SOLAR CHIMNEY FOR EVAPORATIVE COOLING

Manthan M. Modh Nirav A. Panchal Umang M. Parmar Divya S. Patel
Dr. Bansi D. Raja
Department of Mechanical Engineering
Indus Institute of Technology and Engineering, Gujarat (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.

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 duct.

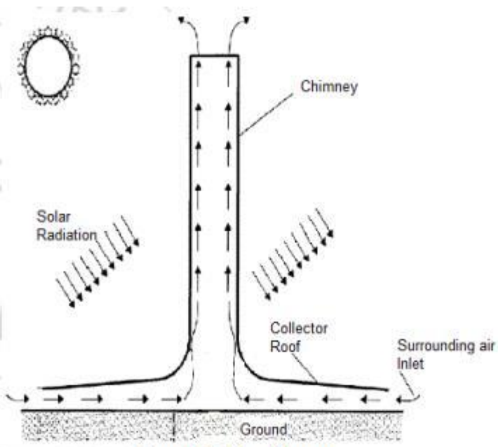


Figure 1: Solar chimney

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 *******. 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

$$Q_T = Q_c + Q_i + Q_f$$

Where,

$$Q_c = Q_{c\,NEW} + Q_s$$

$$Q_s = A_s * I_{bv}$$

$$Q_{c\,NEW} = K\,A\,\frac{T_a - T_3}{dX}$$

$$Q_i = N * 100$$

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

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

Hin and Hout can be calculated from the inlet and outlet conditions and psychometric 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,

$$h_{p-c} = \frac{Nu_l K}{h}$$

Where,

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

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

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 radiation Can be Given as,

$$\frac{q_l}{A_p} = h_{p-c_1}(T_{pm} - T_c) + \sigma\left(\frac{T_{pm}^4 - T_c^4}{\left(\frac{1}{\varepsilon_p}\right) + \left(\frac{1}{\varepsilon_c}\right) - 1}\right)$$

$$= h_w(T_c - T_a) + \sigma\varepsilon_c(T_c^4 - T_{sky}^4)$$

Equation for useful energy can be given as,

$$mC_p(T_4 - T_3) = \left(\left(I_{gh}\tau\alpha_{avg}\right) - \left(U_t(T_{pm} - T_a)\right)\right)A_p$$

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 drops developed across chimney = Friction loss in the chimney + Friction loss in collector + Losses due to acceleration of air in collector + Pressure loss in room + Minor losses (Neglected).

$$\Delta P_{chimney} = \Delta P_{chimney_{loss}} + \Delta P_{collector_{loss}} + \Delta P_{acceleration} + \Delta P_{room_{loss}}$$

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

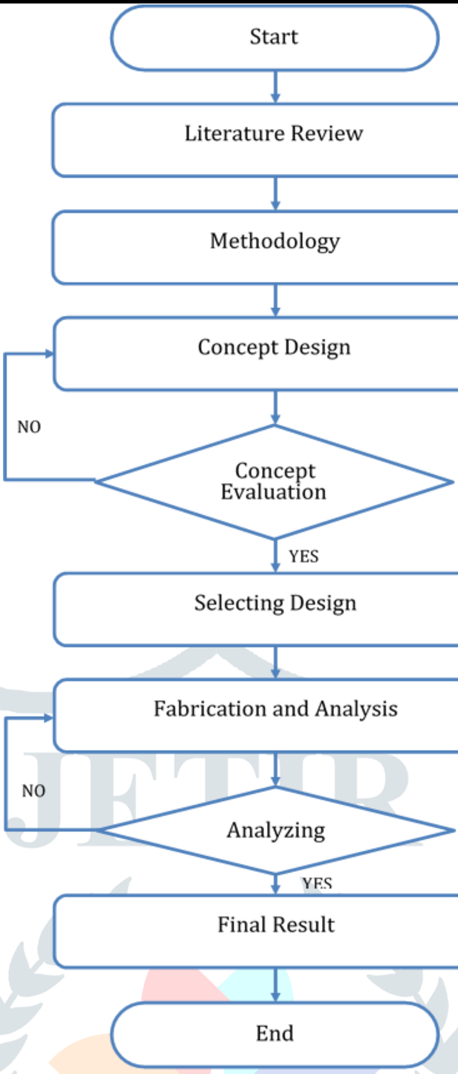


Chart: flow chart of solar chimney

3. Specification of Components:

Sr. No.	Component	Material	Dimension
1	Absorber plate	Mild steel	Diameter = 1.2 m Thickness = 5 mm
2	Collector	Transparent acrylic sheet	Outside Diameter = 1.2 m Inner diameter = 380 mm Thickness = 2 mm Taper angle = 4°
3	Chimney	MS sheet	Height = 2 m Top Diameter = 100 mm Bottom Diameter=380 mm Taper angle = 4°
4	Cooling chamber	Mild steel	300x110x110 mm
5	Connecting tube	PVC flexible tube	Diameter = 10 mm Length = 250 mm

