International Journal of Science and Research Archive
eISSN: 2582-8185
Cross Ref DOI: 10.30574/ijsra
Journal homepage: https://ijsra.net/

(Review Article)

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Natural ventilation enhancement through solar chimney in buildings: A technical review

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International Journal of Science and Research Archive, 2023, 09(01), 056–069

Publication history: Received on 21 March 2023; revised on 29 April 2023; accepted on 02 May 2023

Article DOI: https://doi.org/10.30574/ijsra.2023.9.1.0346

Abstract

The energy demand is increasing day by day in present era and due to increasing the cost of energy by increasing the cost of fossil fuel. The fossil fuel is limited for the future and researchers are continuously working on new options for energy saving or other renewable option. The solar chimney is one of the most feasible retrofit for the buildings which operated by solar irradiance and saved the much of energy used in ventilation cooling and heating of building. The paper is reviewed the solar chimney with various integrated approaches, modeling, simulation, optimization and the techno-economic analysis. The work can be used for the future researchers in this area.

Keyword: Solar Chimney; Air change per hour; Earth air tunnel heat exchanger; Borehole heat exchanger; Integrated approach

1. Introduction

The energy is the basic need of human being as on today for its uses in making food, building ventilation & lighting, comfort conditioning, transportation, agricultural and industrial applications. The energy for human air conditioning including the building ventilation is the primary energy consuming source. The proper ventilation is the need of present building era because the building cluster is increasing abruptly from last few decades. The small amount of saving energy in proper ventilation and day lighting via passive systems will help in considerable amount of energy conservation [1].

Proper ventilation and daylighting systems can significantly minimize the amount of energy used for human air cooling, which is the main energy consumer in residential buildings. The term "ventilation" refers to the process whereby new air is combined with the enclosure's current air to reduce the concentration of contaminants or is utilized to displace the air using piston flow.

The ventilation means fresh air mixed with the existing air in the enclosure to dilute the pollutants. Building ventilation is the purposeful movement of air through a place to maintain a satisfactory level of indoor air quality and, occasionally, to control comfort levels. Ventilation can be either natural or forced. In forced ventilation, air is pushed through a building using mechanical devices like fans. On the other hand, natural ventilation uses wind and other natural factors to create airflow, such as temperature-related density differences (also known as buoyancy or the stack effect).

The natural ventilation can be possible by means of piston flow which is denoted by air change per hour (ACH). This type of ACH can be generated by solar chimney. The standard ACH requirement in India is shown in table 1 for two situations at normal condition and in pandemic conditions.

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Table 1 ACH requirement for various types of facilities and buildings [2]

S. No.	Application	ACH as per NBC 2016	ACH as per SARC-CoV-2 Virus scenario
Residential Building			
1	Living Room	3-6	4-7
2	Bed Room	2-4	3-5
3	Changing Room, Bathrooms	6-10	8-12
4	Corridors	5-10	6-12
5	Entrance Halls	3-5	4-6
6	Garages	6-8	8-10
7	Kitchen	6 min	10 min
8	Basement/Cellar	3-10	4-12
9	Toilets	6-15	8-12
Non Residential Buildings/Public facilities			
1	Assembly rooms/Banks	4-8	8-10
2	Gymnasium	6 min	10 min
3	Shower baths	15-20	18-24
4	Hospitals sterilizing	15-25	18-30
5	Hospital domestic	15-20	18-24
6	Laboratories	6-15	8-18
7	Laundries	10-30	12-36
8	Lavatories	6-15	8-18
9	Isolation/Quarantine Room	-	10 min
10	Offices	6-10	12 min
Commercial shops and stores			
1	Lift cars	20 min	24 min
2	Paint shops (not cellulose)	10-20	12-30
3	Recording control rooms	15-25	18-30
4	Shops and Supermarts	8-15	10-18
5	Bakeries, Dye works	20-30	24-36
6	Cates and Coffee bars, compressor rooms, recording studios	10-12	12-15
Public entertainment /Gathering places			
1	Canteen, Restaurants, Dairies, Conference rooms	8-12	10-15
2	Churches	1-3	10-15
3	Cinema and Theatres, Hair dressing saloon, photo and x-ray dark rooms	12 min	16 min
4	Club rooms, Dance halls, Public house bars	12 min	15 min
5	Store and warehouses	3-6	4-8

