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EXPERIMENTAL STUDY OF SOLAR CHIMNEY PERFORMANCE FOR PASSIVE HEATING

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ABSTRACT:

An experimental investigation on solar chimney used for heating under climate of Iraq is carried out. Experiments were conducted on the chimney installed on vertical wall with absorber plate placed at the front side of the air gap. The solar chimney attached to room of dimensions (2.5×1.29×1.07) m. The chimney is studied to measure the effect of the air gap width with constant height of (1.07 m). Three widths are tested, namely, 0.2 m, 0.3 m and 0.4 m. The experimental results showed that the solar chimney can achieve about (13 °C) difference in temperature between indoor and outdoor as well as it gives acceptable difference in partial cloudy days. The results also indicated that the best performance of solar chimney is with 0.3m air gap width.

KEY WORDS: solar chimney, passive heating, vertical wall, similitude, prototype.

دراسة تجريبية لأداء المدخنة الشمسية للتدفئة السلبية

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الخلاصة

اجريت دراسة عملية على مدخنة شمسية تستخدم للتدفئة في المناخ العراقي. نفذت التجارب على مدخنة مثبتة على الجدار العمودي وتم وضع السطح الماص على الجانب الامامي لفجوة الهواء. المدخنة الشمسية مركبة لغرفة بابعاد (٢.٥م ×١.٢٩م × ١.٠٧م). من اجل دراسة تاثيرعرض فجوة هواء المدخنة مع ارتفاع ثابت لثلاثة اعراض تم اختبارها وهي ٠.٢ متر و٠.٣ متر و ٠.٤ متر اظهرت النتائج التجريبية ان المدخنة الشمسية يمكن ان تحقق ١٣ درجة مئوية فرق في الحرارة بين الداخل والخارج فضلاً عن انه تعطي فرق مقبولاً بالفرق في درجة الحرارة في الايام الغائمة جزئياً واشارت النتائج ايضاً الى ان افضل اداء للمدخنة الشمسية هو مع ٠.٣ متر عرض فجوة هواء.

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INTRODUCTION

In the framework of free renewable energy for application in heating and cooling systems there is a growing interest in passive design employment for either heating or cooling. This design is more dedicated recently- especially in the last years – as a feature of a movement towards architecture development. Using passive heating means is to improve indoor air quality as well as to make life or work environment in the building better and more comfortable. It can also reduce levels of energy consumption and environmental impacts, i.e. greenhouse gas emissions, because it requires no use of mechanical heating. The need for passive design in buildings leads to a large number of numerical and experimental studies carried out on solar chimneys. **Khedari et al** performed experimental study on the natural ventilation in a room of 25m^3 volume using three different solar chimney configurations of 2 m^2 each, they were placed on the southern wall, while the roof southern side included two similar units of 1.5 m^2. They concluded that there is a minor thermal comfort in hot regions when using only roof solar collectors. **Afonso and Oliveira** used a thermal model that combines equations of heat transfer and natural ventilation flow together, so as to simulate solar chimneys. They solved their mathematical model using a finite difference method. In addition, they performed experiments on solar chimneys which was built in Porto, Portugal, in order to compare their model results with the experimental results. **Chen et al** performed experimented with a variable chimney gap-to-height ratio between 1:15 and 2:5 under varied heat flux between (400W/$m^2$to 600W/m^2). Their results showed that there is no optimum gap and air flow rate increases with increasing chimney gap, even up to the gap-to-height ratio of 2:5. In this study it was also observed that with 0.2m air gap and 1.5m height chimney maximum air flow was obtained. **Ong and Chow** performed a study to predict the efficiency of the solar chimney, experiments were conducted on a physical model with 2m height, 0.45m width and different gaps of 0.1, 0.2 and 0.3 m. The results indicated that the highest air flow rate are obtained with larger gaps. **Mathur et al** carried out experimental investigations on a small size solar chimney with vertical passive wall. The experimental set-up comprised a cubical wooden chamber having a size of (1 m × 1 m × 1 m). The experimental results indicated that there is a potential of inducing ventilation corresponding to (55–150) m^3/h airflow rate for (300–700) W/m^2solar radiation incident on the vertical surface. In addition, airflow increases linearly with the increase in solar radiation. The results also showed that the highest rate of ventilation induced with the help of solar energy was found to be 5.6 air change per hour in a room of 27 m^3, at solar radiation 700 W/m^2. **Puangsombut et al.** studied the influences of varying the air gap depth of the solar chimney (3, 5, 7, 9 and 11 cm). Experiment was conducted on a solar chimney with 1.50 m height and 0.70 m width. The used heat fluxes were 190.5, 285.7, 380.9 and 476.2 W/m^2. It was found that the mass flowrate increases with the increase in the width of the solar chimney, while air velocity through the solar chimney decreased. **Harris & Helwig** investigated the performance of a solar chimney by using CFD modelling techniques. The study was conducted under climate of Scotland, Edinburgh at latitude 52°. They found that for a south-facing chimney, an inclination angle of 67.5° from the horizontal was optimum for the location chosen which maximizes the flow rate by 11% for the location of investigation. The study also showed that the performance at 45° was approximately similar to that of a vertical solar chimney. **Bassiouny and Koura** used numerical analysis to predict the flow pattern in the room as well as in the chimney. Using a FORTRAN computer program, they observed that the chimney width has more significant effect on air flow rate in comparison with the inlet area size. In addition, the results also showed that increasing the inlet size three times the air change per hour rises only 11%. However, increasing the chimney width by a factor of three, boosts the flow rate by 25%. **Arce et al** set up a solar chimney in the desert of Tabernas, Spain in the outdoors facing south in the vertical position with 3.5m height ,1m width and 0. 3m depth. A volume flow rate with a maximum value of 0.1 m^3/s was achieved. Numerical study of heat transfers of solar chimneys using for heating and ventilation purpose was carried out by **Nouanegue**

