International Journal of Development and Sustainability
Online ISSN: 2186-8662 – www.isdsnet.com/ijds
Volume 2 Number 1 (2013): Pages 277-297
ISDS Article ID: IJDS12110901

Solar chimney: A sustainable approach for ventilation and building space conditioning

Shiv Lal [1*], S.C. Kaushik [1], P.K. Bhargav [2]

[1] *Centre for Energy Studies, IIT, Delhi, India*
[2] *Central Building Research Institute, Roorkee, India*

Abstract

The residential and commercial buildings demand increase with rapidly growing population. It leads to the vertical growth of the buildings and needs proper ventilation and day-lighting. The natural air ventilation system is not significantly works in conventional structure, so fans and air conditioners are mandatory to meet the proper ventilation and space conditioning. Globally building sector consumed largest energy and utmost consumed in heating, ventilation and space conditioning. This load can be reduced by application of solar chimney and integrated approaches in buildings for heating, ventilation and space conditioning. It is a sustainable approach for these applications in buildings. The authors are reviewed the concept, various method of evaluation, modelings and performance of solar chimney variables, applications and integrated approaches.

Keywords: Ventilation, Thermal comfort, Solar chimney, Earth tunnel heat exchange (ETHE)

Cite this paper as: Lal, S., Kaushik, S.C. and Bhargav, P.K. (2013), "Solar chimney: A sustainable approach for ventilation and building space conditioning", *International Journal of Development and Sustainability,* Vol. 2 No. 1, pp. 277-297.

* Corresponding author. *E-mail address:* shivlal1@gmail.com

1. Introduction

The building sector (Residential and Commercial) consumes largest energy as shown in Figure 1, where Figure 2 shows that the heating, ventilation and space conditioning consumed approximately 50-60% of total energy consumed by building sector.

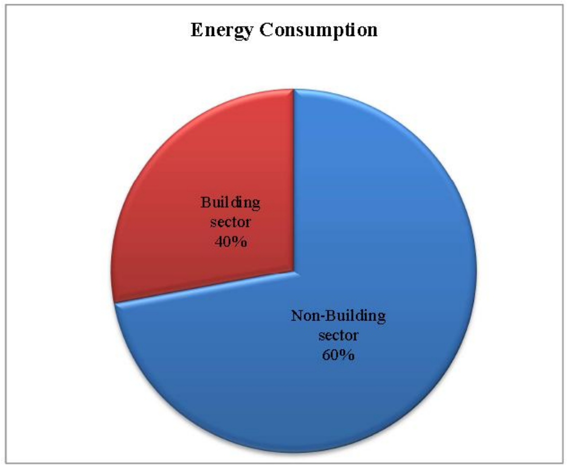


Figure 1: Enegy consumption (Source: ROODMAN, D. AND N. LENSSEN. "A Building Evolution: How Ecology and Health Concerns Are Transforming Construction". World Watch Paper #124, March 1995)

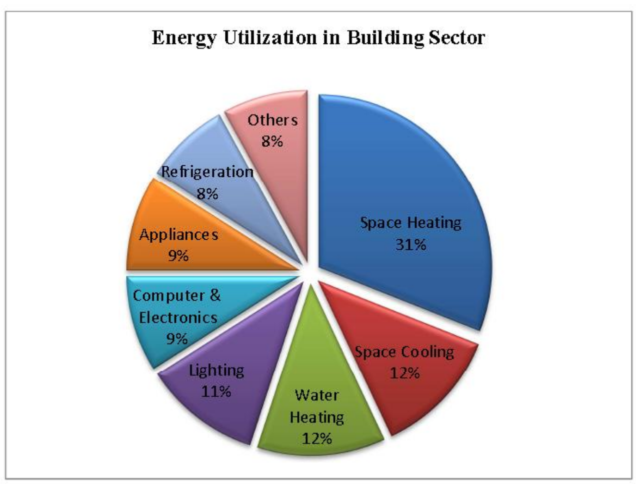


Figure 2: Energy utilization by various applications in buildings (http://buildingsdatabook.eren.doe.gov)

According to the Farlex dictionary ventilation is defined as replacement of stale or noxious air with fresh air and ventilation is needed to provide oxygen for metabolism and dilute metabolic pollutants where carbon dioxide and odour are the main metabolic pollutants. The highest quality indoor air provides by replacing of stale. Higher quality means control of temperature; replenish oxygen, moisture, odour, dust, bacteria and carbon dioxide. The simple ventilation means fresh air is mixed with already existing air in the enclosure to dilute the pollutants or used to displace the air by means of piston flow. The air change rate affects the circulation and fresh oxygen supplied for human comfort.

The air circulation can be possible by natural air flow (Through window, doors and ventilators) or by forced air flow (through fans and blowers etc.). So the ventilation process is divided into two categories as: natural ventilation and Mechanical/forced ventilation. Here authors have reviewed the natural ventilation and space conditioning methods by applications of solar chimney.

The chimney has been used for ventilation and space conditioning for centuries particularly in Europe by the Romans as well as Middle East and north east by Persians (http://en.wikipedia.org/wiki/Solar_chimney). The concept of solar chimney was proposed by Trombe and Michel (1960) at the C.N.R.S. laboratory in France. In early stage solar chimney was used for space heating only and presently it can be used for both heating and ventilation of building.

Barozzi et al. (1992) studied space conditioning in buildings is a function of temperature, relative humidity, irradiation and the method of controlling these parameters. The space conditioning is highly desirable in tropical countries like India, Africa and South America. Today's technology like passive solar applications can be used for thermal comfort of buildings (Hirunlabh, 2001). The first mathematical modelling for the solar chimney (Trombe wall) design was given by Bansal et al. (1993) and reported the concept of increasing the air flow by increasing solar irradiations. This theoretical study also reported an air change per hour with change in the coefficient of discharge. The ventilation provided by the solar chimney is not sufficient for large buildings but enhance the ventilation rate up to some extent. One important application of passive cooling for air ventilation and circulation in the form of wind tower was suggested by Bansal et al. (1994).

The solar chimney in the form of Trombe wall, roof solar chimney and roof air solar collectors are the most convenient and mature technologies used for buoyancy driven natural ventilation systems (Khedari et al., 2000; Zhai et al., 2005; Hirunlabh et al., 1997). The integrated approach like Trombe wall and roof solar collector gives improved rate of ventilation.

Awbi (1994) reported the main design considerations for naturally ventilated buildings as climatic conditions, height, building occupancy loads, and features for enhanced ventilation and classify the ventilation as single side, cross and mixed ventilation. Ong (2003) developed a heat transfer modeling of Trombe wall with considering all effect of mode of heat flow and investigated the effect of wall length on temperature, mass flow rate and instantaneous efficiency. Bassiouny et al. (2009) developed a FORTRAN programme to solve the mathematical modelling and found that the optimum flow rate could be achieved at 45° to 70° inclination angle for latitude 28.4° for 0.1 to 0.35m chimney width at 500W/m^2 solar intensity. Bilgen and Nouanegue (2009) studied the conjugate heat transfer in the solar chimney system for ventilation of dwelling and conservation equations have been solved by finite difference control volume method and revealed that the solar radiation affects the volume flow rate, temperature field and Nusselt number. Gan (2006) used CFD for simulation of buoyancy driven ventilation system and created two domains in study where one smaller and the other larger. The investigated performance of larger domain found very sensitive for both ventilation and heat transfer.

