experimentally obtained readings (E).

Result Table 1. shows the velocity of air inside chimney obtained by measuring the time required to raise the smoke inside chimney. In this method the smoke was allowed to rise from the bottom of the chimney to the top of chimney, during which time was noted. By knowing the time required by the smoke to rise from the bottom to the top of chimney, diameter and length of chimney, velocity and hence mass flow rate of the air inside chimney can be calculated.

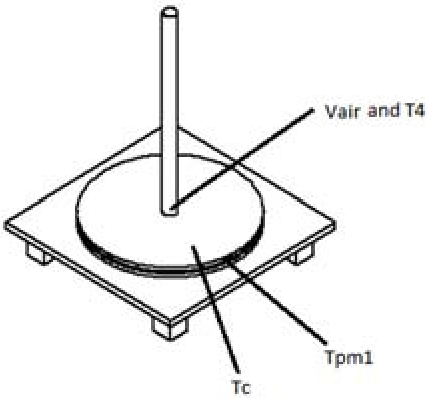

Figure 8: Nodes of measurement

One more set of reading was taken on 26th November, 2015 with hot wire anemometer. In the hot wire anemometer based on cooling effect produced by air passes through the hot wire, and velocity of air is measured. Result table 2 shows the results obtained from hot wire anemometer.

5. Conclusions

It is clean technology that uses solar energy as a heat source which produces neither greenhouse effect gases nor hazardous wastes. Efficient use of solar radiation, the solar collector utilizes both the direct and diffuse solar radiation.The plant therefore is able to generate power under cloudy conditions, although reduced.

Solar chimney can also be used to create the draft for passive heating and cooling of building. Pressure draught developed by solar chimney depends on solar radiation.

Air mass flow rate is obtained from the solar chimney, hence can be used to provide natural ventilation for the house. Result obtained from mathematical model and experimentation isclose and hence mathematical model for solar chimney is successfully developed.

It being observed that value of velocity of air inside chimney obtained from hot wire anemometer is in close range with theoretical value obtained from mathematical modelling as compared to experimental value of velocity of air inside chimney obtained from smoke method.

References

[1] A. Koonsrisuk, S. Lorente and A. Bejan, Constructal solar chimney configuration, International Journal of Heat and Mass transfer.
[2] Jörg Schlaich and Wolfgang Schiel, Solar chimneys, Encyclopedia of Physical Science and Technology, Third Edition 2000.
[3] Amel Dhahri and Ahmed Omri, A Review of solar Chimney Power Generation Technology, International Journal of Engineering and Advanced Technology (IJEAT) ISSN: 2249 – 8958, Volume-2, Issue-3, February 2013.
[4] R. K. Rajput, Power system engineering, Firewall media, 2006, pp. 198
[5] S. P. Sukhatme and J. K. Nayak, Solar energy principles of thermal collector and storage, Third edition, Mc Graw Hill.

[6] D. Yogi Goswami, Frank Kreith and Jan F. Kreider, Principles of Solar Energy, Second edition, Taylor and Francis.
[7] Duffie and Beckman, Principles of Solar energy, 1991

Author Profile

Ishan Upadhyay received the B.E. degree in Mechanical Engineering from Konkan Gyanpeeth College of Engineering, Mumbai University in 2012. He is now pursuing M.E. in Energy Engineering from K. J. Somaiya College of Engineering, Mumbai University.

Honeykumar. G. Vishwakarma received Bachelor of Engineering degree in Mechanical Engineering from K. J. Somaiya College of Engineering, Mumbai. Currently doing internship in Renewable Energy Lab, K. J. Somaiya College of Engineering.

Dr. A.G. Bhave received the degree of Docteur-Ingenieur in Thermique Industrielle, in the area of solar thermal energy, from Universite Paris XII in 1985. He has worked in the renewable energy area since, and is working as a professor in the Mechanical Engineering Department of K. J. Somaiya College of Engineering, Mumbai since 2009.