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Experimental Studies on Solar Chimney for Building Space Heating and Ventilation Enhancement: Energy, Exergy and Economic Analysis

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Abstract

Solar chimneys are with or without heat storage widely used for improving the ventilation and thermal comfort in buildings. The energy, exergy, economic analysis of solar chimney and the CO2 mitigations (EEEC) are evaluated in this communication. The improved solar chimney with MS plate and MS box was designed and developed by the author in the CBRI Roorkee. The observations of typical day of December have been taken for the presentation and the whole month data have been used to evaluate the EEEC parameters. The maximum energy efficiency has been observed by 26.68% during 12 hours of the typical day, and at the same time the exergy efficiency has obtained 3.69%. Approximately 2285kWh energy can be saved during a year through solar chimneys. The payback period of an improved solar chimney with MS plate (SCWMSP) is estimated to be less than one year and with MS box (SCWMSB)) it is likely to be one year. CO2 can also be saved with the energy conservation parameter observed saving of 4.37 ton / year CO2 by SCWMSP, on the other hand if SCWMSB have implemented than CO2 would be save by 5.51 ton/year.

Keywords

Energy, exergy, techno-economic analysis, CO2 mitigation

1. Introduction (Heading 1)

Natural ventilation is the process of air supply contribution for indoor space by natural in-out method, significance of that is fan or other mechanical system are not applicable. This is called the air inhalation of the building. Natural ventilation provides a safe and healthy environment and provides some cooling effect without using mechanical systems. It is also advantageous regarding economic and environmental contest of energy use. The natural ventilation can be enhanced by using solar chimney as an essential accessory of the building. Solar chimneys are simply a passive air heater which is covered by glass for trapping the solar radiation t produce enough heat for generating the chimney effect [1]. Theoretical and experimental studies have been conducted by various researchers to determine the size of solar chimney and also established mathematical modeling to evaluate the air flow rate and temperature of different parts, air gap between glazing and absorber surface, elevation of the air inlet and exit, and effect of insolation rate and ambient air temperature. Few works have been found concerned with thermal modeling and exergy analysis [2].

Energy analysis is a general method to find out the energy efficiency of the system, but it gives quantity analysis only. The first law or energy analysis could not give any suggestion about the quality of energy, that's why second law analysis incorporates this problem. Exergy is something like net positive works which convertible into useful work or availability. The availability is slightly differing from exergy. Exergy term was proposed by Rant in 1956 but Gibbs in 1873 given the theory of exergy based on work [3].

Kotas [4] demarcated the exergy tool for optimization and design of a thermal system. It stated that "the exergy of a steady stream of matter is equal to the maximum amount of work obtainable when the stream is brought from its initial state to the dead state by processes during which the stream may interact only with the environment". Exergy is a net positive energy that can be used to generate positive output and it depends on the property of a system and its surroundings.
Dincer [5-6] quoted the Exergy as another word used to describe available energy or the determination of energy available to do work over the heat sink. Exergy presents the most natural and appropriate universal standard for the quality of energy by using the environmental parameters as reference state. It is a common standard for investigation of exploitability of a reservoir.

Wall published a book on exegetics [7] and presented a concept for sustainable engineering through exergy tools. Wall [8] elaborated the definition of exergy and stated that it is a tool for design and optimization of thermal energy system along with energy utilization. Bejan [9] analyzed exergy extraction based on time varying heat transfer from solar collectors. The maximization of exergy output is the fundamental problem of thermal design in solar collectors.
A sustainable energy system may be developed as reliable and environmentally friendly, cost effective, energy efficient, and it can be effectively utilizing the local network and resources. The exergy analysis is extensively used in design, simulation and for performance assessment based on the second law of thermodynamics which gives quality perception of energy production and utilization. It can be adequately used to analyses both renewable and nonrenewable energy resources.
Hepbasli [10] reviewed mathematics of exergetic analysis of renewable energy resources as collectors, photovoltaic and hybrid PV/thermal solar collectors, wind energy, geothermal, biomass, ocean and tidal power generation systems for sustainable future.

Altfeld et al. [11] evaluated the second law optimization of flat-plate solar air collector, where main interest was to design a solar air heater with high heat transfer and low friction losses, and it was optimized by using net exergy flow. It was observed that the heat transfer characteristics of the absorber are less important in the case of a highly insulated solar air heater.

The energetic optimization of a flat plate solar collector was studied by Farahat et al. [12] and revealed that the overall loss coefficient is not a constant parameter and the precise calculation of this parameter increase the accuracy of exergy efficiency. The exergy efficiency should be affected by optical efficiency, incident solar energy per unit area of absorber plate, fluid inlet temperature and pipe diameter

Gupta and Kaushik [13-14] investigated the theoretical effect optimal performance parameter as aspect ratio for the collector; solar insolation; mass flow rate of air and duct depth on energy and exergy output rates for forced flow solar air heater. Solar chimney is a rectangular cross sectional vertical channel where heat is transferred through naturally convection mode and heated air uplifted via buoyancy effect.

Lal [15-16] carried out experimentally and CFD simulation studies of solar chimney. The CFD simulated results are found to be in good agreement with experimental absorber plate temperature, but CFD and experimental glass temperature difference increases due to higher wind losses from the glass till evening. The optimum air gap value has been found as 60 mm which is 1.5 times higher than the hydrodynamic boundary layer thickness of MSC. The optimized air gap to inlet opening ratio was evaluated by R_Gio=0.2 and optimized glass tilt angle was evaluated by θ_g=5 degree for higher performance with turbulence considerations.