6	Squash courts	4 min	6 min
7	Underground vehicle parking	15-30	18-36
Educational Facilities			
1	Utility rooms	15-30	18-36
2	School rooms	6-7	12 min
3	Lecture Theatres	5-8	12 min
4	Libraries	3-5	12 min

Bilgen (1982) proposed a concept of solar chimney for ventilation enhancement in buildings. The energy behind the working of solar chimney is passive solar energy and it was studied by the Handy et al. (1998). Gao et al. (2022) latest by studied the natural ventilation enhancement of the buildings by Roof Solar Chimney (RTSC). The similar studies have been carried out by Tongbai et al. (2014), Zhang et al. (2021) and Shreshtha et al. (2022).

The solar chimney assisted natural ventilation system in the form of a Trombe wall was theoretically studied by Bansal et al. in 1993. A mathematical model for heat transport in solar chimneys was developed by Ong in 2003. In 2009, Bassiouny and Korah examined the effects of the solar chimney's inclination angle on the ventilation rate and flow pattern in space. They discovered that for latitude 28.4°, 0.1-0.35m chimney width, and 500W/m^2 sun intensity, the optimum flow rate could be attained between 45° and 70° inclination angles. The theoretical study of solar chimney have been carried out by various researchers like Barozzi et al. (1992), Hirunlabh (1999), Khedari (2000) Afonso and Drori (2004), Bansal et al. (2005), Okutucu et al. (2010), Lal et al. (2012), Jain et al. (2012), Lal et al (2013) and Lal (2022) etc.

The various experimental studies have also been carried out by the researchers for performance assessment, performance improvement parameters, energy and exergy analysis, optimization of solar chimney and other affecting factors by Awbi (1994), Khedari et al. (1997), Chen et al. (2003), Mathur and Mathur (2006), Arce et al. (2009), Mostafa et al. (2011), Lal et al. 2013, Lal et al (2014) and Lal (2022). Lal (2014) studied the simulation and feasibility of solar chimney along with the experiments.

The solar chimney is the feasible, economically viable and socially acceptable option for increasing the building ventilation. This study deals with the review of solar chimney option for building ventilation which is the best sustainable approach for building vending ventilation and thermal comfort.

2. Solar chimney design

2.1. Basic system design

The wall mounted solar chimney is working on the principle of buoyancy when air is heated changes its density and uplift because of its low density and its space will be filled by cold air. The figure 1 shows the schematic view of solar chimney, where the high and low pressure regions are represented by positive and negative signs, respectively. As a result of the pressure difference brought in the solar chimney due to increase the temperature, the air rises in the chimney, creating a suction force that causes ambient air to fill the air volume difference and ensure effective ventilation of the space. The major component of the solar chimney is a black hollow thermal mass with openings at the top for hot air to escape and at the bottom for fresh air to enter and glass is fitted in front of the chimney for trapping the solar radiation. When the chimney's damper is in position 1, it improves ventilation and lowers the temperature in the space and room will be heated in another position 2, where hot air will be recalculated in the room. By forcing hot air back into the space, as position 1 in the callout illustrates, it can function in reverse to warm a room in a cold climate.

The impact of chimney physical factors on air flow rate was researched by Du et al. [2011]. The results showed that a second-floor chimney should be slanted at a perfect 4 degrees from horizontal, and that a length to breadth ratio of 12:1 is ideal for achieving the highest air mass flow rate. Mathur et al. (2006) developed a rooftop solar chimney (RTSC) for building ventilation at Jaipur city and observed that the sufficient ventilation can be generated by fitted the RTSC retrofit to any existing building. Gao et al. (2022) enhanced the RTSC with induced wind channel and observed the ventilation rate increment by 212% with increasing the chimney angle from 30° to 90° angle and uniform solar radiation 600W/m2.