Qirong et al. (2011) proposed an integrated approach of Trombe wall, roof solar collector and chimney and investigated the effect of total length and width of chimney on the performance of the system. They reported that the performance of integrated system found better as compared to the single solar chimney. The numerical study also carried out to evaluate the performance parameters for ventilation rate as a function of inclined angle of the second floor, length ratio of vertical to inclined, and chimney inclined angle. The optimum ratio of length to width was 12:1 and optimal inclination angle is found to be 4º by numerical study. The length of solar chimney (vertical section height) should be as large as possible within the restriction of building code to increase the flow rate of air.

Zamora and Phoenic (2009) used codes (version 3.6.1) for the numerical study of natural convection in channels or solar chimney. They used Reynolds $k - \omega$ turbulence model to simulate the turbulent case. The solar chimney was configured for a wide range othe Rayleigh numberer (varying between 10^5 to $1o^{12}$ for symmetrical isothermal heating), several values of wall to wall space and different heating conditions.

Gan (2011) derived the general expressions for correlation of Nusselt number, Reynolds number and Rayleigh number and these expressions can be used for calculating the heat transfer rate and air flow rate in ventilation cavity for given height and width. The heat flux and heat distribution ratio also calculated.

Ekechukwu (1997) analyzed solar chimney for ventilation and reported that the simple air heater increases ventilation up to some extent but not sufficient. Mathur et al. (2006) also experimentally analyzed window size solar chimney and found increasing summer performance of the inclined roof solar chimney. They studied the effect of various performance parameters like chimney width, height and solar radiation.

The performance of solar chimney can be improved by using glazing, increasing height, air gap, integrating Trombe wall with roof solar collector (single pass and double pass), and inclination angle.. Lee and Richard (2009) investigated the effect of these parameters along with chimney height, air gap and potential for different climatic conditions. Hirunlabh (2006) investigated the glazing effect on the performance of solar chimney and found double glazing is a suitable option as compared to single and triple glazing. Gan and Riffat (1998) were analyzed the glazed solar chimney experimentally and the data validated by simulation in CFD and found to increase the air flow rate up to 17% in the summer by using double glazing. The single pass roof solar collector (SPRSC) and double pass roof solar collector's (DPRSC) performance were compared by Wang et al. (2005) and found that DPRSC can be operated 10% more efficiently for space heating in winter and for natural ventilation in other seasons. They used roof solar collectors with damper for controlling the air flow. A FORTRAN computer program was developed to validate the experimental results.

The heat transfer analysis combined with energy analysis of solar chimney based on assumptions as wall adiabatic of constant heat flux. Vrachopoulos et al. (2007) presented a study of natural convection phenomena inside a wall solar chimney with one wall adiabatic and one under a heat flux. Their main research focused on the numerical study of buoyancy driven flow field inside the chimney and heat transfer analysis of the turbulent flow model. The k-ξ model is likely to provide superior performance for flow boundary layers under strong adverse pressure gradient that's why it was selected for simulation.

The maximum literature available for ventilation enhancement in daytime but Aboulnaga and Abdrabboh (2000) reportedthe results for improving night ventilation by use of combined wall and roof solar chimney. ACTION psychometric software was used in that study for mean cooling load calculation at corresponding induced ACH and optimized parametric configurations for maximum air flow for suitable height. For wall-roof solar chimney height of 1.95 to 3.45m the air flow rate increased up to three times (0.81 to 2.3 m^3/s) as compared to single roof solar chimney and the air change per hour was achieved by 26. Zhou et al. (2011) used the shape stabilized phase change materials (SSPCM) for thermal storage in solar chimney for increasing ventilation at night. The ACH was 40 by using SSPCM and improving the thermal comfort level up to some extent. The night time Cop found 7.5 is higher than 6.5 without using SSPCM.

For thermal comfort it is more important to cool the ventilation air in the summer season by earth to air heat exchanger, air tube passed through the sanitary space, ventilation integrated by evaporative cooling, adsorption cooling etc. Wang et al. in 2004 and Santamouris et al. (2007) cooled the ventilated air by EAHE in their analysis, and Wang found experimentally 2.4kW cooling capacity with tightened envelop and spiral tube was used to increasing 25% flow rate. Sumathy et al. (2003) worked on natural ventilation in a solar house along with solid adsorption cooling and increased 20% ventilation rate at night. The new cooling method for circulating air was suggested by Macias et al. 2009. In which the circulating air cooled by using the sanitary area. The air pipe was passed through sanitary area and it cooled by low temperature of this area. The authors have used this technology in dry hot climatic conditions for low cost buildings. A solar chimney was used by passive cooling ventilation and saved more than 50% energy. It can be applied to the area where solar irradiation is high and wind speed is low.

A full scale model was built by Kishore et al. (2001) and analyzed it for whole year thermal comfort conditioning. They used solar chimney for heating in winter season and integrated evaporative cooling approach was suggested for summer. But for rainy season they also controlled the humidity up to some extent by using a dehumidifier. The 20% cost was increased by using new approach as compared to conventional room but in view of comfortness increasing cost doesn't have matter. Miyazaki et al. (2011) predicted the evaporative cooling system experimentally and simulated M-cycle evaporative cooling channel and they found it feasible option of thermal comfort. The system used to be capable for 40-50w/m^2 radiative cooling load. The chimney width optimized for maximum convective cooling capacity and air flow rate.

The solar chimney system is the most prominent technique used in building ventilation for sustainable development. There is scope to reduce energy demand, used in circulation and cooling of air up to some extent in domestic and commercial buildings. The number of factors are affecting the use of solar chimney in household buildings. More work is required to minimize the cost, improving the effectiveness and to make it in fascinating design. The aim of this paper is to review the solar chimney technology through its classification, performance variables, methodology, various designs, and integrated technology for thermal comfort and to find the scope of research in this area.

2. Working principle of solar chimney

The solar chimney is one of the technology which working on the buoyancy principle. Where's the air is heated through greenhouse effect which generated by solar radiation (heat energy). The expenditure involved is not so high. So many techniques can be used in cooling or heating of buildings. The solar chimney can be used in roof level or inside wall also. The solar chimneys are solar passive ventilation systems it means they are non mechanical. The heat is carried out through convective cooling principle. The solar chimney is designed based on the fact that hot air rises upward; they reduce unwanted heat during the day and exchange interior (warm) air for exterior (cool) air. The solar chimney mainly made of a black hollow thermal mass with opening at the top of chimney for exit the hot air. The air passed through the room and exit from the top of chimney. The two purposes are solved one is the better ventilation and secondly it reduces the temperature inside the room. It can be worked as reverse for heating the room also. The Trombe wall is working as solar chimney shown in Figure 3 and merits of solar chimney are: Merits: There is no mechanical part, Low maintenance, No electrical Consumption, No global warming, No Pollution and It can be used for both heating and cooling and demerit only is to increases the cost of building.