and Bilgen considering three methods of heat transfer (conduction, convection and radiation) in vertical solar chimney. The main governing parameters were: the Prandtl number (Pr =0.7), the Rayleigh numbers(Ra) from 5 $\times 10^8$ to 10^{11} and variable chimney gap-to-height ratio between 6 and 15. They solved the Conservation equations using finite difference method. The Numerical results showed that the volume flow rate and heat transfer by free convection are increases with the Rayleigh number. **Larbi and El Hella** conducted numerical study to predict the efficiency of the solar chimney. Commercial CFD software FLUENT was used in the numerical simulation of air flow and heat transfer within the chimney under climate of Algeria. They found that the minimum radiation of 219 W/m² was in December and the highest solar radiation of 588 W/m² was in June. Thus, the solar chimney efficiency varies between 15 to 40%. Also, their results showed that the maximum airflow velocity was obtained with incident solar radiation of 500 W/m². **Khanal & C. Lei** Experiments were conducted with an inclined passive wall solar chimney (IPWSC) model using a uniform heat flux on the active (absorptive) wall. In this model inclination angles of the passive wall in the range of 0–6° were examined. The flow velocity is found to be strongly affected by the inclination of the passive wall, and the results depicted that the maximum flow velocity was achieved at an inclination angle of 6°. **Majeed & Mishaal** studied experimentally performance of the solar chimney used for heating of a space, under climate of Iraq. A solar collector with inclination angle of (40°) installed on the south face of a model having a size of 3.45 m^3. The absorber plate of the solar collector was attached directly to glass cover, and allowed heat transfer by convection from its back surface to the air in the channel of the solar chimney. Their results showed that the heat supplied by solar chimney covered the heat load of the space. The results also showed the temperature difference between indoor and outdoor reached to 9 °C.

EXPEIMENTAL MODEL

The experimental work was conducted on the roof of a two storey building at the Technical Engineering College-Baghdad, which is located at (33°) latitude north and (44°) longitude east, facing south in the vertical position. The test model was operating outdoors. A 3:1 scale model was built to simulate full scale room building at Technical Engineering College-Baghdad having size of (7.5m×3.87m×3.21m). Hence the dimensions of model were 2.5m length, 1.29m width and 1.07 height. The south facing wall of this model was fitted with the solar chimney as shown in figure (1). The experimental test model shown in figure (2) was fabricated from 18mm of wood thickness that has a thermal conductivity about 0.524W/m °C. This type of wood was selected according to the calculated value 0.558W/m °C, obtained from similitude it with prototype over heat transfer coefficient. Consequently the overall heat transfer coefficient value of model is 1.64 $\mathrm{W/m^2\,^\circ C}$. The wooden wall of test model was connected on an iron frame using screw and double sides foam tape. The model was supplied with a door at the back side (1.07m×1.29m). The air circulates from the space to the chimney through two ports measuring of (1.29 and 0.1) located at bottom and top of the inside wall. In order to absorb enough solar radiation, the absorber copper plate with 106 cm height, 128cm width and 0.1cm thickness was painted with matte black paint and fixed on an iron frame. The back and front of absorber plate edges were covered with rubber tape having a thickness of 0.5cm. The absorber plate was covered with 0.6cm commercial glass and allowing a distance of 1 cm, as an air gap, between absorber plate and glass. The main purpose of the air gap was to minimized convection heat losses from the absorber plate surface. The glass was bound on absorber plate using iron band. The absorber plate, glass and iron frame (passive wall) was attached to south facing wall of the test model (at the front side of the air gap). Different air gap widths were obtained by moving the passive wall away from the test model. Experiments were conducted on the model with air gaps of 20, 30 and 40 cm as shown in fig (3).

Temperatures were measured by 14 thermocouples type "k" (Nickel 10% Chromium versus 5% Aluminum, Silicon) in the range of -100 to 1500°C. Thermocouples were positioned at selected locations. As shown in figure (4). Thermocouples (T1, T2 and T3) were fixed on the absorber plate coated with thermal insulator to prevent the effect of environment conditions on the thermocouples readings. Three thermocouples (T4, T5 and T6) were used for measuring air temperature in the chimney. The air temperature at 0.1 distance from each wall of the model was measured by six thermocouples (T9, T8 and T14). Thermocouple 9 for air near the north model, T14 and T8 was used to measure the temperature of air near the roof and floor respectively. The temperature of air near the east and the west walls were measured by thermocouple12 and thermocouple13, while thermocouple 7 was used to measure the air temperature near the south wall. Thermocouple 11 was used for measuring the air temperature at the center of model. The ambient temperature was measured by thermocouple10. The solar radiation intensity was measured by solar power meter with a resolution of 0.1 w/m² and accuracy as ±5% of its reading. This solar power meter was placed parallel to the passive wall.

The monthly average temperature was calculated for absorber, ambient, or indoor as:

$$T_{avg} = \sum_{i=1}^{N} T_i / N$$

where, N= number of test days.

RESULTS AND DISCUSSION

Measured ambient parameters (solar radiation and ambient temperature)

In order to examine the influencing factors of the solar chimney thermo-circulation phenomenon, the intensity of solar radiation and the outdoor temperature are major parameters which play important role on performance of the solar chimney. The ambient temperature is shown in Fig (5). The ambient temperature is plotted against the time for different days in winter. The highest temperature recorded was (21°C) on 12/2/2017 at 1:00 pm, while the lower temperature was (1°C) on 2/2/2017 at 8:30 Am. Fig (6) shows incident solar radiation on the chimney vertical wall. The maximum solar radiation for sunny days was about (880-770w/m) at noon, while the minimum solar radiation was about (75-220w/m²) at evening. In partially cloudy days (19-Jan and 22-Jan) solar radiation disturbances were observed. The (1-Feb and 2Feb) represents a chilly and cloudy days with highest and lowest solar radiation received were (300 and 0 w/m²) respectively. The incident radiation on the outer surface of the chimney is not affected by the air gap. The solar radiation affected the flow and the temperature of air in the chimney.