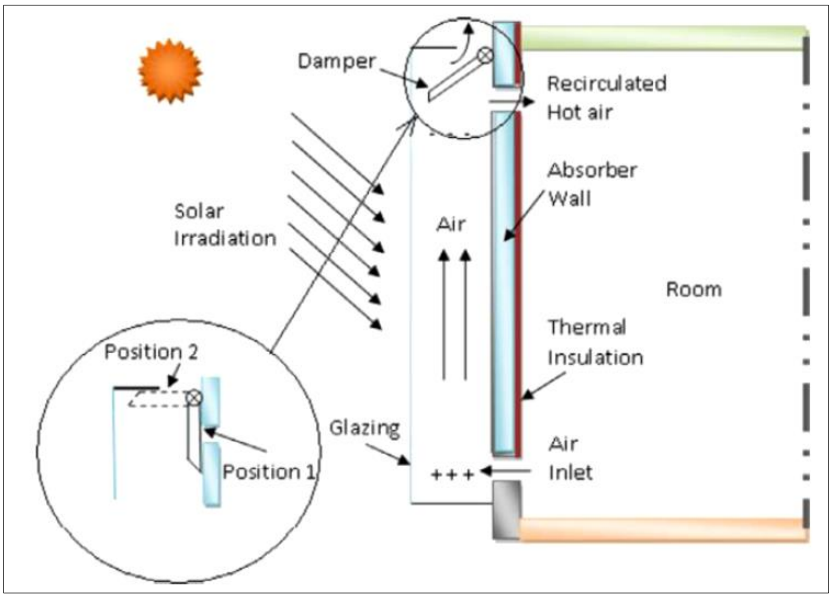

Figure 1 Schematic view of solar chimney for building ventilation [Lal et al. (2013)]

2.2. Various Model Developments for solar chimney

The mathematical model for ACH was developed by Bansal et al. (1993). Theoretical model for ACH, performance, and for other parameters evaluation was developed by Ekechukwu and Norton (1995) and Ong (2003). Brun et al. (2010) experimentally and numerically investigated of the naturally ventilated cavity with the heat transfer concept. Afonso et al. (2000) experimentally assessed the solar chimney and simulated the same. Many researchers have experimentally studied the solar chimney for building ventilation in different-different countries, few of the studies are very important due to there important outcomes and design etc. these are Arce et al. (2009), Bassiouny et al. (2008), Chen (2003), Ding et al. (2004), Farías et al. (2008), Mathur et al. (2005), Zha et al. (2017), Kumar et al. (1998) etc.