In view of the authors, the work on the exergy efficiency of solar chimney in building application is scant. Therefore, in the present paper an attempt has been made to analyses solar chimney system and evaluates the energy efficiency, exergy efficiency, and techno-economic analysis and CO2 mitigation for sustainable development. for building applications with the help of exergy analysis tool.

2. Materials and Methods

2.1. Energy and Exergy Analysis

From the first law of thermodynamics, energy is conserved in every system means energy is always conserved. It is called the "quantity conservation of energy". It decided the quantity factor not the quality factor; unknowing which form of energy is higher or low quality/grade. The second law is a true measure of conservation of energy, and it classifies the quality of energy as high (work) and low (heat) grade energy. It helps to find out the higher irreversible zone in a system by which losses can be reduced.

The instantaneous of heat collection in solar chimney is given by,

$$\eta = \frac{\dot{m}_f C_f (T_{fo} - T_{fi})}{I_s A_c} \tag{1}$$

The exergy is defined as the maximum amount of positive work which can be obtained from a given form of energy by a system as it reaches equilibrium with reference state [Kotas, 1984]. The second law states the law of degradation of energy, and it is equivalent to the irreversibility within the system. Irreversibility is the loss of exergy due to all real processes and it occurs due to entropy generation. There are two main sources of entropy generation in a building integrated solar chimney, one due to the friction of passing fluid (air), and the other one due to thermal heat transfer or temperature change of air [17-18]. The following assumptions made to considered to derive the exergy balance equations: the potential and kinetic energies are negligible, the process is steady state and steady flow, air is an ideal gas, so its specific heat is constant, the humidity of air is negligible.

The exergy of solar radiation is incoming to the solar chimney, and it converts into thermal (heat) exergy. The exergy of solar radiation input to the solar chimney is given by Petela [19] as follows: [Here, $T_a = T_o$]

$$E_{x,rad} = I_s \times A_s \left[1 - \frac{4}{3}\left(\frac{T_o}{T_s}\right) + \frac{1}{3}\left(\frac{T_o}{T_s}\right)^4\right] \tag{2}$$

Here T_s is solar temperature and it is equal to be 6000 K [10].

Exergy output is follows:

$$E_{x,heat} = \left(1 - \frac{T_o}{T_f}\right) \times \dot{Q}_u \tag{3}$$

The Exergy employment efficiency to elevate the inside air temperature is given as follows:

$$\Psi_{solar} = \frac{E_{x,heat}}{E_{x,rad}} \tag{4}$$

The hot air has the exergy potential to generate the chimney effect in the solar chimney. This process is being considered as steady flow process and exergy can be derived by the generalization of the Petela equation.

The exergy balance for steady flow process is given as:

$$E_{x,in} + E_{x,heat} = E_{x,out} + E_{x,work} + \dot{I} \tag{5}$$

There is no work out in this solar chimney then,

$$E_{x,work} = 0 \tag{6}$$

Exergy of air entering to the chimney is given by:

$$E_{x,in} = \dot{m}_{in}[(h_{in} - h_o) - T_o(s_{in} - s_o)] \tag{7}$$

Exergy out from the chimney outlet is given by:

$$E_{x,out} = \dot{m}_{out}[(h_{out} - h_o) - T_o(s_{out} - s_o)] \tag{8}$$

And mass balance is $\dot{m}_i = \dot{m}_{out} = \dot{m}_f$

Substituting the values of heat exergy, work exergy, input and exit exergy, we get:

$$\dot{I} = E_{x,in} + E_{x,heat} - E_{x,out} \tag{9}$$

Above equation can be written as,

$$\dot{I} = \left(1 - \frac{T_o}{T_f}\right) \times \dot{Q}_u - \dot{m}_f[(h_{out} - h_{in}) - T_o(s_{out} - s_{in})] \tag{10}$$

In above equation of irreversibility, $(h_{out} - h_{in})$ and $(s_{out} - s_{in})$ can be find out by,

$$h_{out} - h_{in} = c_p(T_{out} - T_{in}) \tag{11}$$

$$s_{out} - s_{in} = c_p \ln\left(\frac{T_{out}}{T_{in}}\right) - R \ln\left(\frac{P_{out}}{P_{in}}\right) \tag{12}$$

And again, the total irreversibility of the system is given by

$$\dot{I} = \left(1 - \frac{T_o}{T_f}\right) \dot{Q}_u - \dot{m}_f c_p(T_{out} - T_{in}) + \dot{m}_f T_o c_p \ln\left(\frac{T_{out}}{T_{in}}\right) - \dot{m}_f R \ln\left(\frac{P_{out}}{P_{in}}\right) \tag{13}$$

From the definition of irreversibility

$$\dot{I} = T_o \dot{S}_{gen} \tag{14}$$

Then entropy generation in the system is given by,

$$\dot{S}_{gen} = \frac{1}{T_o}\left[\left(1 - \frac{T_o}{T_f}\right) \dot{Q}_u - \dot{m}_f c_p(T_{out} - T_{in}) + \dot{m}_f T_o c_p \ln\left(\frac{T_{out}}{T_{in}}\right) - \dot{m}_f R \ln\left(\frac{P_{out}}{P_{in}}\right)\right] \tag{15}$$