The effect of absorber wall

The daily variation of the ambient, the absorber walls and the room center temperatures are illustrated in Figures (7 to 12). The absorber temperature between period (0:00 AM to 6:00 AM) is lower than the temperature of room center, temperature the absorber wall function is reversed (cooling the room space instead of heating it). The main reason of this phenomena is a radiative of black body to sky along the hours of the night, since the view factor between absorber plate and glass is one thus the high heat transfer occurs. After the sunrises all temperature start to increase with time. The temperature reach to the maximum values at noon due to rising in the solar radiation. The temperature then drops in the evening. In a sunny day in January (24-1-2017) with 20 cm air gap width as shown in Figure (7), the temperature of the room center increases with the increase in the temperature of the absorber wall due to the increment of the solar radiation. The maximum difference between room center and ambient temperatures achieved was (11.8°C) at 1:00 PM when the absorber wall was (63°C). Low capability of a thermal storage in the absorber wall leads to its temperature reached to a lowest value at night. At the same air gap width on 22-1-2017 (which was a partially cloudy day as seen in Figure (8)) a variation of solar radiation is observed due to the presence of clouds. The maximum temperature of the absorber wall was (49°C). Figure (9) represented a sunny day for air gap width of 30 cm on 30-1-2017 which shows same behavior as to sunny day of 20 cm air gap. The absorber wall temperature obtained was (61°C), the maximum temperature difference between room center and ambient was (13.9C) at 1:30 PM. Figure (10) reveals the performance of solar chimney under low solar radiation. The absorber wall was directly influenced by intensity of solar radiation. The effect of cloudiness resulted in reducing the temperature on 2-2-2017 at 30 cm air gap width. The highest temperature of the absorber wall obtained was (38°C), consequently the maximum temperature difference between room center and ambient was (5.4°C) at 2:00 PM. For a sunny day in 19-2-2017 with air gap width of 40 cm, as illustrated in Figure (11), the temperature of the absorber wall starts rise in the morning until reaches to maximum value was (59°C) at 1:10 PM. Thus the temperature difference between room center and ambient increased to (10.4°C). Since the temperature of the absorber wall is dependent upon solar radiation, its temperature tends to decreased in the afternoon. Subsequently, the temperature difference between room center and ambient was decreased. While for a cloudy day 12-2-2017, as shown in Figure (12), the peak temperature of the absorber wall of (38°C) which occurs at about 1:10PM. The temperature difference between room center and ambient was (4°C). Then the absorber wall temperature decreased until reached to the temperature of room center at 6:30PM. The average monthly variation of solar radiation, temperature at the room center, absorber wall temperature and the ambient temperature are displayed in figures (13 to 15). These figures show temperature variation during the chimney operation period, for several days in January and February months for different air gaps. Through the figures it can be observed that the temperature of the absorber wall was the highest, while the ambient temperature was the lowest. The temperature of the center of room had a value higher than ambient temperature. This result is consistent for each gap and each month. From the figures it can be indicated that the absorber wall temperature and the room center temperature followed the solar radiation and have a big difference from ambient temperature along period from morning to night. The maximum temperature of the absorber wall and the room center were practically always achieved at period from (12:00 PM to 2:00 AM), while the minimum before 9:00 AM.

The effect of gap width

In order to determine which air gap of the solar chimney was more efficient, various combinations of air gaps width of three different sunny days have been taken. The thermal behavior of the solar chimney was assessed, by establishing the temperature difference between room center and ambient as well as the temperature difference between the temperature near the roof and temperature near the floor of the test model. Figure (16) represents the temperature difference between room center and ambient for three cases along the time. The maximum temperature difference was (14°C) achieved with air gap of 30 cm at 1:30 PM, while the difference for air gaps 20 cm and 40 cm was (12°C) at 2:00 PM. The thermal-circulation is demonstrated in Figure (17) as temperature difference between roof and floor walls for three cases. The peak thermal-circulation occurs at 1:00 PM for 30 cm air gap. This means that an air gap width of 30 cm is the most appropriate. To verify the experimental results, a comparison was carried out for inclined solar chimney under same dimensions and conditions of experimental study of Chen, Zheng D to assess the performance of the solar chimney with the different positions (inclined and vertical).

Figures (18) shows the experimental results of present study together with the experimental results of Chen, Zheng D. The results represent the temperature difference between the indoor and outdoor. However, there is a minor difference between the two results along the time from 8 AM to 11:30 AM. Later on the results of Chen, Zheng D are more consistent with results of 20 cm and 40 cm air gap width in the present study. The difference of the gap width of 30cm of present study after 12:00 AM is more than the **Ref 13** by about 1.5 °C, because of eddies that take place in inclined absorber.

CONCLUSIONS

In the present work, the effect of solar chimney on passive heating of a space was investigated experimentally. A vertical wall solar chimney with absorber plate placed at the front side of air gap is attached to room measuring of (2.5×1.29×1.07) m. Three air gap width of solar chimney were tested, namely, 20 cm, 30 cm and 40 cm. The main conclusions are:

1- The solar radiation affected the flow and the temperature of air in the chimney.
2- The room temperature follows the solar radiation intensity and a significant difference between room temperature and ambient temperature is noted during the day.
3- The vertical solar chimney improves the temperature difference between indoor and outdoor temperature in partial cloudy days by about (7.5 °C), while a little difference in cloudy days.
4- The indoor air temperature can be heated to (12 °C) of the outdoor temperature using vertical wall solar chimney with air gaps of 20 and 40 cm, in sunny days.
5- The solar chimney with air gap width of 30 cm has the best performance, where the maximum difference of temperature reached was (14 °C) at 1:30PM.