2.3. Design and parametric analysis of solar chimney

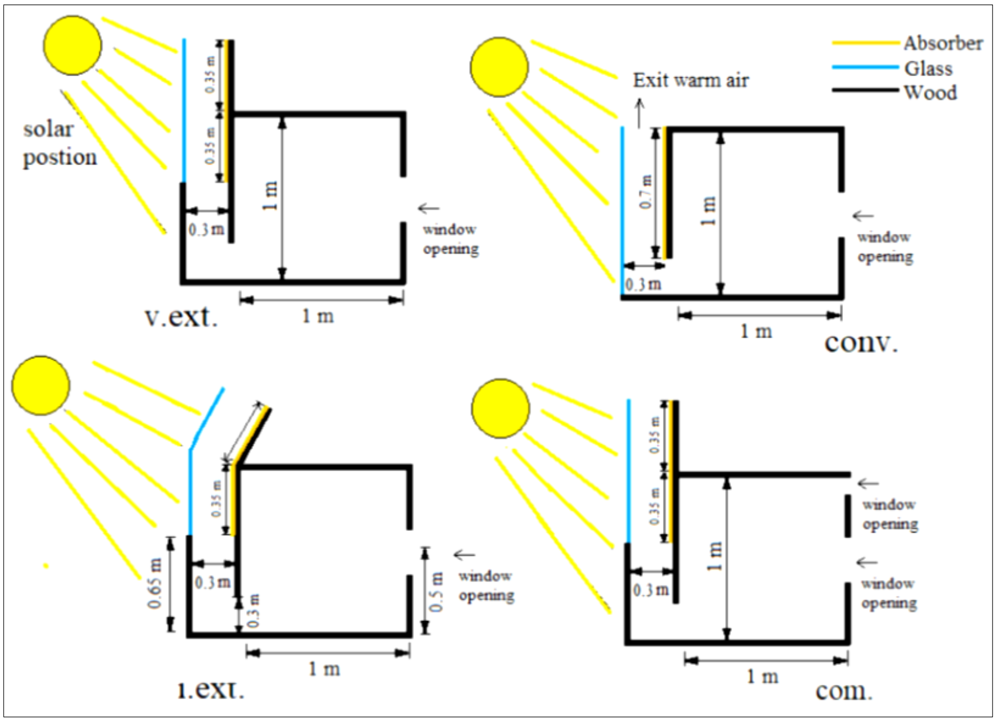

Figure 2 Small scale rooms attached to different chimney model [Hasim et al. (2020)]

The dynamic physical model of solar chimney was developed by Herreo et al. (2007). Ekechukwu et al. (1995) designed a solar chimney for natural ventilation circulation and measured the performance of the same.

Hasim et al. (2020) proposed few models of solar chimney inside a room as shown in figure 2 and numerically investigated the ventilation enhancement. The similar studies have been carried out by the Zamora and Kaiser (2010). Some software also implemented by the researchers for investigating the performance and simulated the model for new parametric studies. Feasibility and parametric analysis of the solar chimney was studied using computational fluid dynamics (CFD) by the Kong et al. (2020 and Lal (2014). Figure 3 shows the proposed modified experimental solar chimney which was projected at CBRI Roorkee. The parametric study was carried out with the effect of inlet opening, air gap, air gap to inlet ratio and glass inclination angle on ACH of solar chimney.

It was observed that the optimum inlet opening, air gap, air gap to inlet ratio and glass inclination angle were 300 mm, 60 mm, 0.2 and 5°respectively. Matius et al. (2021) also optimized of solar chimney's and PV cell tilt angle at various Orientations and similar study for optimum tilt angle was carried out by Sakonidou et al. (2008).

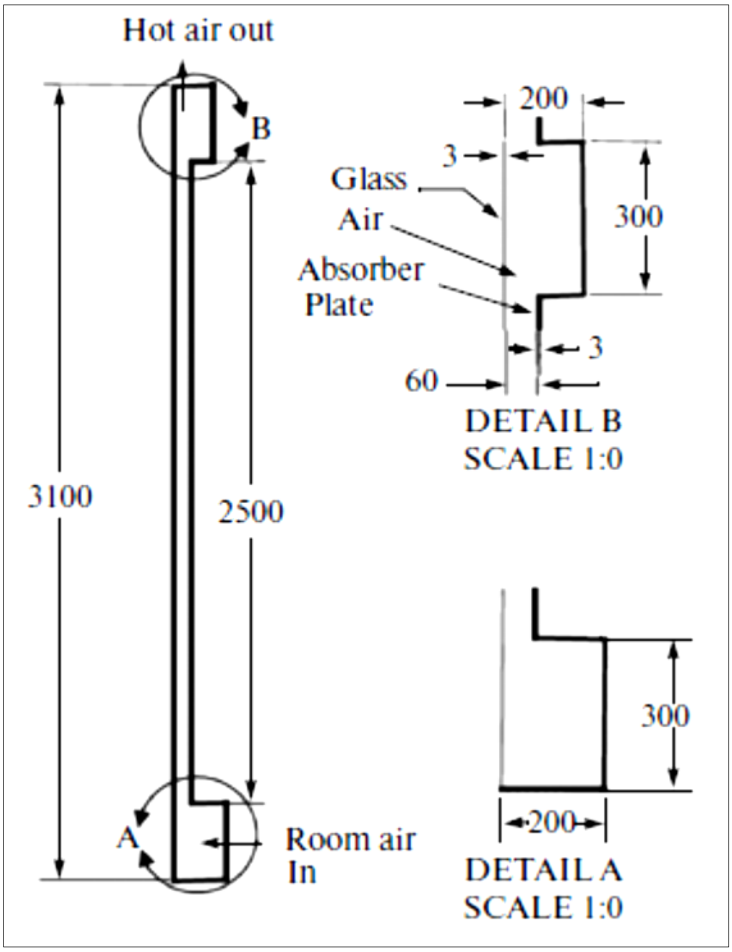

Figure 3 Detail modeling of modified solar chimney [Lal 2014]