The exergy efficiency of the chimney is given by,

$$\psi_{chimney} = \frac{E_{x,out}}{E_{x,in} + E_{x,heat}} \tag{16}$$

But in actual practice supplied exergy is only heat exergy, then

$$\psi_{chimney} = \frac{E_{x,out}}{E_{x,heat}} \tag{17}$$

$$\psi_{chimney} = 1 - \frac{\dot{I}}{E_{x,heat}} \text{, or} \tag{18}$$

$$\psi_{chimney} = 1 - \frac{T_O \dot{S}_{gen}}{\left(1-\frac{T_O}{T_f}\right)\times \dot{Q_u}} \tag{19}$$

The net exergy efficiency of solar chimney can be written as:

$$\psi_{net} = \Psi_{solar} \times \psi_{chimney} \tag{20}$$

A solar chimney is simply structured with a hollow frame which has one side absorber plate and other side transparent glass. Whereas top and bottom openings indicated the outlet and inlet vent. This system is fitted on the south facing wall of the experimental room. The inlet vent is directly connected with the experimental room and two dampers are provided at outlet to ambient or room. In summer it works as a ventilation enhancement system and in winter it works as air heater for the room. The room heating mode and ventilation enhancement modes are presented in the schematic diagram as shown in figures 1 and 2 respectively.

$$= \Psi_{solar} \times \psi_{chimney}$$

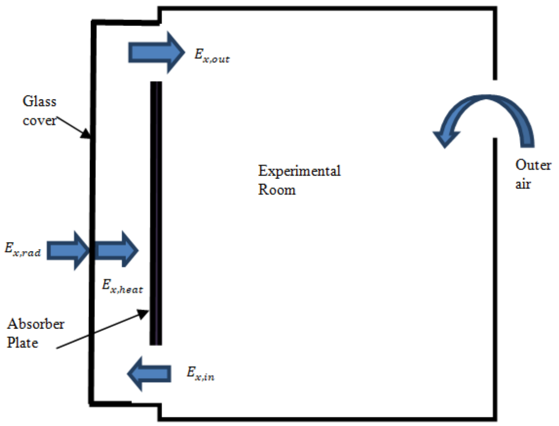


Figure 1. Exergy diagram for SC space heating mode

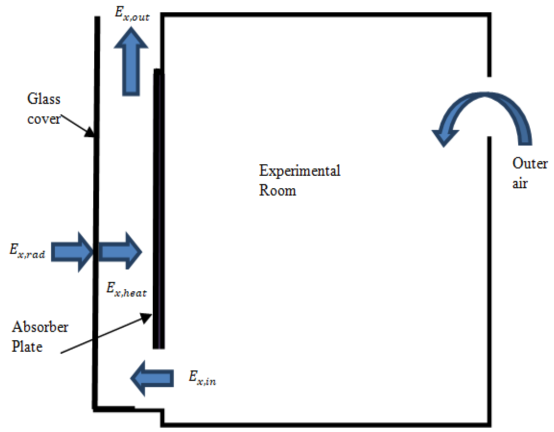


Figure 2. Exergy diagram for SC ventilation mode

2.2. Physical Properties of Air

The following relations are proposed for physical properties of dry air for low temperature (300-400K) as per the assumption of linear variations with respect to temperature. The tabulated data were taken from Holman [20] to find out the relation by minimum square root error method solved in Excel 7.0 software. [21]

Density:

$$\rho_f = 1.1667 - 0.00295(T_f - 300) \tag{21}$$

Specific heat:

$$C_p = [1.005417 + 0.00008298(T_f - 300)] \times 10^3 \tag{22}$$

Dynamic viscosity:

$$\mu = [1.849167 + 0.004398(T_f - 300)] \times 10^5 \tag{23}$$

Thermal conductivity:

$$k = 0.026268 + 0.0000741\left(T_f - 300\right) \quad (24)$$

Volumetric coefficient used in Grashof number

$$\beta_v = {}^{1}/_{T_m} \quad (25)$$

Table 1. The input parameters and Solar chimney data

S. No.	Specification	Assumed data
1.	No. of Glazing	1
2.	Transmittance	0.9
3.	Absorptance of collector surface plate	0.8
4.	Thermal conductivity of glass	0.744W/m. K
5.	Thickness of glazing	3 mm
6.	Length of collector	3100 mm
7.	Width of collector	3 mm
8.	Air Gap	60 mm
9.	Inlet area is equal to exit area	0.09 m2
10.	Maximum aspect ratio	0.4
11.	Length between inlet and outlet	2800 mm
12.	Coefficient of discharge	0.65
13.	Inclination of collector/chimney with horizontal	90º
14.	Top loss coefficient	5 W/m^{2}K
15.	Bottom loss coefficient	0.5 W/m^{2}K
16.	Acceleration due to gravity	9.81m/s^2
17.	Specific heat of air*	1005J/kg.K
18.	Heat transfer coefficient of air	25
19.	Maximum window opening For medium heat gain (15-30 w/m^2)	20% floor area

Table 2. Air properties [20]

S. No.	Property	300K	350K	400K	450K
1.	Thermal Conductivity W/mK	0.02624	0.03003	0.03365	0.03707
2.	Kinematic viscosity µ*10^5 kg/ms	1.8462	2.075	2.286	2.484
3.	Kinematic viscosity υ*10^6 m^2/s	15.69	20.76	25.90	31.71
4.	Prandtl Number	0.708	0.697	0.689	0.683
5.	Specific heat kJ/kgK	1.0057	1.0090	1.0140	1.0207
6.	Density Kg/m^3	1.1774	0.9980	0.8826	0.7833