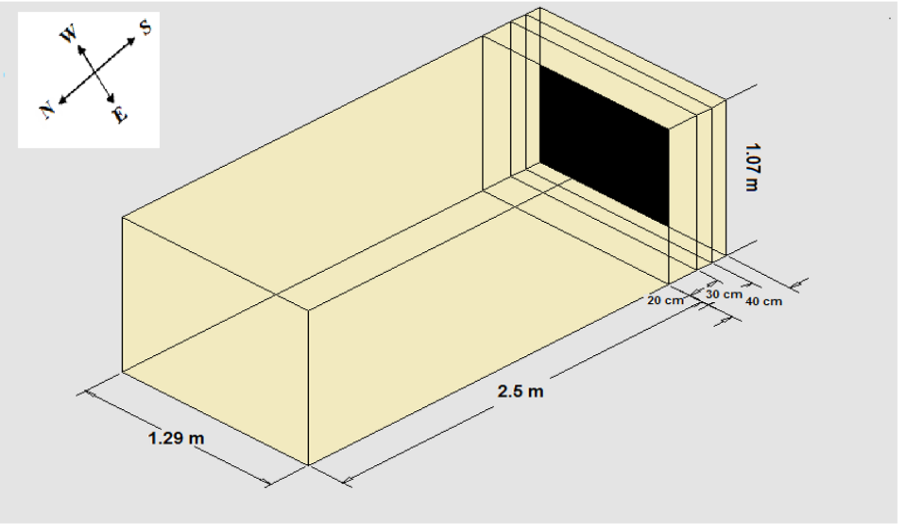


Fig.1. Schematic of the test model

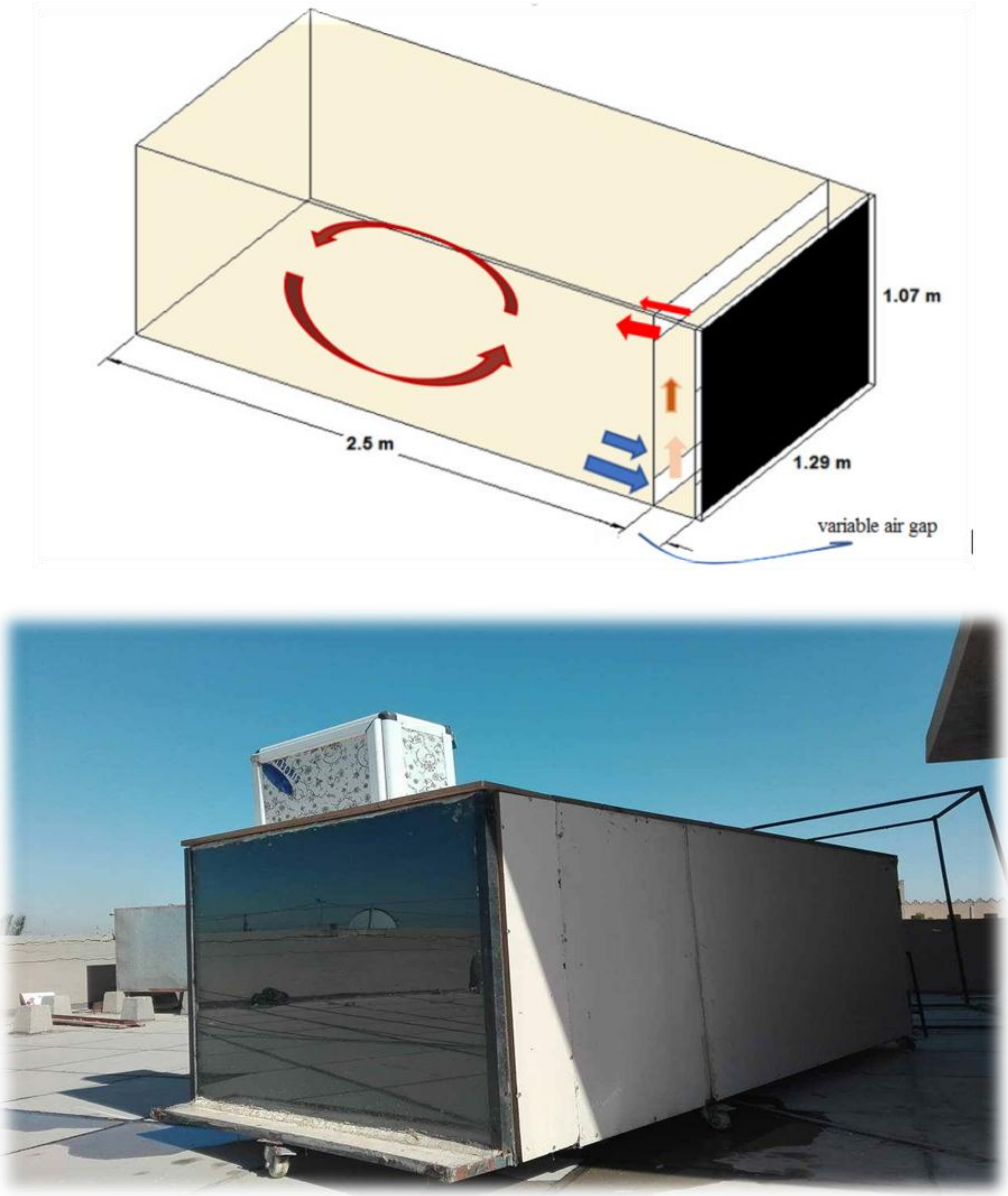
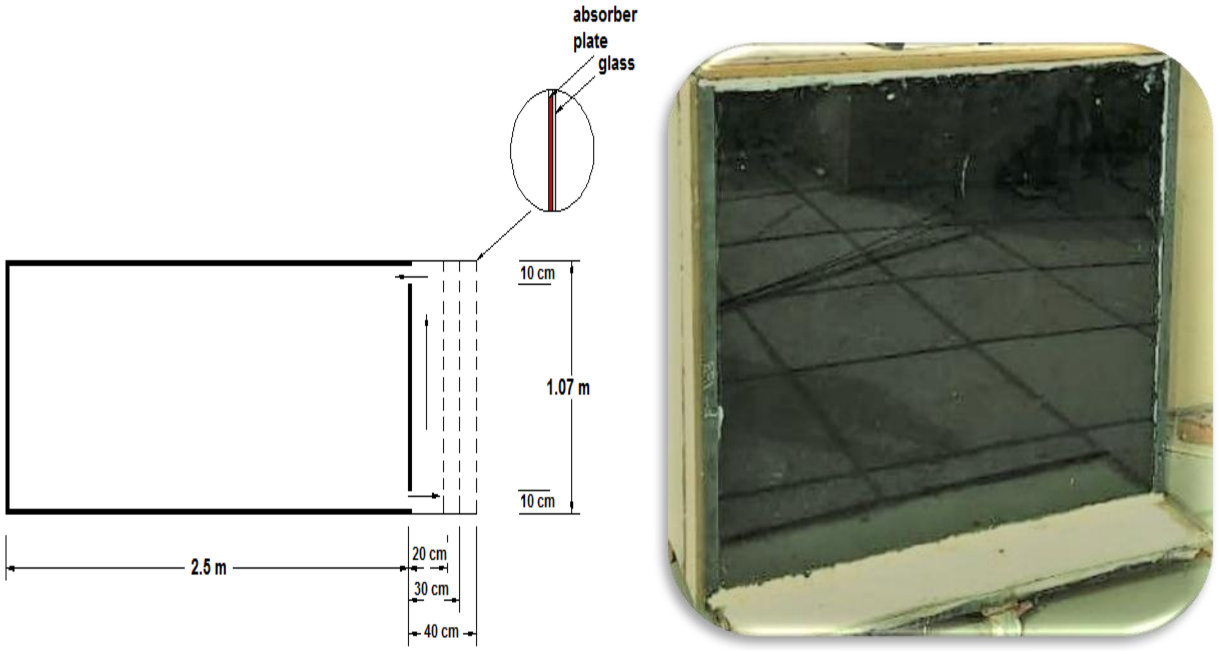