The studies on optimization of solar chimney inclination angle, space flow rate, ventilation rate was carried out by Bassiouny and orah (2009); height to base ratio, length effect in trapezoidal prism inclined solar chimney by Balhadj et al. (2021) as shown in figure 4; optimal mixed convection for maximum energy recovery with porous channel by Baoutin and Gossselin (2009), collector air gap to height ratio by Bassey et al. (1994), materials by Maia et al. (2009).

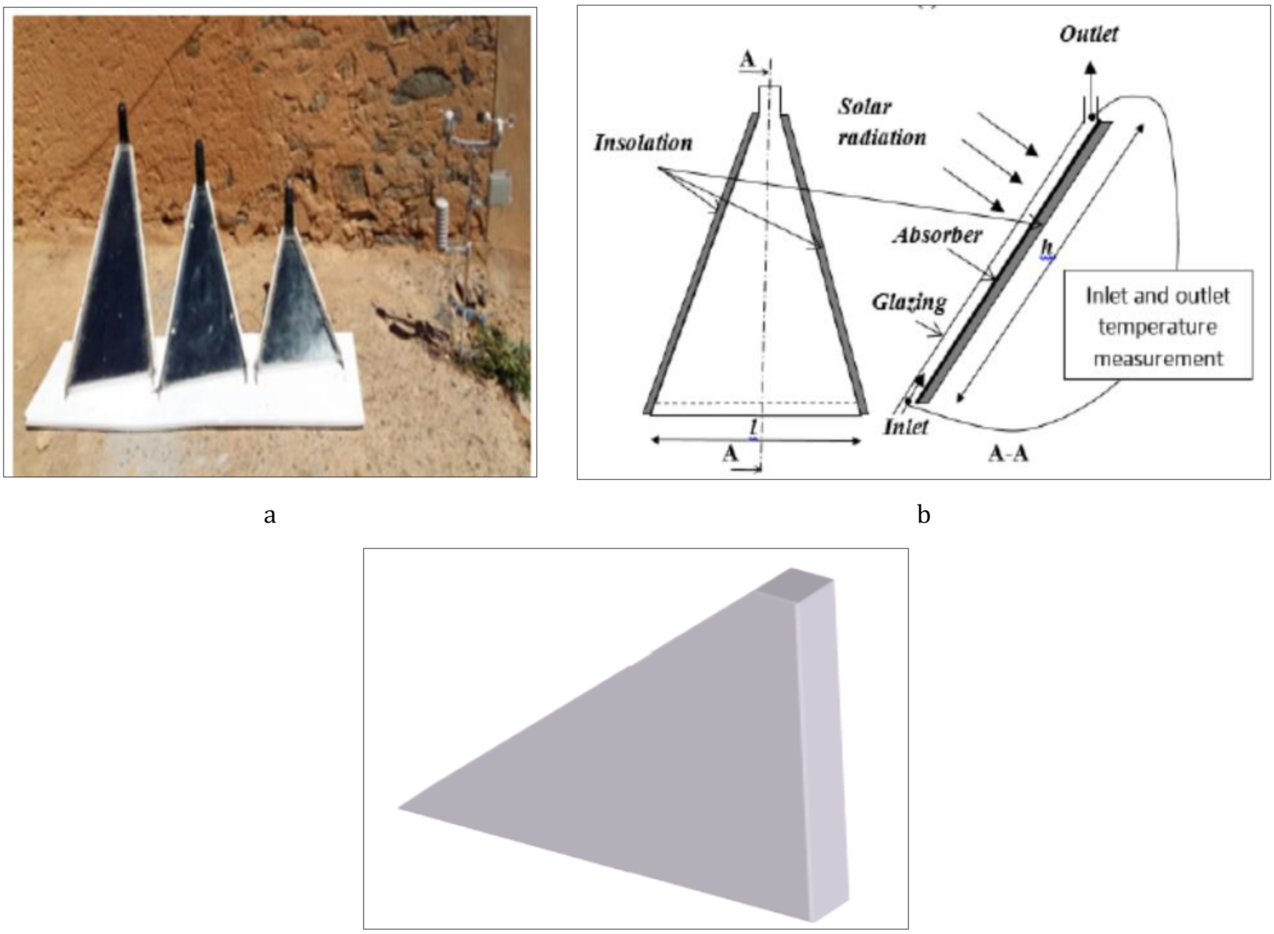

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Figure 4 (a) Solar chimneys and weather station installation, (b) Schematic experimental setup, (c) 3D illustration of the solar chimney (trapezoidal prism shape) [Balhadj et al. (2021)]

2.4. Thermodynamic analysis

The thermodynamic modelling, heat transfer analysis energy analysis and exergy analysis are the major criteria's for thermal analysis of any system. The thermal management system occurs in solar chimney when it heated from trapped solar irradiance which was presented by Andreozzi et al. (2009). The system can be used in day time only when solar irradiance are comes in to picture but modified solar chimney can be working for whole day because it has inbuilt thermal mass which stored the solar thermal heat in day time and gives to the chimney in night time. The other important parameters which are affected the solar chimney performance are the material of absorber, colour of absorber, glass transmittance, length of the solar chimney and the solar irradiance angle on the trapped surface. tHe performance was assessed by various researchers and implied the some parameters which are discussed in above line, the work presented by Dossbernarde et al. (2003), Burek and Habeb (2007), Kasayapanand (2008), Nouanegue and bilgen (2008), Cuce and Cuce (2019) and Ren et al (2019). Some of the researchers are presenting their work on the basis of the different weather regions and found the suitability of solar chimney in that region. AboulNaga (2000) studied the solar chimney for hot-arid climatic conditions for low rise buildings and Fitzgerald et al. (1988) studied the same in hot climate. In a tropical country Abraham et al. (2020) presented their work for ambient obstacle and cross-wind.