*Ref [ ]

Table 3. Properties of materials

Material	ρ, kg/m^3	C_p, $J/kg°C$	k, $W/m°C$	$Emissivity$	Absorptivity, α	Transmitivity
Mild Steel	7800	500	52	0.95	0.95	0
Glass	2500	820	1	0.9	0.06	0.84
Air	1.225	1006.43	0.0242	---	---	----

2.3. Experimental Setup

A solar chimney has been designed and developed along with the specific room 16.253 m3 volume at CBRI Roorkee, India [Latitude 29º51’ and Longitude 77º 53’ at 274 m mean sea level] which is shown in Figure 3. The solar chimney has been designed based on 400W/m2 annual average solar insolation which can develop 4.0 ACH. The inlet and exit vent area kept constant equal to 0.09 m2. The gap between centres of inlet to outlet vent is approximately 2.85 m.

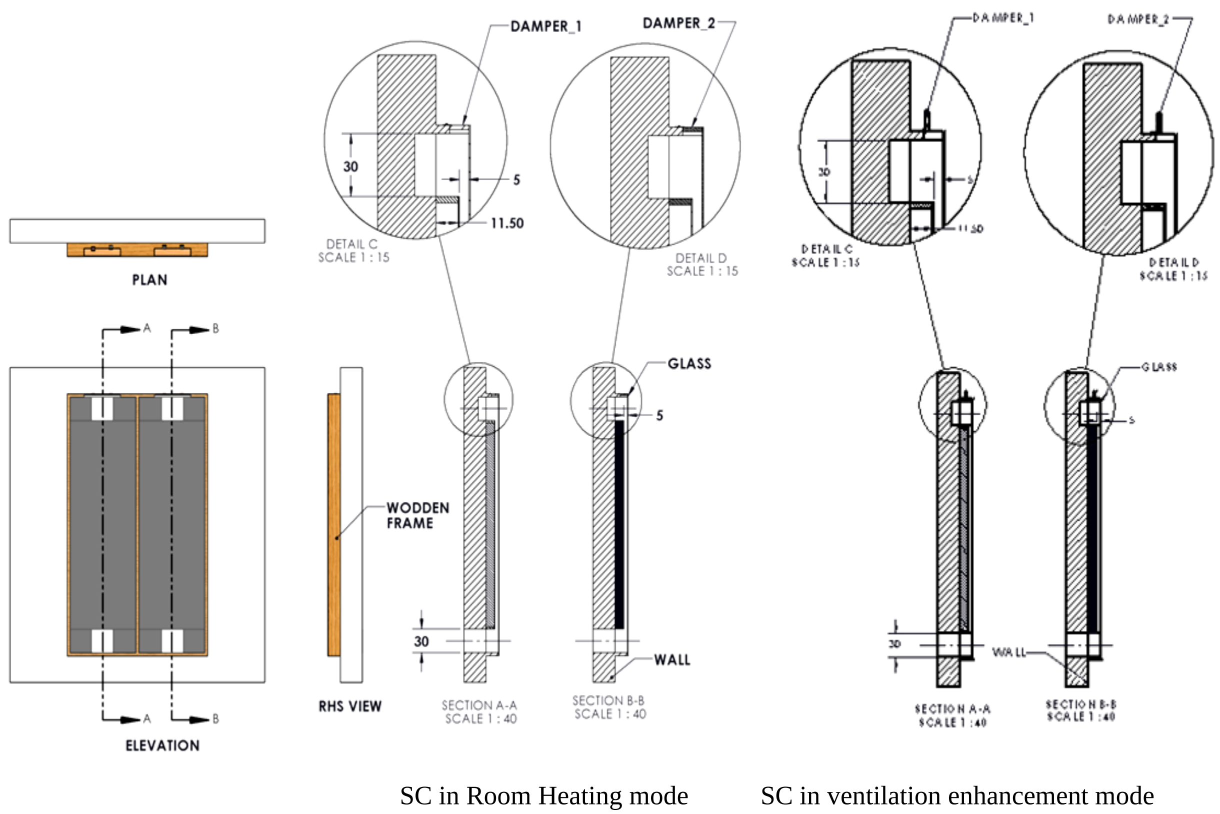


Figure 3. Schematic Diagram of designed solar chimney configurations

The metallic box is used to store water or any other liquid as a heat storage. This feature of this solar chimney is to give an optimum tilt angle of 5 degrees [15] to increase the performance and reduce the back flow in the chimney. It is necessary in summer when stack’s effect generates measurable flow. The optimum air gap is also taken in the setup by 60 mm. Dampers are provided at the top os solar chimney to change the mode of utilization for summer and winter. The other details of experimental solar chimney are expressed in table 4 and 5. The absorber plates of both the chimney configurations are coated with nickel chrome black paint to increase the absorptivity up to 80%.

2.4. Cost Analysis

A solar chimney has been designed and developed along with the specific room 16.253 m3 volume at CBRI Roorkee, India.