Fig. 2. The experimental test model



(a) (b)

Fig. 3. **(a)** Schematic of different air gap **(b)** passive wall

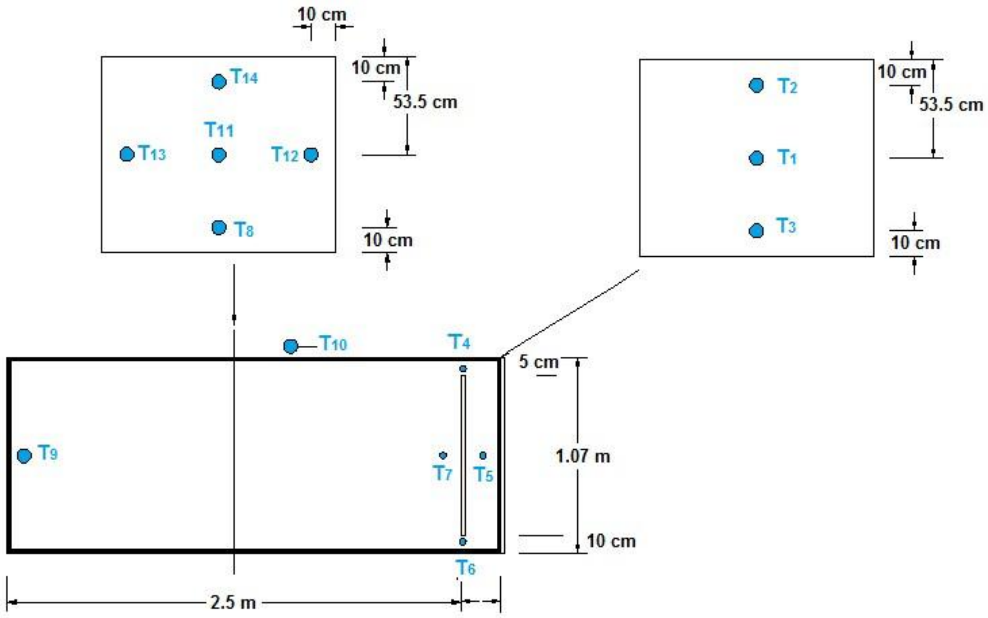


Fig. 4. Locations of thermocouples

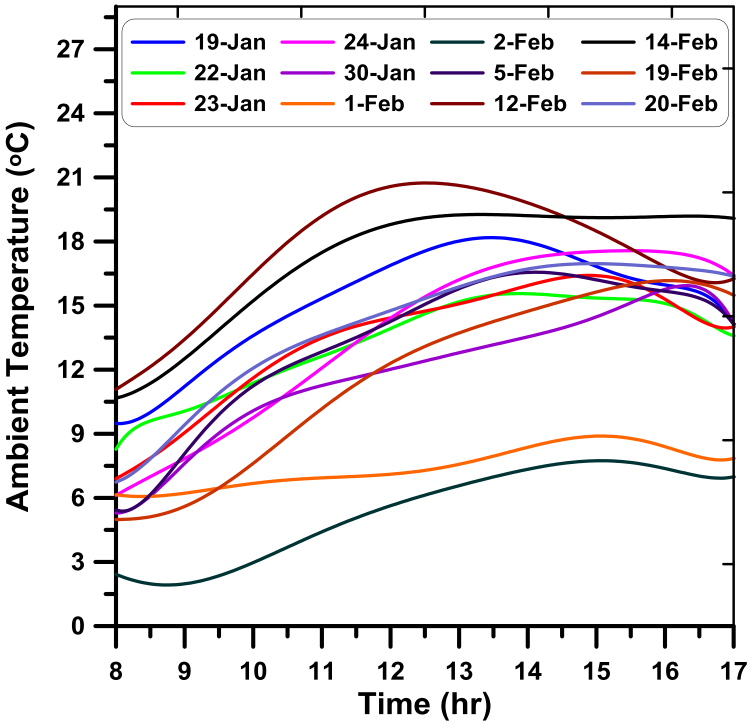


Fig. 5. Evolution of measured ambient temperature during the days of experiments.

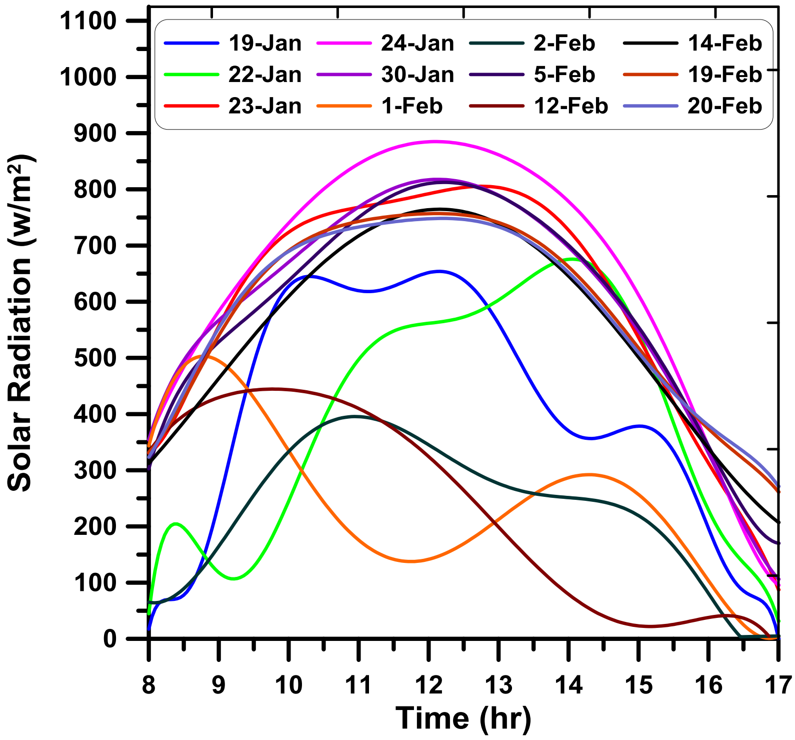


Fig. 6. Evolution of measured incident solar radiation of experiments.