2.5. Application of solar chimney in various types of buildings

The solar chimney is widely used in various applications but the ultimate aim is to increase the air flow rate. Graca et al. (2005) designed a solar chimney for children's museum in San Diego and creates proper ventilation. Abdulhamid and Tukur (2019) enhanced the natural ventilation of a hospital building through the solar chimney. Lal et al. (2013) used a solar chimney for enhancement of natural ventilation in a MIG type residential house in India. Abraham and Ming (2021) approved that the solar chimney is most effective into generate the sufficient natural ventilation in high rise buildings. Bacharoudis et al. (2007) employed the solar chimney in natural ventilation enhancement when one wall taken adiabatic and another wall under a heat flux. The shaft in a building can work for ventilation enhancement by using it as a solar chimney and the similar study was carried out by Bansal et al. (1994). Khedari et al. (2000) assessed the variation in ventilation and indoor temperature fluctuations due to of solar chimney in school building. Miyazaki et al .(2006) apply the solar chimney technology in office building in Japan to improve the ACH. Onyango and Ochieng (2006) estimated the potential of solar chimney in rural area of developing countries. The increasing ACH means reducing the pollution in buildings, this concept was utilised by Richter (2021) for mitigation of air pollution through application of the solar chimney. Das and Kumar (1989) used the solar chimney in increasing the air flow rate in solar dryer, the similar studies in dryers were used by Afriyie et a. (2009), Ferreira and Maia (2008).