Table 4. The cost of solar chimney with MS plate (Rs. 79.53 USD^{-1} as on 31 August 2022)

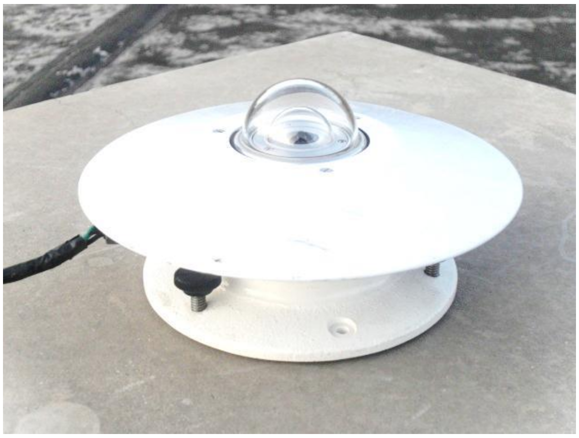
S. No.	Material & on as on / misc. charge	Cost (USD)
1.	Wooden frame (4175x38.1x150)	42.85
2.	Mild steel plate (849x2550x3)	37.66
3.	Colour, Paint etc.	12.98
4.	Glass putty	19.48
5.	Rubber got and handles etc.	10.39
6.	Labour charges	32.46
	Total	155.81

Table 5. The cost of solar chimney with MS box (Rs. 79.53 USD^{-1} as on 31 August 2022)

S. No.	Material & on as on / misc. charge	Cost (USD)
1.	Wooden frame (4175x38.1x150)	55.64
2.	Mild steel box (849x2550x10)	112.97
3.	Colour, Paint etc.	16.85
4.	Glass putty	25.29
5.	Rubber got and handles etc.	13.49
6.	Labour charges	84.30
	Total	308.54

2.5. Instrumentation

The SC experimental data collection was carried out in the winter and summer season because of its application evaluation in both heating and ventilation enhancement mode. The solar irradiance (diffused and global) was measured by the solar Pyranometer of Eppley Netherland make (model: SPlight 2) and these data were collected by data logger. A data logger (make: digitec) was also used to measure/collect the temperature data with the sensor of T-type thermocouples. The vane type air flow meter was used to collect the data of air flow at inlet and outlet of the solar chimney. The pyranometer, data logger and vane type air flow meter are shown in figure 4.



(a) Pyranometer for Global radiation

(b)Pyranometer for diffused radiation

(c) Data logger for radiation

(d) Data logger for temperature

Figure 4. Measuring equipment used during experiment

2.6. Uncertainty Analysis

The uncertainty during the experimental work may occurred due to the various possible errors happen in the instrumentation (like memory, electronic circuit, transmitters of data logger, wire resistance etc.) and weather condition, and it is also coming in the picture due to the error in the type of thermocouple junction, calibration method used, observation taken, and methods used for evaluation [22]. The total experimental uncertainties of temperature, flow and solar radiation measured during the experiment on solar chimney are presented in Table 6.

Table 6. Uncertainties of the experimental parameters

Parameters	Units	Uncertainty
Temperature (T-type thermocouples used)	˚C	± 0.21
Solar energy	W/m2	± 0.185
Air flow	m/s	± 0.21

The standard errors of various measurements are presented in figure 5, It is observed that the maximum channels observed the error under the limit.