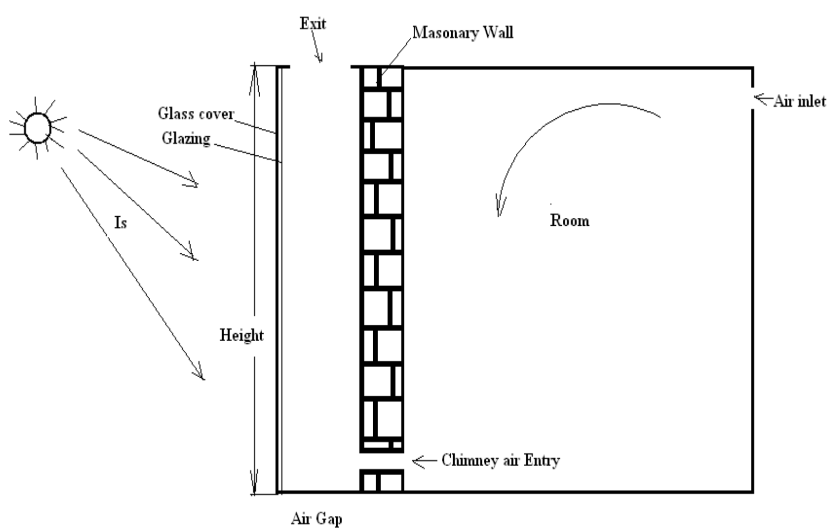


Figure 3. Solar chimney used in building ventilation

3. Classification of solar chimney

The solar chimney is basically a solar air heater, its position may be vertical or horizontal and according to the position it will be a part of a wall or roof.

1. The solar chimney can be classified according the position as (i) Vertical solar chimney and (ii) Inclined solar chimney.
2. It can be classified according to position solar chimney for building ventilation is classified as (i) Wall solar chimney or Trombe wall (ii) Roof solar chimney and (iii) Integrated wall and roof solar chimney.
3. The solar chimney performance is depends on the glazing either single glazing, double glazing or triple glazing. The ventilation rate is mainly depends on the height of solar chimney, so it is one of the basis for classification (i) Small height (ii) Medium height and(iv) Large height.
4. The solar chimney is also classified according to the use for (i) building ventilation (circulation) (ii) Building heating (dwelling) (iii) Air dryer (crop dryer) and (iv) Power generation.
5. The solar chimney classification also associated with cooling and heating of building. It means solar chimney can be classified with integrated approaches as (i) Integrated with evaporative cooling system (ii) Integrated with earth air tunnel heat exchanger and (iii) Integrated with absorption and adsorption cooling.
6. The Solar radiation receiving area is covered with glass cover, the small radiations should be less entering to the system and large wavelength radiation minimum exit from glass cover so maximum green house effect can be generated. The green house effect is associated with solar radiation and number of glazing. The solar chimney classified according to number of gazing used as (i) Single glazing and (ii) Multi glazing.

4. Case Study

Mainly the research is going on various applications of solar chimney. The flow due to effect of buoyancy is generated by temperature difference or pressure difference between inlet and outlet positions. For building application it can be used as trombe wall, roof solar chimney or integrating both for more effect. But if the high gradient difference is possible between inlet outlet positions, it will give drastically improved the flow of air. Then the high velocity flow can be used for power generation.

4.1. Solar chimney for ventilation of buildings

This stack effect described in principle of solar chimney can be used for multistory building by using wind tower or wind catcher for inlet air in the room and the solar chimney at other faces for each floor was suggested. This solar chimney at 30˚ inclination angle having collector area 3.0 m^2 each with wind tower of height more than the building used by Bansal et al. in 1994 as shown in Figure 4.

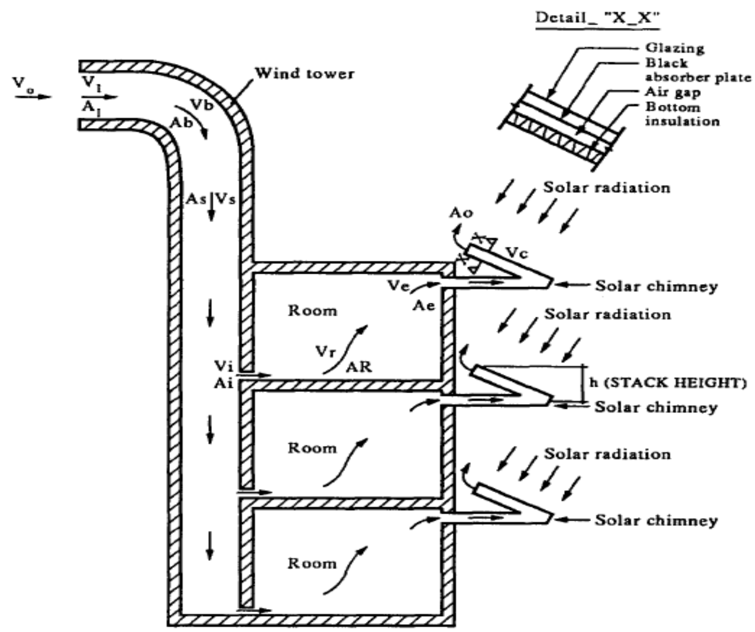


Figure 4. Schematic of wind tower solar chimney system (Bansal et al. 1994)

The air flow rate per unit area of roof solar collector is decreased with increasing the length of RSC. The optimum solar collector length for maximum air flow should be shorter in order of 100-200cm. Hirunlabh et al. (2001) suggested the special configuration as shown below in Figure 5 for maximum air flow rate. The multiple solar collectors at fixed and variable angles shown in Figure 5 (b, c, d) and reported that the three solar collector at different angles as 30, 45, 60 degree gives better performance than fixed angle at 30 degree.

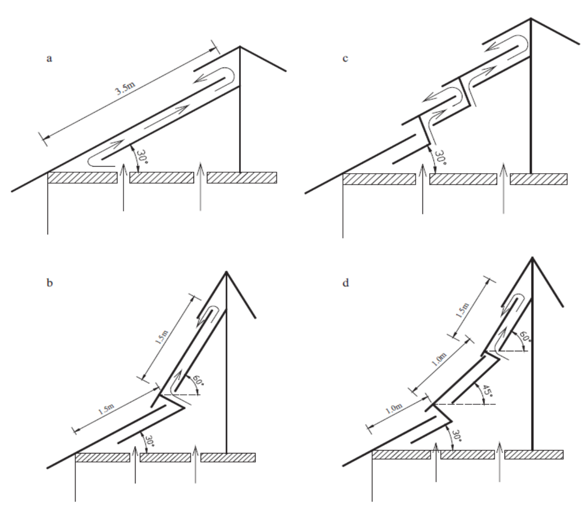


Figure 5. Four different configurations of the solar roof collectors (Hirunlabh et al., 2001)

4.2. Solar Chimney for space heating and ventilation

The simple solar chimney or trombe wall can be operated in both applications as: space heating mode and ventilation mode. Gan (1998) used trombe wall for both heating and ventilation mode by controlling the positions of dampers so it can be used for both winter and summer season. He constructed a trombe wall in south facing by concrete and masonry with blackened and covered exterior by glazed glass and provided three holes as shown in Figure 6 where two holes in masonry wall at bottom and top position. A damper was fitted in top hole for closed it in summer season and open in winter season. One more damper was fitted at exit opening in the chimney for closing it in winter and open in summer.