2.6. Phase change Materials application in solar chimney

Solar chimney is working by utilising the solar energy to heat the air inside the chimney which creats the buoyancy effect. The absorber can store the heat for continues working of chimney in off-sun time or night time. Lal et al. (2013) used a water tank at the place of absorber to store the heat and estimated the sufficient ventilation as per norms in the building. Some of the researchers have been used phase change materials for heat storing in solar chimney these are li et al. (2020), Xaman et al. (2019) and Wang and Lei (2019).

3. Integrated solar chimney design

The solar chimney and photovoltaic (PV) integration concept was given and demonstrated by Camilo et al. (2019) and observed building demanded power generation by PV cell and ventilation enhancement by solar chimney, the similar studies have been carried out by Jasim et al. (2022), Yelpale et al. (2014). Cao et al. (2021) studied the integration approach of solar chimney and PV system alongwith the phase change materials (PCM) and evaluated the sufficient ventilation rate in night time due to the application of PCM. Dai et al. (2003) used the solar adsorption cooling cavity along with the solar chimney to enhance the ventilation with the thermal comfort. Gan and Riffat (1998) numerically studied the solar chimney with heat recovery. Kumar and Rishnaveni (2015) analysed the performance of integrated approach of solar chimney and evaporative cooling and found a good ventilation as well as thermal comfort in summer season, the similar studies were carried out by Maerefat et al. (2010). The solar chimney and radiative cooling cavity were parametrically studied by Suhendri et al. (2022). Lal and Kaushik (2017 and 2018) studied the solar chimney integrated with earth air tunnel heat exchanger and in another study it was integrated solar chimney with borehole heat exchanger and presented the best performance for both ventilation and thermal comfort, the EATHE as shown in figure 5 and Solar chimney integrated for thermal comfort and ventilation were also studied by Maerefat et a. (2010). Zamrano and Alvarado (1984) studied the integrated approach of solar chimney and solar dryer.

Figure 5 SC-EATHE and SC-BHE integrated approach for enhancement of ventilation and thermal comfort of Building [Lal and Kaushik (2017 and 2018)]

4. Performance evaluation and Techno-economic analysis

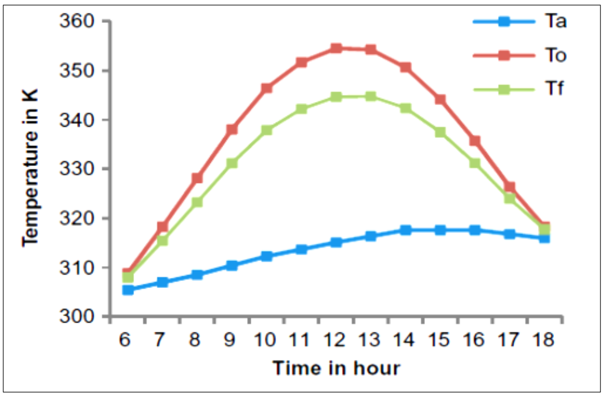

Figure 6 Variation of ambient, air and exit solar chimney Temperatures [Lal et al. (2013)]

The temperature variation in the solar chimney as per the ambient temperature, and at exit is shown in figure 6 and observed the maximum flow fund at the middle of the day when hotness is maximum and at the same time the more ventilation will be required means highest air flow rate has to be found as shown in figure 7.