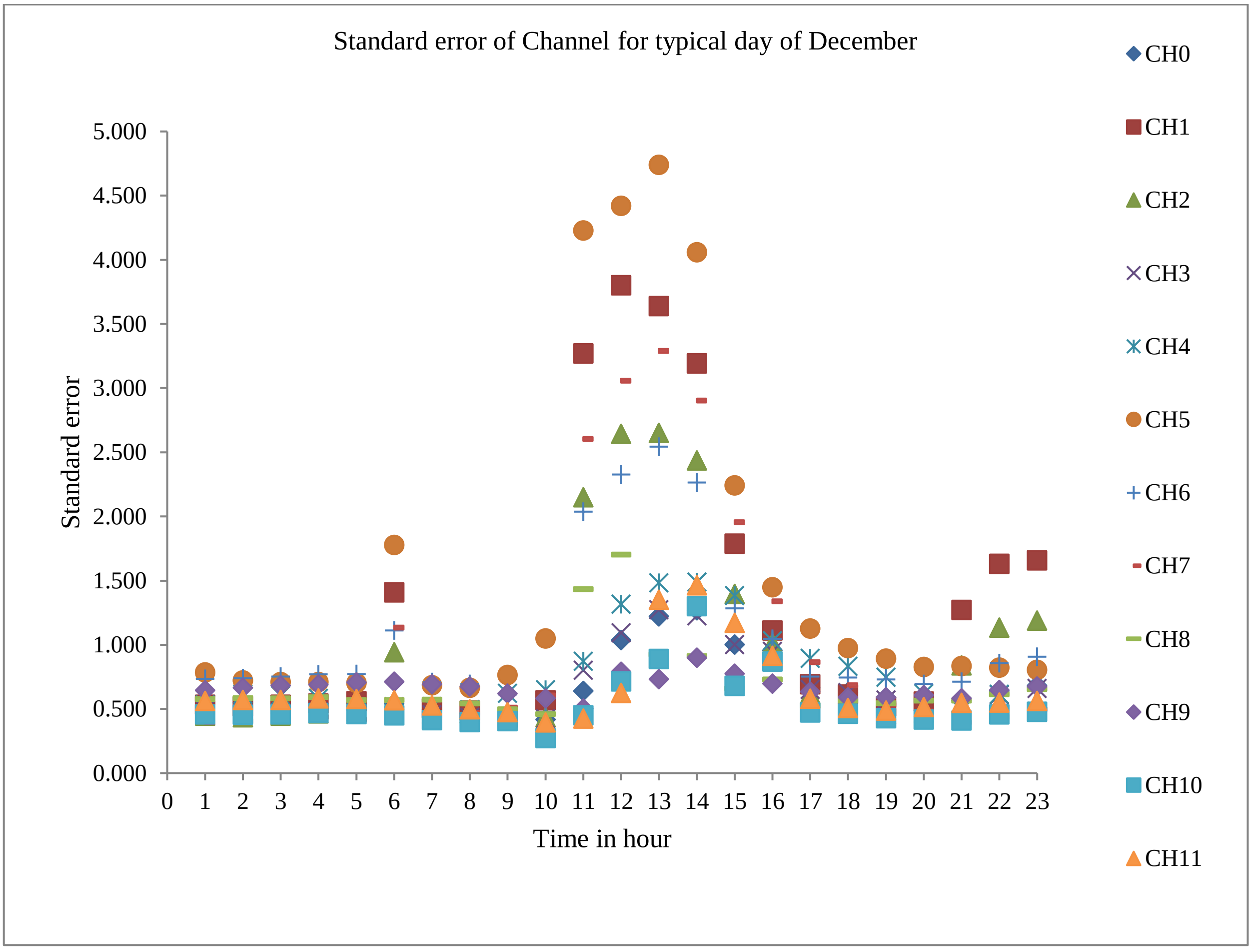


Figure 5. Standard error in measurement through data logger of different channels.

3. Result and Discussions

3.1 Measurement of environmental parameter

The environmental parameters are observed and presented the solar radiation (Diffuse and Global), ambient temoerature data for a full typical day of December in in figure 6. The typical day is defined by Duffy and Bechman and it is the 10th day of December month. Its maximum global radiation is observed at about 576.25 W/m2 at 12:00 hours, and maximum diffuse solar radiation is measured at about 109.34 W/m2 at 11:00 hours. The ambient air temperature is found maximum 20.1˚C at 13:00 hours and minimum 3.2 ˚C at 7:00 hours of the day.

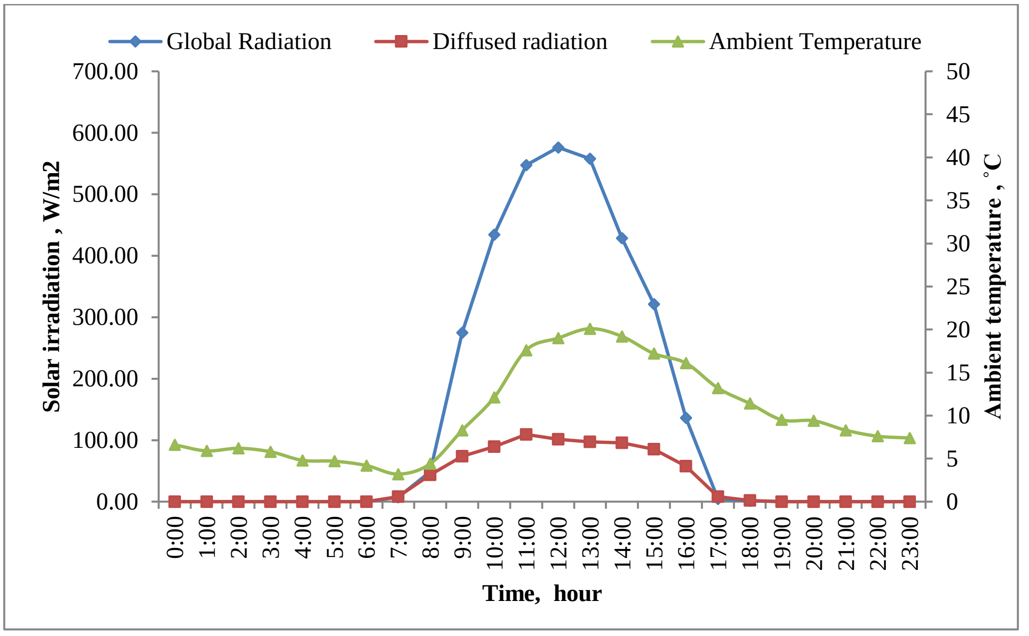


Figure 6. Solar radiation for the typical day of December

3.2. Net Pressure Changes in Solar Chimney

The net pressure changes in solar chimney for the typical day are shown in figure 7, it reveals that the highest-pressure changes observed at 12:00 PM and minimum in the morning. It is stated that the maximum pressure difference means observed highest air flow velocity, which occurs due to change in the pressure via thermal heating in solar chimney.

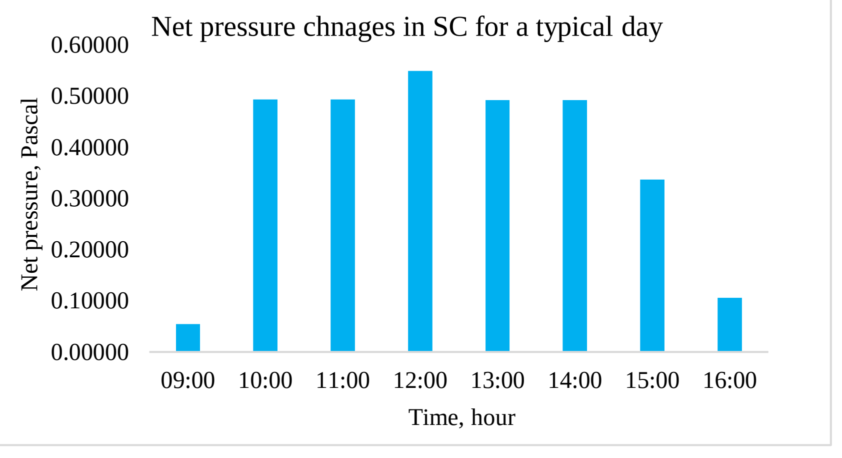


Figure 7. Net pressure changes in solar chimney

3.3. Temperature Variation for Typical Day

Figure 8 shows the full day temperature variation of ambient, experimental room outer wall, reference room, MS plate, MS box with water, Experimental room and Room temperature due to nanofluid fill in the MS box. The performance of room heating through MS box is better than the MS plate for through the day.