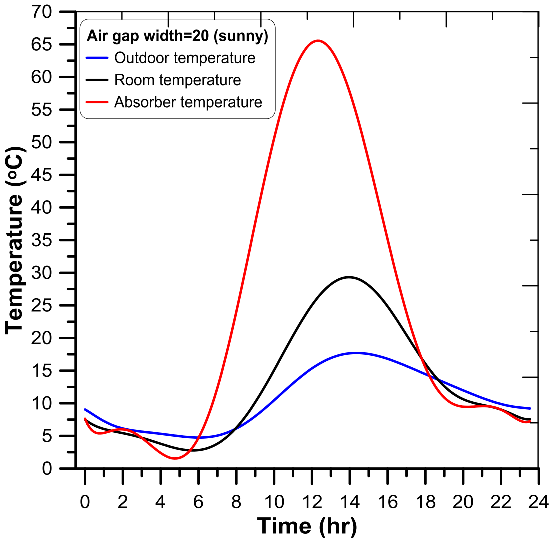


Fig.7.Variation of outdoor temperature, indoor temperature, and absorber temperature with time (24 Jan sunny day gap 20 cm) for 24 hr.

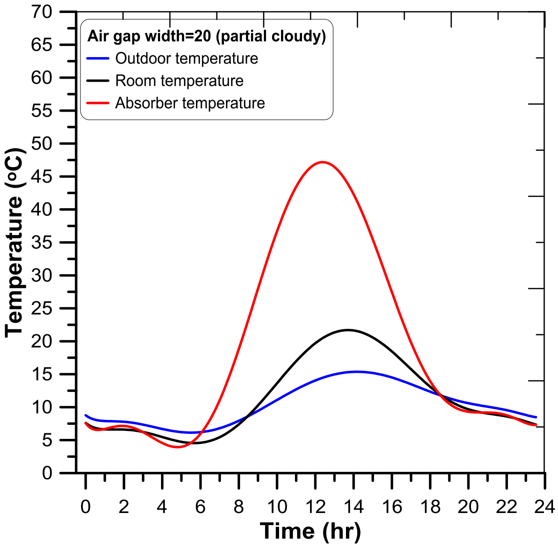


Fig.8.Variation of outdoor temperature, indoor temperature, and absorber temperature with time (22 Jun partial cloudy day gap 20cm) for 24 hr.