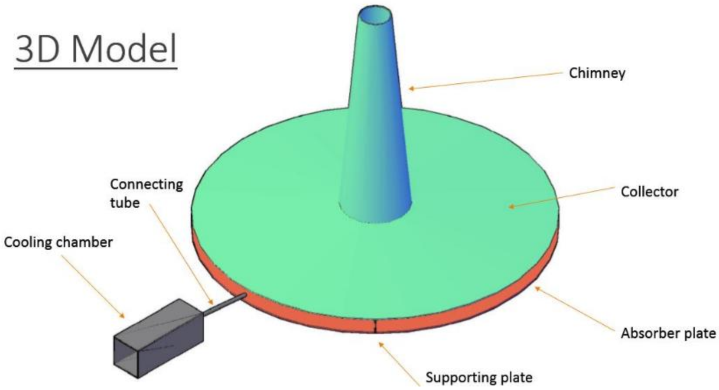
4. Validation

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 = 2 m

D = 1.2 m



5. Calculation:

5.1.1 Useful Heat Gained by the Collector

- Not all of solar radiation hits the sloped surface can be used:
- Some solar radiation is reflected and re-emitted away
- Some of the gained energy is lost again to the surrounding

$$q_u = S.A_P - q_1$$

Where,

q_u = Useful heat gained by the collector

S= solar energy absorbed in absorber

A_P= Area of the absorber plates

q_1 = Heat lost from the collector

5.1.2 Heat Losses from the Collector

The thermal losses depend on:

- The temperature difference between the absorber plate and the ambient air
- The overall heat losses coefficient, $U_1\, [\frac{W}{M^2}, K]$

$q_1 = U_1.A_P.(T_{pm} - T_a)$

T_{pm}= Mean temperature of absorber plates

T_a = Ambient air temperature

5.1.3 Heat Losses from Collector

Whenever the absorber plate is warmer than the ambient air, heat is lost from the collector through:

- the cover (top), [W]
- $q_t = U_t.A_p.(T_{pm} - T_a)$
- the bottom, [W]
- $q_b = U_b.A_p.(T_{pm} - T_a)$
- the sides, [W]
- $q_s = U_s.A_p.(T_{pm} - T_a)$

5.1.4 Overall Heat Loss Coefficient

Then, the total heat losses are:

$q_l = q_t + q_b + q_s$

Since the heat loss equations are expressed on the basis of the same temperature difference, it is then possible to evaluate the overall heat loss coefficient, U_I by

$$q_i = U_i . A_p . (T_{pm} - T_a)$$
$$U_I = U_t + U_b + U_s$$

Typical values of U_I ranges from 2 to 10 W/$m^2.K$

5.1.5 Heat Balance of Collector

$$q_u = A_p(S - U_I(T_{pm} - T_a))$$

This expression depends on two factors:

1. U_I : is a function of the mean plate temperature, T_{pm}
2. T_{pm} : is the mean plate temperature, which is unknown

- We need to express q_u in terms of a known temperature.
- The only known temperature is the fluid inlet temperature.

6. Experimental Data

Time	Ambient air temp. (◦C)	Temp. of cooled chamber (◦C)	Temp. at Centre of absorber plate (◦C)	Temp. at the top of chimney (◦C)
04:17	43	37	66.2	60.4
04:30	41.8	36.4	65.7	59.6
05:46	40	35	60.4	55.4

***without evaporative liquid**
***Air velocity range- 1.5 to 1.9 m/s**

Time	Ambient air temp. (◦C)	Temp. of cooled chamber (◦C)	Temp. at centre of absorber plate (◦C)	Temp. at the top of chimney (◦C)
12:00	40.6	34.1	58	54.4
02:30	43.8	33.2	63.7	62.6
04:54	42.2	34.8	64	56.2

***with water**
***Air velocity range- 1.6 to 2 m/s**

Time	Ambient air temp. (◦C)	Temp. of cooled chamber (◦C)	Temp. at Centre of absorber plate (◦C)	Temp. at the top of chimney (◦C)
1:45	40.1	33.1	58	52.3
04:08	41.8	27.9	63.7	56.9
05:12	39.2	30.2	59.4	53.5

***with petrol**
***Air velocity range- 1.5 to 1.9 m/s**

7. Conclusion:

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 is close 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.

Reference:

- R. K. Rajput,2006. Power system engineering, Firewall media, pp. 198
- S. P. Sukhatme and J. K. Nayak, Solar energy principles of thermal collector and storage, Third edition, Mc Graw Hill.
- D. Yogi Goswami, Frank Kreith and Jan F. Kreider, Principles of Solar Energy, Second edition, Taylor and Francis.
- Duffie and Beckman, 1991,Principles of Solar energy,
- http://www.doityourself.com/stry/5- advantages-to-using-a-solar-chimney
- http://www.baltimoreaircoil.com/english/what-is-evaporative-cooling
- Ishan Upadhyay, Honey Kumar G. Vishwakarma, Dr. A. G. Bhave, IJSR, Design and Development of Solar Chimney (Ishan) Benefits using solar chimney
- Mahmut Sami Buker, Saffa B. Riffat,Recent developments in solar assisted liquid desiccant evaporative cooling technology,Institute of Sustainable Energy Technology, University of Nottingham, Nottingham,UK
- M. Maerefat, A.P. Haghighi,Mech. Eng. Department,Faculty of Engineering, Natural cooling of stand-alone houses using solar chimney and evaporative cooling cavity,Tarbiat Modares University, Tehran Iran