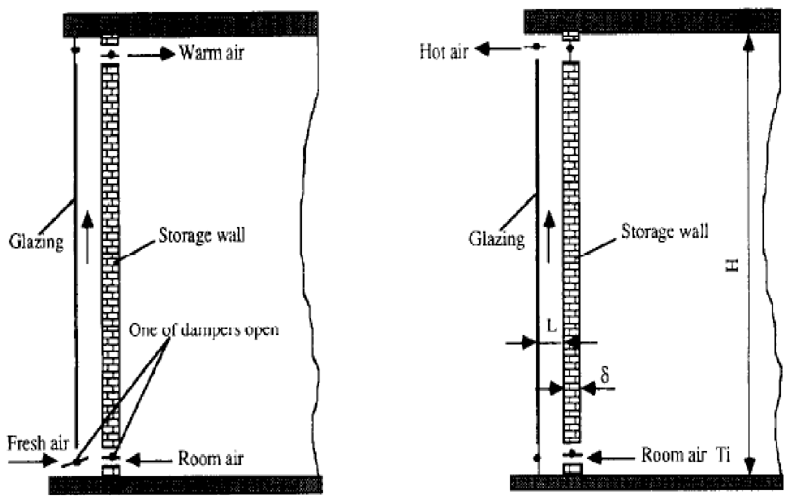
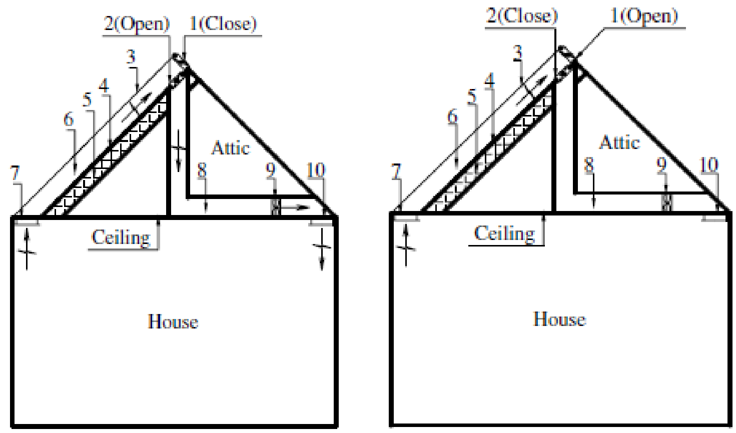


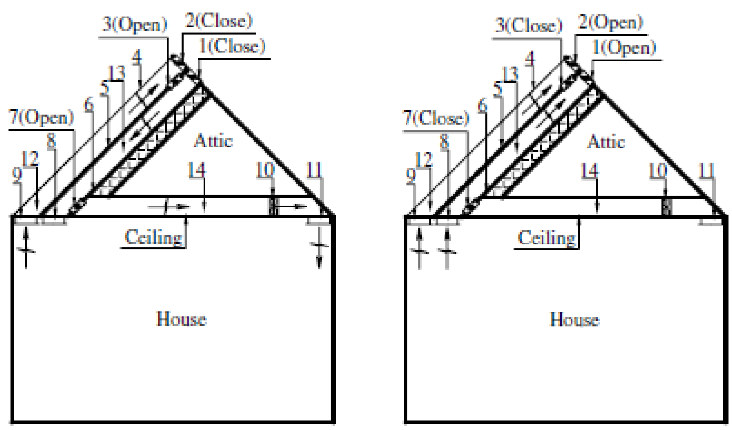
Figure 6. Schematic diagram of trombe wall for (a) winter heating and (b) summer cooling (Gan, 1998)

Wang et al. (2005) suggested single pass and double pass roof solar collectors in two modes as space heating and natural ventilation mode as shown in Figure 7 (i) & (ii). The dampers used to control the situation of application. The 1 close 2 open positions shown in Figure 7 (a) means hot air is circulated in to the room and it is space heating mode for natural ventilation damper position will be reverse which shown in next figure. The double pass means double grazing and the flow position is in series for space heating and parallel in ventilation mode. The Performance of double pass RSC found approximately 10% higher than the single pass RSC and it shows the glazing effect.



(a) (b)

Figure 7 (i) Structure of single pass roof solar collector (a) Space heating mode. (b) Natural ventilation mode. 1—damper,2—damper, 3—glass cover, 4—absorber plate, 5—insulation plate, 6—-air channel, 7—tuyere, 8—air duct, 9—fan, 10—tuyere (Wang et al. 2005)



(c) (d)

Figure 7 (ii) Structure of double pass roof solar collector (a) Space heating mode. (b) Natural ventilation mode. 1—damper,2—damper, 3—damper, 4—glass cover, 5—absorber plate, 6—insulation plate, 7—damper, 8—tuyere, 9—tuyere, 10—fan, 11-tuyere, 12—air channel 1, 13—air channel 2, 14—air duct (Wang et al., 2005)

4.3. Solar Chimney for space cooling and thermal comfort

Thermal comfort is not only space heating but it is space conditioning which integrated operation technique for controlling the air temperature, humidity and quality of air. It can be possible by solar chimney and integrated approaches.

The underground temperature is less than the annual average air temperature in summer but it will be higher in winter. The average underground temperature below 2-3m depth is 20-25˚C. The geothermal soil temperature in Omaha, Nebraska found 12˚C when outdoor temperature was 31˚C (Wang et al 2004). Wang et al. (2004) experimentally cool the room air by geothermal temperature and gives satisfactory results. So many researchers like Bansal, Sodha, Mathur, Sawhany, and Thanu etc. have been working on EAHE. It can be satisfactorily worked up to 7-8 hour after that COP will be reducing and it ground required recharging time it is a limitation of EAHE. This geothermal heat exchange system is called earth to air heat exchanger (EAHE). Maerefat and Haghighi (2010) used this technology integrated with solar chimney for passive cooling and ventilation of buildings as shown in Figure 8.