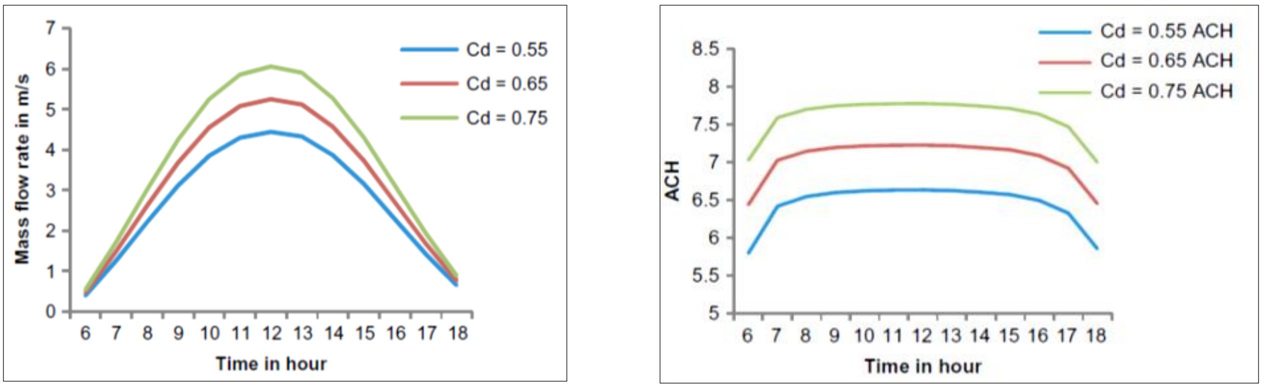

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Figure 7 (a) Mass flow rate v/s Time and (b) ACH v/s time of the solar chimney [Lal et al.2013]

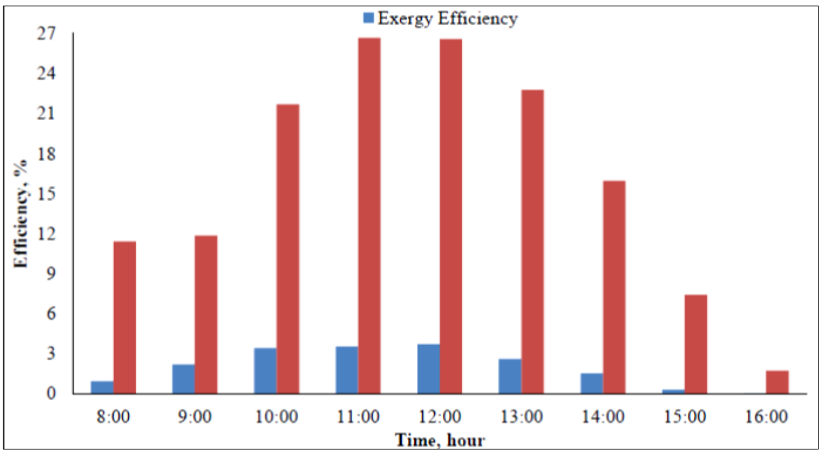

Figure 8 Energy and Exergy efficiency for a typical day of May 2013 [Lal (2022)]

Lal (2022) techno-economically analyzed the solar chimney for both with or without the MS box (as heat storage attachment) and evaluated the payback period less than one year. It was also estimated the saving of electrical energy by 2515kWh and the CO2 mitigated about4.37 ton and 5.51 ton per pear by with or without MS box applications in solar chimney. It was observed that the maximum efficiency of the solar chimney was evaluated by 26.68% and the Exergy efficiency was evaluated by 3.69% as shown in figure 8.

5. Conclusion

The solar chimney is a suitable option for reducing the heating, cooling and ventilation load of building because the maximum load of building is the cooling heating and ventilation. This option is most viable and observed less than 1 year payback period which is very less and indicated most feasible approach. The design of the solar chimney is varying according to the application and the maintenance was observed very less. The solar chimney can be integrated with various options of sustainable approaches in buildings like PV system, EATHE, BHE and evaporative cooling etc. The solar chimney having wide scope for the study and the future scope observed such as follows:

- Material advancement
- Absorber plate design and heat storage
- Chimney design as per the aura and the architectural look of building
- Presently glass is utilized for trapping the solar irradiance and this can be changed by other materials with high transparence.
- It can be analyzed by other software's like TRANSIS, MATLAB, CFD and other building modeling and simulation software.
- The utilization of the integrated approach can be experimentally verified by some other researchers in future.

Compliance with ethical standards

Acknowledgments

I acknowledge my thanks to the Dr. Shiv Lal, Rajasthan Technical University Kota India who provided the idea and research direction in the present scenario,

Disclosure of conflict of interest

I would like to declare that no conflict of interest exits in this manuscript. The work described is original research and none of the material in this paper has been published or is under consideration for publication elsewhere. All the ethical practices have been followed during writing. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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