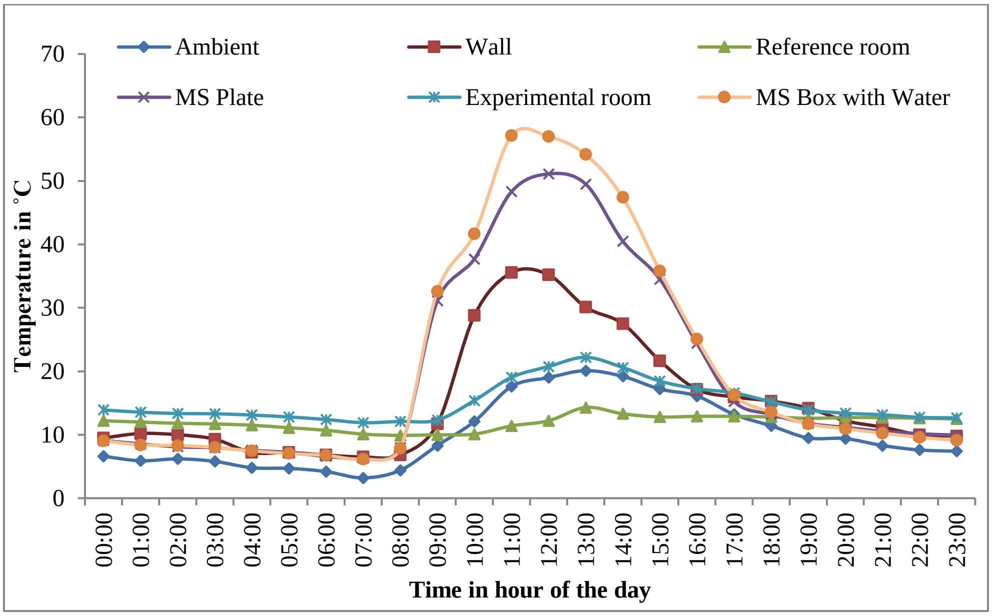


Figure 8. Temperature variation throughout the typical day of December

3.4. Heating and Ventilation Potential of Solar Chimney for Energy Conservation

The average cooling effect is measured by the temperature reduction through enhanced ventilation. The ACH for the typical day is shown in Figure 9. The average temperature reduction is measured as 2°C in the room due to more than 4 ACH and it is found between 8AM to 4 PM. The average mass flow rate is noted as 0.02664 kg/s. The estimated amount of cooling effect is 1.37kWh per day. It is not ominously higher, but the proper design of solar chimney can provide sufficient ventilation for the building, and it can save significant electrical energy needed for ventilation. The annual estimated saving of energy required for cooling and ventilation are 328.8kWh and 192kWh respectively. Highest energy can be saved when solar chimney can be used in heating mode. The total energy can be saved in heating mode by 1765.2 kWh (when it is assumed to be used for four months in a year).

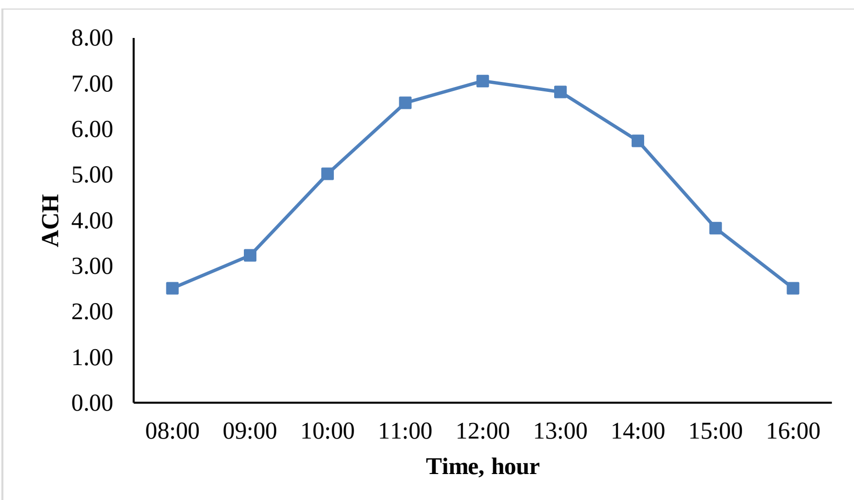


Figure 9. ACH generated from solar chimney for the typical day

3.4. Energy and Exergy Analysis of Solar Chimney

Figure 10 shows the energy and exergy efficiency of the solar chimney in face of solar radiation availability. The maximum efficiency was approximately 26.68% observed at 11 hours, whereas the minimum efficiency occurred at 16:00 hours. Maximum exergy efficiency was evaluated by 3.69% at 12:00 hour and it reduces afterward when solar time increased. The efficiency of the solar chimney is less because of the high loss from the glass side and lack of back side insulation. The efficiency can be increased by double glazing by 5-10%.