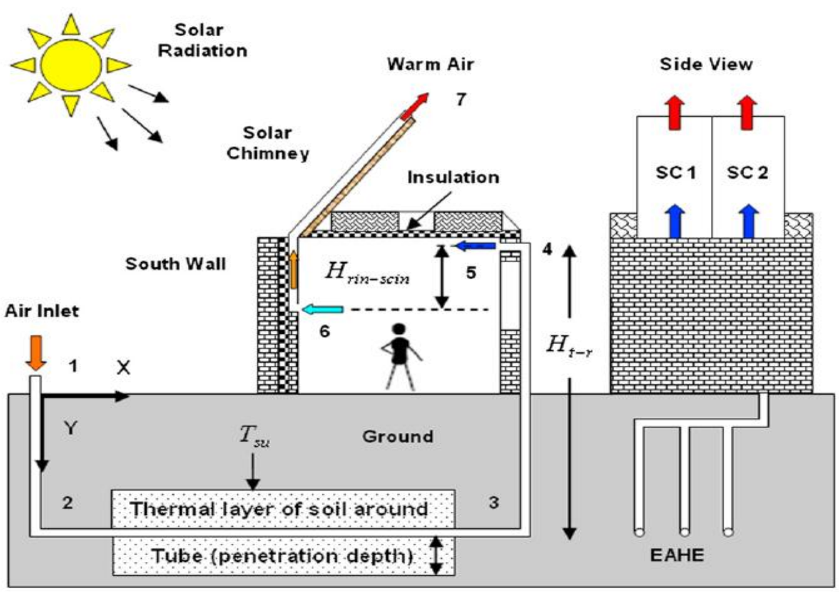


Figure 8. Schematic diagram of integrated earth to air heat exchanger and solar chimney (Maerefat and Haghighi, 2010)

The air enters to the EAHE from point 1and it passed through 2 and 3 where it is cooled by low geothermal temperature, and the cooled air finally reached 4-5 points opening in the room. The optimum diameter of cooling pipe was 0.5m and 20 m length pipe which provided the sufficient heat exchangers and reported reduction in the ambient temperature up to 18-20˚C in difficult conditions let 50˚C and it also gives better thermal comfort at the time of low temperature. The number of optimum EAHE and solar chimney requirement according to the cooling demand is shown in Table 1. It shows the effect of ambient air on when it increases more EAHE required and for low irradiations more number of solar chimney demanded.

Table 1. System performance at different indoor and outdoor conditions (Maerefat and Haghighi, 2010)

Cooling demand (W)	Ambient air temp. (ºC)	Solar radiation (W/m²)	ACH	Room air temp. (ºC)	Number of SC	Number of EAHE
500	40	100 500 900	3.28 5.16 4.83	29.61 31.13 31.40	5 3 2	3 3 3
500	45	100 500 900	3.01 4.30 4.02	30.92 31.12 31.27	6 3 2	4 4 4
500	50	100 500 900	3.05 3.45 3.06	31.02 31.62 31.52	6 3 2	6 5 5
1000	40	100 500 900	4.98 4.10 3.63	30.51 31.95 30.69	8 2 2	6 2 4
1000	45	100 500 900	4.15 3.27 3.00	30.00 31.15 30.90	8 3 2	6 5 5
1000	50	100 500 900	4.18 3.05 3.15	31.95 31.98 31.53	8 3 3	7 6 12
1500	40	100 500 900	5.20 3.29 3.00	31.36 30.61 30.35	8 3 2	4 5 5
1500	45	100 500 900	3.95 3.62 3.17	31.00 31.70 31.60	9 4 3	9 9 12
1500	50	100 500 900	Thermal comfort cannot be provided			

Khedari et al. (2003) presented a study on performance of solar chimney with air conditioned building. Where they used 1 ton split AC for a 25m³ volumes single room and one RSC with 14 cm air gap composed of CPAC monier concrete tiles integrated to similar air gaps trombe wall. They reported that the average daily consumption of electricity was reduced by 10-20%.

Another important method for cool the air is convention evaporative cooling method which is normally used in hot and dry climatic conditions. The thermal performance of passive solar air conditioned building with evaporative cooling was measured by Chandra et al. (1985). They used three different cases for evaporative cooling and found that maximum cooling was achieved by water spray over the roof. Kishore et al. (2001) proposed two passive models for winter and summer option as shown in Figure 9.

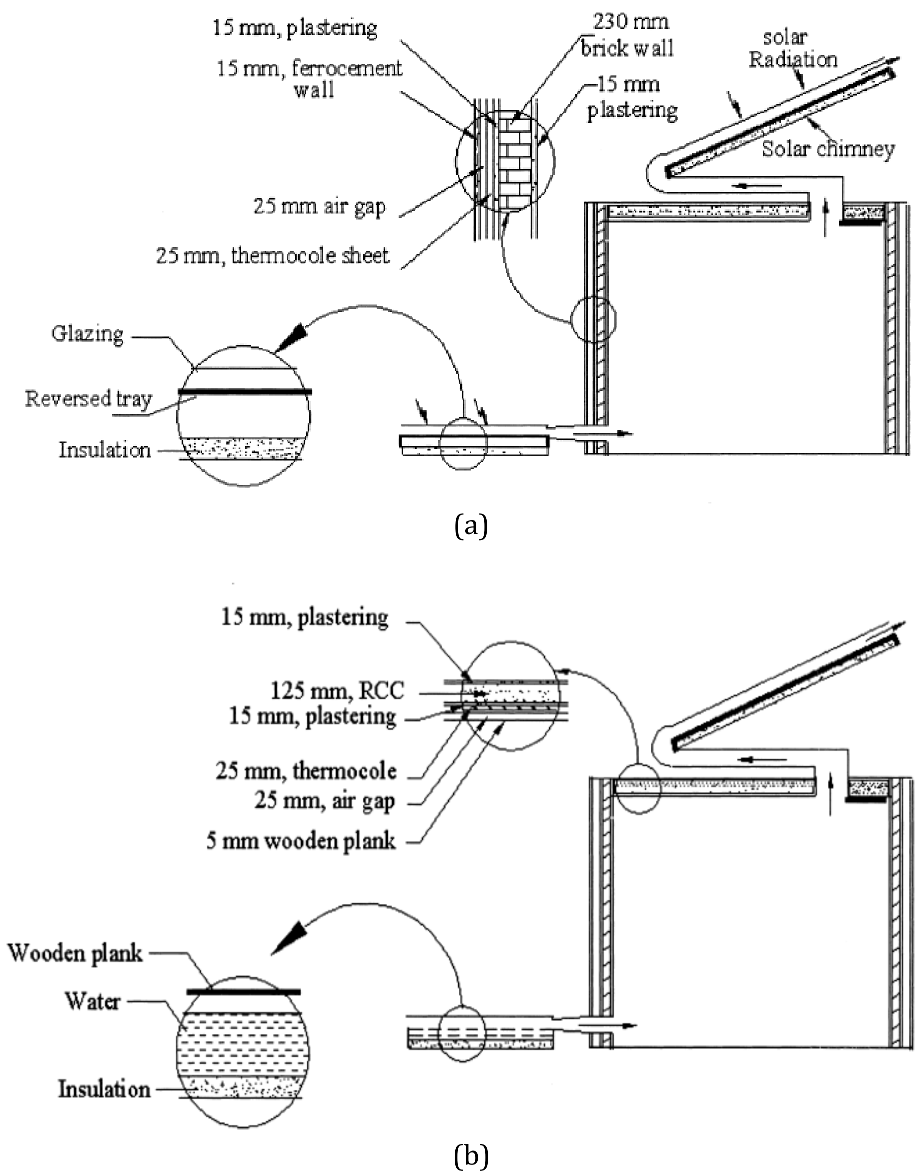


Figure 9. (a) Schematic diagram of passive model 1 system for winter operation. (b) Schematic diagram of passive model 1 system for summer operation (Kishore, 2001)

The cross section shows that water will be used for summer cooling only. The roof was insulated by thermocole and wooden blocks provided to reduce the heat transfer from roof. The combination of trombe wall and RSC were used to increase the ACH. The cost of room increased up to 20% but the concept will reduce the power consumption. It has good potential for thermal comfort and it will be beneficial in long term.