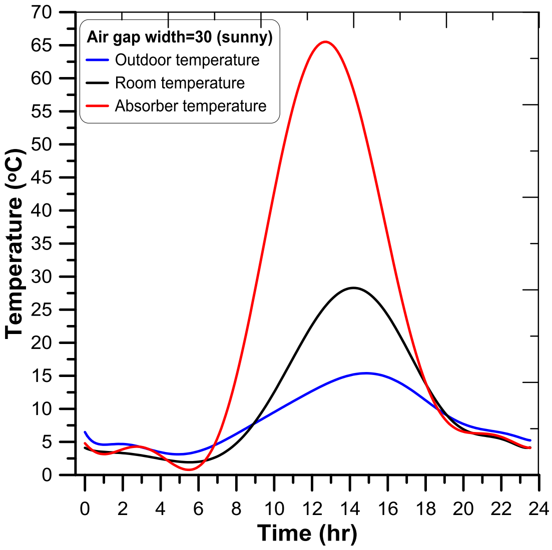


Fig.9.Variation of outdoor temperature, indoor temperature, and absorber temperature with time (30 Jan sunny day gap 30cm) for 24 hr.

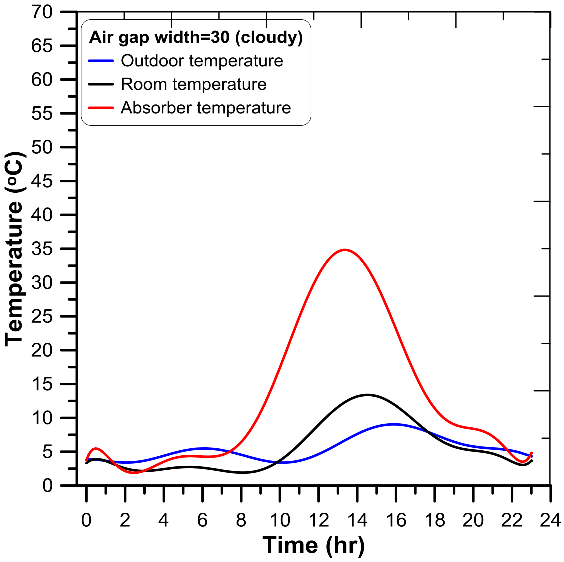


Fig.10.Variation of outdoor temperature, indoor temperature, and absorber temperature with time (2 Feb cloudy day gap 30cm) for 24 hr.

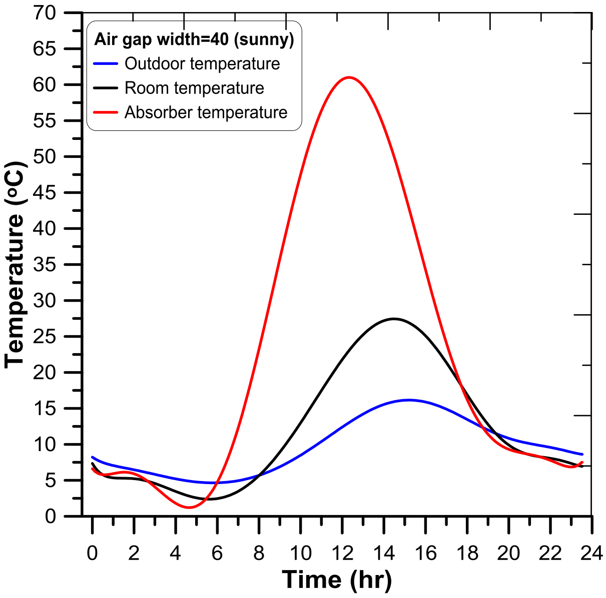


Fig.11.Variation of outdoor temperature, indoor temperature, and absorber temperature with time (19 Feb sunny day gap 40cm) for 24 hr.

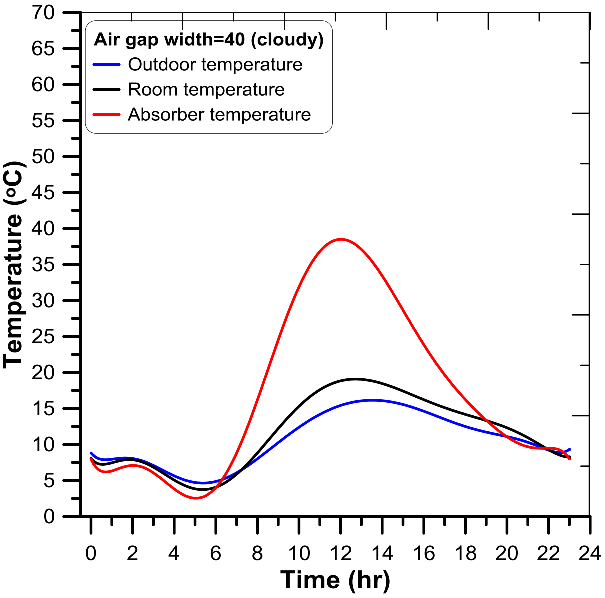


Fig.12.Variation of outdoor temperature, indoor temperature, and absorber temperature with time (12 Feb cloudy day gap 40cm) for 24 hr.

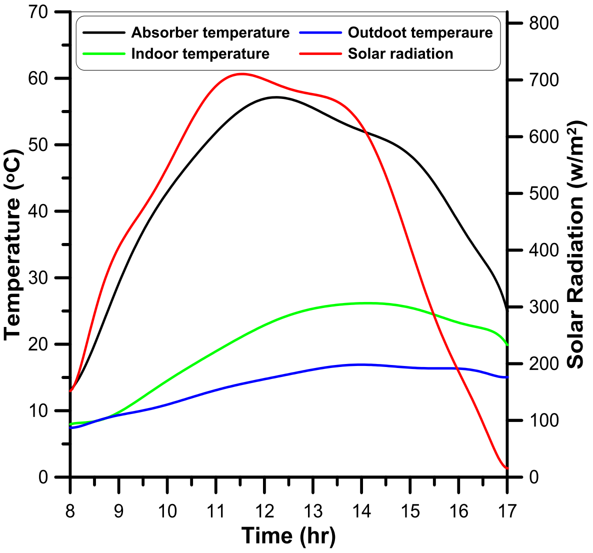


Fig.13. Average monthly variation of outdoor temperature, indoor temperature, absorber temperature and intensity of radiation with time (gap 20 cm).