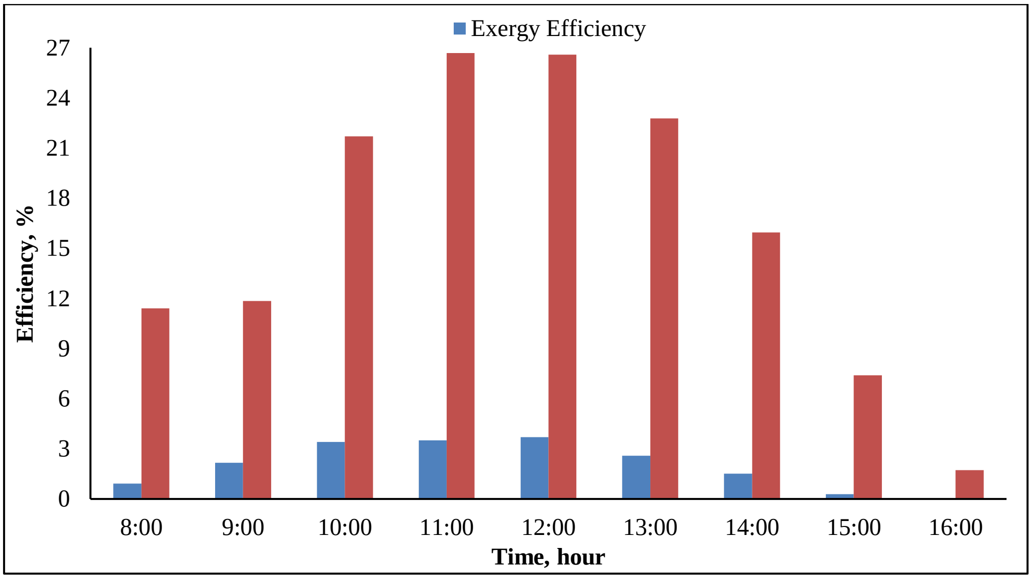


Figure 10. Energy and Exergy efficiency for a typical day of May 2013

3.6. Techno-economic evaluation and co2 mitigation potential

The economic assessment of such a solar chimney is adopted from Kandpal and Garg [23]. A simple payback period is defined by the ratio of cost of solar chimney to the annual energy saving. It can be calculated by;

$$PP = \left[\frac{C_{SC}}{AES}\right]$$

Where, PP is payback period, C_sc is the cost of solar chimney and AES is annual energy saving in heating and ventilation. Approximately 2285 kWh electricity is saved by the application of solar chimney in a house of 16.253 m2. The total electricity saving in terms of money is Rs 18280.00 annually (@8 Rs per unit in Roorkee). And the total cost of the solar chimney retrofit is Rs 12392.00 so the simple payback period is less than one year. Approximately 2515 kWh energy is saved due to the application of MS box. This energy saved can be represented by Rs 20120.00. And the simple payback period is approximately likely to be one year. The MS box is used as heat storage, and it gives last long performance in heating and cooling mode.

The lignite coal is assumed as fuel in power plants in Rajasthan and U.P. states of India. Where all the values of high heat value, carbon content coefficient and oxidation factor were selected from the table of North Carolina analysis [24]. The specific coal consumption per kWh is taken as 0.77kg/kWh from Mittal et al [25]. The total coal consumption is 2.66 ton by

SCWMSP and 3.31 ton by SCWMSB during the year 2012, therefore production of 3803.33kWh electricity is required to fulfill this energy demand by the building of the same building.

The estimated CO_2 is saved by 4.37 ton/year through SCWMSP and 5.51 ton per year through application of SCWMSB for ventilation and heating of a 16.253 m2 building area. And Lot of energy demand and air pollution can be reduced by the application of solar chimney.

4. Conclusions

The experimental data are collected for both peak winter and summer season at CBRI Roorkee, India. There are temperatures at various points like: absorber plate, glass, wall, inlet, outlet, experimental room and reference room are measured by using thermocouples and stored in data logger. The velocity is measured at both inlet and outlet positions. The solar radiation and ambient temperature are also measured at the site. The performance of building integrated MSC has been evaluated on a typical day of December month (Peak winter).

The solar chimney configured with metallic plate and with metallic box and experimentally examined, it is found the better space heating performance of metallic box solar chimney rather than conventional solar chimney. It produced better results even at night and observed 5-10°C temperature correspond to the ambient temperature and in Day rime in winter it produced 2-5°C temperature higher than ambient temperature. The conventional solar chimney produced night and daytime temperature 2-3°C and 0.4-2°C respectively correspond to the ambient air temperature. But metallic plates performed in night and daytime 1-4°C and 2-3°C respectively higher than the ambient air temperature. The plate temperature observed higher at upper side. The air temperature and velocity are observed higher near to the plate and mid of the air gap between glass and absorber respectively.

The maximum energy efficiency has been observed by 26.68% during 12 hours of the particular day, and at the same time the exergy efficiency has been obtained by 3.69%. Approximately 2285kWh energy can be saved during a year through solar chimneys. CO_2 is also saved with energy conservation and 4.37 ton / year CO_2 saving have been estimated by SCWSP, on the other hand if SCWMSB had implemented then CO_2 would be saved by 5.51 ton/year.

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