The solid adsorption cooling assisted by solar chimney can be used for cooling of houses (Sumathy et al., 2003). Where, Sumathy proposed enhancement of natural ventilation in a solar house with a chimney along with solid adsorption cooling as shown in Figure 10.

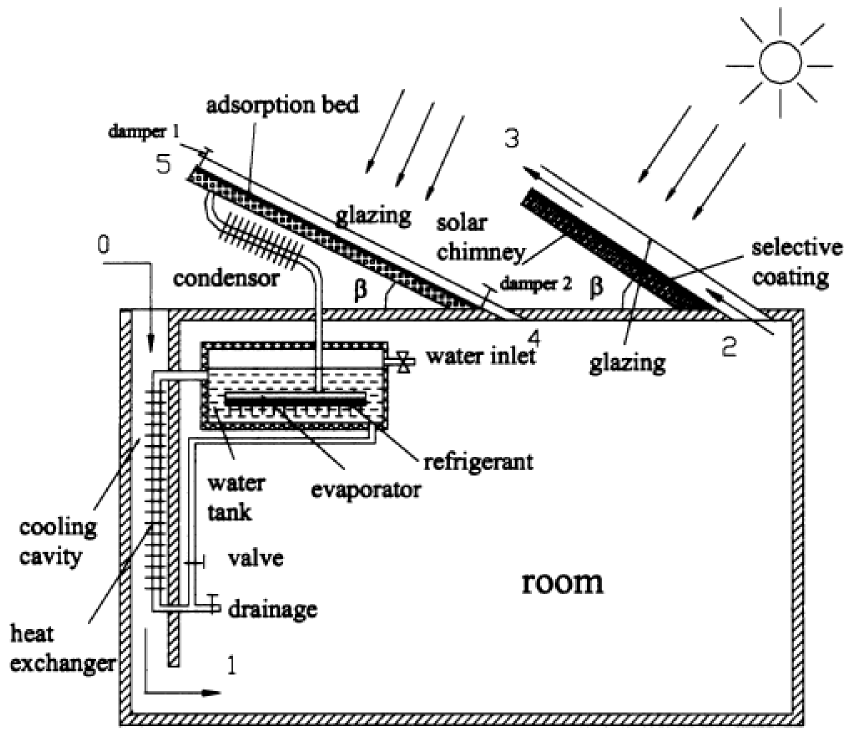


Figure 10. Schematic of the solar house with solar chimney and adsorption cooling cavity (Sumathy et al., 2003)

Where 5 is the solid adsorption bed mounted on roof at β angle. The heat received by glazing at top of adsorption bed perhaps bed generate a cooling effect. The cooling is transferred to cavity from which air flowing and enter the room. The night ventilation increased up to 20% because of adsorption heat produced in adsorption cooling is utilized to induce ventilation.

5. Mathematical models and discussion

The above discussed mathematical modeling has been taken from Ong (2003), and Bansal et al. (1993). The various important mathematical modeling, dimensions of solar chimney and other resulting parameters are shown in Table 2.

Table 2. Mathematical modelings for solar chimney calculations

S.No.	Authors	Model size and type	Model	Solution Technique	Results
1.	N. K. Bansal R. Mathur M. S. Bhandari, 1993	Wall mounted Solar chimney $1.5x1.5x0.15m^3$ for 3.6 ACH and $4x4x4m^3$ room size	Energy balance for absorber plate $(\alpha.\tau).\bar{S}(t) = h_f(T_p - \bar{T}_f) + U_t(T_p - T_a) + U_b(T_p - T_R)$ Energy balance for flowing fluid $m.C_p.\frac{dT_f}{dx}.x = h_f.w.\Delta x.(T_p - T_f)$ Volume flow rate $Q_i = C_d.A_o[2.(^{\Delta T}/_{T_o}).g.H.sin\beta]^{1/2}.[(1+A_r^2)]^{1/2}$ and $Q_o = C_d.A_o[2.(^{\Delta T}/_{T_i}).g.H.sin\beta]^{1/2}.[(1+A_r^2)]^{1/2}$		Optimized absorber area $2.25m^2$ for ACH-3 to 6 Air flow rate 2.33m/s
2.	K.S. Ong, 2002 K.S. Ong, C.C. Chow, 2003	Wall mounted Solar Chimney 2x0.45x0.48 (Gap varying as 0.1, 0.2, 0.3)	Energy balance Equations $T_g: S_1 + h_{rwg}(T_w - T_g) + h_g(T_f - T_g) = U_t(T_g - T_a)$ $T_f: h_w(T_w - T_f) = h_g(T_f - T_g) + \dot{q}''$ $T_w: S_2 = h_w(T_w - T_f) + h_{rwg}(T_w - T_g) + U_b(T_w - T_R)$	Solving by matrix inversion method	Air velocity 0.25 to 0.36 m/s
3.	N.K. Bansal, Jyotirmay Mathur, Sanjay Mathur, Meenakshi Jain, 2005	Window Size $1x1x0.13\ m^3$ Chimney $1x1x1\ m^3$ Room	For vertical glass cover $S_1A_g + h_{rwg}A_w(T_w - T_g) = h_gA_g(T_g - T_f) + U_tA_g(T_g - T_a)$ For the air in the flow channel $h_wA_w(T_w - T_f) + h_gA_g(T_g - T_f) = q'$ For the absorber wall $S_2A_w = h_wA_w(T_w - T_f) + h_{rwg}A_w(T_w - T_g) + U_bA_w(T_w - T_R)$	Programming in C++	Flow velocity found 0.24m/s latitude 27° N and altitude 75.82E
4.	E.P. Sakonidou, T.D. Karapantsios, A.I. Balouktsis, D. Chassapis , 2008	Small Chimney $1x0.74x0.11m^3$	Model for optimum tilt for maximum air flow $I_T = I_{dir}R_b + I_{diff}\left(\frac{1+\cos s}{2}\right) + I_{rg}\left(\frac{1-\cos s}{2}\right)$ $v = C_d.\frac{\rho(T_{air})}{\rho(T_o)}.\left[\frac{L.g.(\sin(s))^2.(T_{air} - T_o)}{T_o}\right]^{1/2}$	Compared experimental results with CFD model	Optimum tilt between 65 to 76 degree For latitude 41°70', longitude 23°34', altitude 32 m

Bansal et al. (1993) optimized the absorber area of solar chimney for $16m^3$ room volume and 3 to 6 ACH and reported $2.25m^2$ optimum absorber area and 0.233 m/s air velocity. Mathur and Mathur (2006) experimentally analyzed the window size solar chimney and optimized the tilt angle. The air gap between absorber plate and glass cover does not play any significant role on the performance of solar chimney but height of inlet vent takes important role where mass flow rate and ACH will be increases by increasing this height, it is clearly shown in Table 3.

Table 3. Experimental and theoretical results for different air gap and stack height (Mathur and Mathur, 2006)

Absorber height (m)	Inlet height (z) (m)	Air gap (d) (m)	Stack height (m)	ACH at 300 W/m^2		ACH at 500 W/m^2		ACH at 700 W/m^2		Recorded ambient temperature range (K)
				Exp.	Theo.	Exp.	Theo.	Exp.	Theo.	
0.9	0.1	0.1	0.95	2.0	2.497	2.4	2.992	2.662	3.125	298–300
	0.1	0.2	0.95	2.80	2.949	2.0	3.392	3.73	3.879	297–299
	0.1	0.3	0.95	2.4	2.704	2.66	3.461	2.93	3.671	294–296
0.8	0.2	0.1	0.9	2.66	2.608	2.93	3.067	4.0	3.518	297–300
	0.2	0.2	0.9	4.53	3.633	4.26	4.049	3.73	4.688	300–306
	0.2	0.3	0.9	5.33	4.054	4.53	4.895	5.33	5.175	298–304
0.7	0.3	0.1	0.85	3.2	2.406	4.0	3.09	4.4	3.524	297–305
	0.3	0.2	0.85	4.0	3.619	5.2	4.205	5.2	4.942	296–298
	0.3	0.3	0.85	4.4	4.173	4.8	5.160	5.6	5.810	295–302

The location of the solar chimney particularly latitude is affecting the performance because it decided the optimum angle for maximum flow condition. Mathur and Mathur (2006) given the 45 degree optimum angle for 27 degree North latitude and optimized the inclination angles for latitude between 0 to 65ºN, it is shown in Table 4. Reddy (2012) experimentally optimized the tilt angle for Trichurapalli, India (longitude +78˚69'E and latitude +10˚81'S) and found the 45º optimum inclination angle. The system becomes inefficient and the return on investment will dramatically diminish if the solar chimney inclination angle and the position is not correct for particular location.

Table 4. Optimum Inclination of solar chimney at different latitudes (Mathur and Mathur, 2006)

S.No.	Latitude In degree	Optimum inclination of solar chimney in degree	S.No.	Latitude In degree	Optimum inclination of solar chimney in degree
1.	0	55	8.	35	50
2.	5	50	9.	40	50
3.	10	50	10.	45	55
4.	15	50	11.	50	55
5.	20	45	12.	55	60
6.	25	45	13.	60	60
7.	30	45	14.	65	60

6. Conclusion

The types, classification, application and mathematical methodology of available solar chimney technology for building ventilation are reviewed in this paper. The various performance factors in available designs for passive heating and cooling application in buildings also presented. The performance mainly depends on the temperature and pressure differences. The methodology shows the simplest solution to calculate the air flow rate. Applications are depends on the type and configuration of chimney. The heating and cooling of buildings by solar chimney aspects are clearly shown. The conventional air conditioning system can be fully replaced by adopting these integrated techniques for building space conditioning, it reduces the building energy load and sustainability will increase. The conventional construction cost is increasing slightly by use of solar chimney but in long term it will be beneficial.

References

Afonso, C. and Oliveira, A. (2000), "Solar chimneys: simulation and experiment", *Energy and Buildings*, Vol. 32 No. 1, pp. 71-79.

Alter, L. (2011), "The Trombe wall: Low tech solar design makes a comeback" available at:http://www.treehugger.com/sustainable-product-design/the-trombe-wall-low-tech-solar-design-makes-a-comeback.html/ (assesses October 2012).

Arce, J., Jimenez, M.J., Guzman, J.D., Heras, M.R., Alvarez, G. and Xaman, J. (2009), "Experimental study for natural ventilation on a solar chimney", *Renewable Energy*, Vol. 34 No. 12, pp. 2928-2934.

Assadi, M.K., Dalir, F. and Hamidi, A.A. (2011), "Analytical model of atrium for heating and ventilating an institutional building naturally", *Energy and Buildings*, Vol.43 No.10, pp. 2595-2601.

Bansal, N.K., Mathur, J. andBhandari, M.S. (1993),"Solar chimney for enhanced stack ventilation", *Building and Environment*, Vol. 28 No. 3, pp. 373-377.

Bansal, N.K., Mathur, R. and Bhandari, M. (1994), "A study of solar chimney assisted wind tower system for natural ventilation in buildings", *Building and Environment*, Vol. 29, No. 4, pp. 495-500.

Bansal, N.K., Mathur, J., Mathur, S. and Jain, M. (2005), "Modeling of window-sized solar chimneys for ventilation", *Building and Environment*, Vol. 40 No.10, pp. 1302-1308.

Barozzi, G., Imbabi, M., Nobile, E. and Sousa, A. (1992), "Physical and numerical modeling of a solar chimney-based ventilation system for buildings", *Building and Environment*, Vol. 27 No. 4, pp. 433-445.

Bassiouny, R. and Korah, N.S.A. (2009), "Effect of solar chimney inclination angle on space flow pattern and ventilation rate", *Energy and Buildings*, Vol. 41 No. 2, pp. 190-196.

Bassiouny, R. and Koura, N.S.A. (2008), "An analytical and numerical study of solar chimney use for room natural ventilation", *Energy and Buildings*, Vol. 40 No. 5, pp. 865-873.

Bilgen, E. (1982), “Solar heating-Ventilating system using a solar chimney”, *Solar Energy*, Vol. 28 No. 3, pp. 227-233.

Building Energy data book (2007), U.S. department of energy (available at: http://buildingsdatabook.eren.doe.gov/docs%5CDataBooks%5C2007_BEDB.pdf).

Building Energy data book (2011), U.S. department of energy (available at: http://buildingsdatabook.eren.doe.gov).

Bureau of Indian standards (1987), Handbook of functional requirements of buildings. ISBN 81-7061-011-7.

Chandra, S., Kaushik, S.C. and Bansal, P.K. (1985), “Thermal performance of a non-air-conditioned building for passive solar air-conditioned: Evaluation of roof cooling system”, *Energy and buildings*, Vol. 8, pp. 51-69.

Chantawong, P., Hirunlabh, J., Zeghmati, B., Khedari, J., Teekasap, S. and Win, M. (2006), “Investigation on thermal performance of glazed solar chimney walls”, *Solar Energy*, Vol. 80 No. 3, pp. 288-297.

Chen, Z., Bandopadhayay, P., Halldorsson, J., Byrjalsen, C., Heiselberg, P. and Li, Y. (2003), “An experimental investigation of a solar chimney model with uniform wall heat flux”, *Building and Environment*, Vol. 38 No. 7, pp. 893-906.

Dai, Y.J., Sumathy, K., Wang, R.Z. and Li, Y.G. (2003), “Enhancement of natural ventilation in a solar house with a solar chimney and a solid adsorption cooling cavity”, *Solar Energy*, Vol. 74 No. 1, pp. 65–75.

Ding, W., Hasemi, Y. and Yamada, T. (2005), “Natural ventilation performance of a double-skin facade with a solar chimney”, *Energy and Buildings*, Vol. 37 No. 4, pp. 411-418.

Drori, U. (2004), “Induced ventilation of a one-story real-size building”, *Energy and Buildings*, Vol. 36 No. 9, pp. 881-890.

Gan, G. (1998), “A parametric study of Trombe wall for passive cooling of buildings”, *Energy and Buildings*, Vol. 27, pp. 37-43.

Gan, G. (1998), “A numerical study of solar chimney for natural ventilation of buildings with heat recovery”, *Applied Thermal Engineering*, Vol. 18 No. 12, pp. 1171-1187.

Gan, G. (2011), “General expressions for the calculation of air flow and heat transfer rates in tall ventilation cavities”, *Building and Environment*, Vol. 46 No. 10, pp. 2069-2080.

Hirunlabh, J. (2001), “New configurations of a roof solar collector maximizing natural ventilation”, *Building and Environment*, Vol. 36 No. 3, pp. 383-391.

Hirunlabh, J. (1999), “Study of natural ventilation of houses by a metallic solar wall under tropical climate”, *Renewable Energy*, Vol. 18 No. 1, pp. 109-119. http://en.wikipedia.org/wiki/Solar_chimney (assessed on September 2012).

Khedari, J. (2000), “Ventilation impact of a solar chimney on indoor temperature fluctuation and air change in a school building”, *Energy and Buildings*, Vol. 32 No. 1, pp. 89-93.

Khedari, J., Hirunlabh, J. and Bunnag T. (1997), “Experimental study of a roof solar collector towards the natural ventilation of new houses”, *Energy and Buildings*, Vol. 26 No. 2, pp. 159-164.

Khedari, J., Rachapradit, N. and Hirunlabh, J. (2003), "Field study of performance of solar chimney with air-conditioned building", *Energy*, Vol. 28, No. 11, pp. 1099-1114.

Lee, K.H. and Strand, R.K. (2009), "Enhancement of natural ventilation in buildings using a thermal chimney", *Energy and Buildings*, Vol. 41 No. 6, pp. 615-621.

Liping, W. and Angui, L., (2004), "A numerical study of vertical solar chimney for enhancing stack ventilation in buildings", Plea2004 - The 21th Conference on Passive and Low Energy Architecture Eindhoven Netherlands, pp. 1-5.

Macias, M., Gaona, J.A., Luxan, J.M. and Gomez, G. (2009), "Low cost passive cooling system for social housing in dry hot climate", *Energy and Buildings*, Vol. 41 No. 9, pp. 915-921.

Maerefat, M. and Haghighi, A.P. (2010), "Natural cooling of stand-alone houses using solar chimney and evaporative cooling cavity", *Renewable Energy*, Vol. 35 No. 9, pp. 2040-2052.

Maerefat, M. and Haghighi, A.P. (2010), "Passive cooling of buildings by using integrated earth to air heat exchanger and solar chimney", *Renewable Energy*, Vol. 35 No. 10, pp. 2316-2324.

Maia, C., Ferreira, A., Valle, R. and Cortez, M. (2009), "Theoretical evaluation of the influence of geometric parameters and materials on the behavior of the airflow in a solar chimney", *Computers & Fluids*, Vol. 38 No. 3, pp. 625-636.

Mathur, J. and Mathur, S. (2006), "Summer-performance of inclined roof solar chimney for natural ventilation", *Energy and Buildings*, Vol. 38 No. 10, pp. 1156-1163.

Miyazaki, T., Akisawa, A. and Nikai, I. (2011), "The cooling performance of a building integrated evaporative cooling system driven by solar energy", *Energy and Buildings*, Vol. 43 No. 9, pp. 2211-2218.

Mustafa, O. (2008), "Renewable building energy systems and passive human comfort solutions", *Renewable and Sustainable Energy Reviews*, Vol. 12 No. 6, pp. 1562-1587.

Nouanegue, H. and Bilgen, E. (2009), "Heat transfer by convection, conduction and radiation in solar chimney systems for ventilation of dwellings", *International Journal of Heat and Fluid Flow*, Vol. 30 No. 1, pp. 150-157.

Ong, K.S. (2003), "A mathematical model of a solar chimney", *Renewable Energy*, Vol. 28, No. 7, pp. 1047-1060.

Ong, K.S. (2003), "Performance of a solar chimney", *Solar Energy*, Vol. 74, No. 1, pp. 1-17.

Raman, P., Mande, S. and Kishore, V.V.N. (2001), "A passive solar system for thermal comfort conditioning of buildings in composite climates", *Solar Energy*, Vol. 70 No. 4, pp. 319-329.

Reddy, V.S., Premalatha, M. and Ranjan, K.R. (2012), "Experimental studies on solar chimney for enhanced stack ventilation", *International journal of sustainable energy*, Vol. 31 No. 1, pp. 35-42.

Roodman, D. and Lenssen, N. (1995), "A building evolution: How ecology and health are transforming construction", World watch paper #124 (Available at: http://www.worldwatch.org/node/866).

Wang, L. and Li, N. (2010), "Evaluation of buoyancy-driven ventilation in respect of exergy utilization", *Energy and Buildings*, Vol. 42 No. 2, pp. 221-229.

Wei, D., Qirong, Y. and Jincui, Z. (2011), "A study of the ventilation performance of a series of connected solar chimneys integrated with building", *Renewable Energy*, Vol. 36 No. 1, pp. 265-271.

Zamora, B. and Kaiser, A. (2009), "Optimum wall-to-wall spacing in solar chimney shaped channels in natural convection by numerical investigation", *Applied Thermal Engineering*, Vol. 29 No. 4, pp. 762-769.

Zhai, X., Dai Y. and Wang, R. (2005), "Comparison of heating and natural ventilation in a solar house induced by two roof solar collectors", *Applied Thermal Engineering*, Vol. 25 No. 5-6, pp. 741-757.

Abbreviation

CFD	Computational fluid dynamics
SPRSC	Single pass roof solar collector
DPRSC	Double pass roof solar collector
ACH	Air change per hour
RSC	Roof solar chimney
DPC	Damp proof course level
SSPCM	Shape stabilized phase change materials
EAHE	Earth to air heat exchanger

Nomenclature

Q	Volume rate air flow in m^3/s
A	Area of smaller opening in m^2
V	Velocity of air in m/s
k	Coefficient of effectiveness
h_f	Heat transfer coefficient in $W/m^2.K$
A_r	Area ratio
Δ	Difference
v	Volume of the room in m^3
g	Gravitational constant in m/s^2
h_1 & h_2	Heights of stack inlet and outlet above datum in m
T_a	Ambient temperature
T_f	Average fluid temperature

T_i & T_o	Inlet and outlet temperature of stack in Kelvin
T_p	Absorber plate temperature
I_s	Average solar radiation in W/m^2
U_l	Heat loss coefficient of collector
$\dot{m}$	Mass floe rate of air in kg/s
c_p	Specific heat of air in kj/kg.K
w	Width of chimney in m
Δx	Thickness of chimney in m
z	Buoyancy constant

Greek words

β	Solar chimney is inclination angle in degree
ρ	Density of air in kg/m^3
ρ_i	Density inside stack in kg/m^3
α	Absorptance of collector plate
τ	Transmittance of glazing