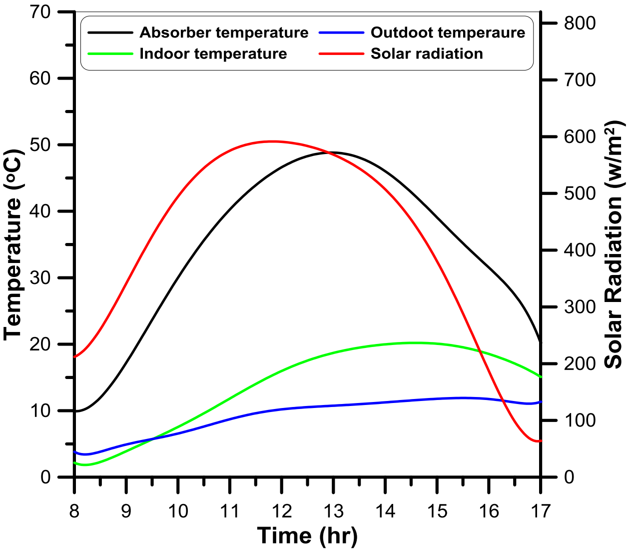


Fig.14. Average monthly variation of outdoor temperature, indoor temperature, absorber temperature and intensity of radiation with time (gap 30 cm).

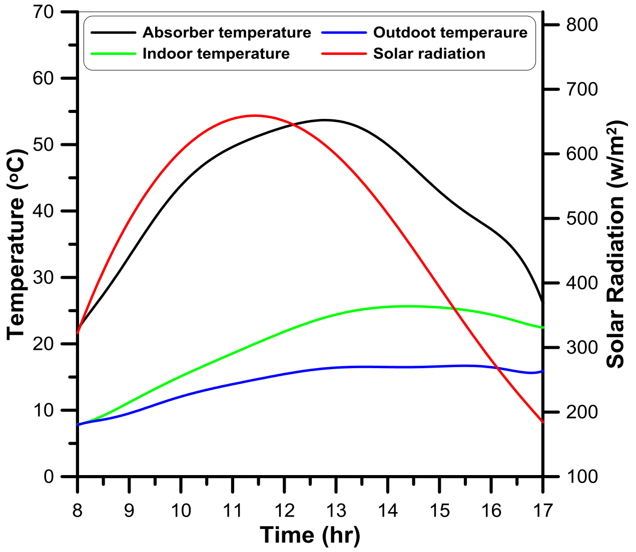


Fig.15. Average monthly variation of outdoor temperature, indoor temperature, absorber temperature and intensity of radiation with time (gap 40 cm).

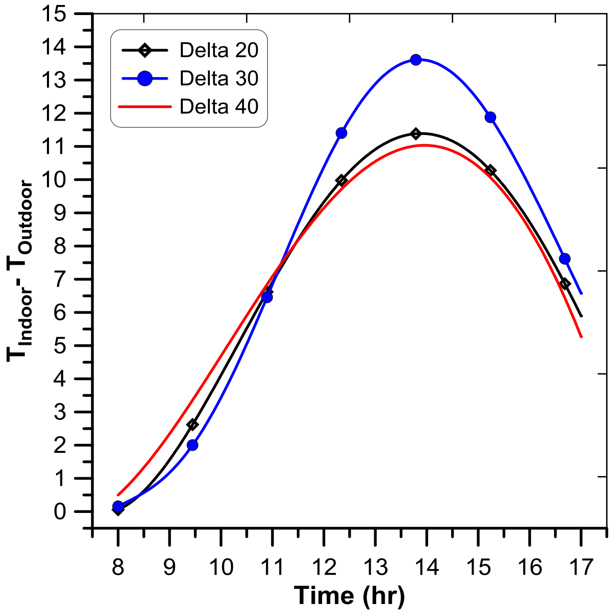


Fig.16. Temperature difference between room center and ambient.

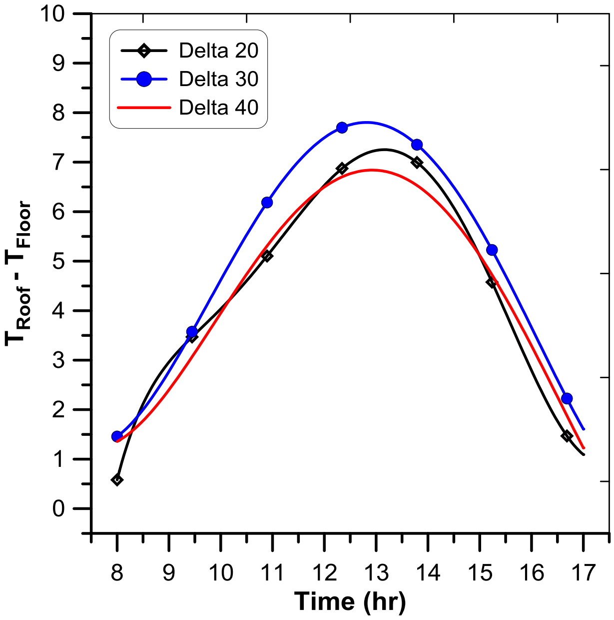


Fig.17. Temperature difference between roof and floor.
gap 30cm) for 24 hr.

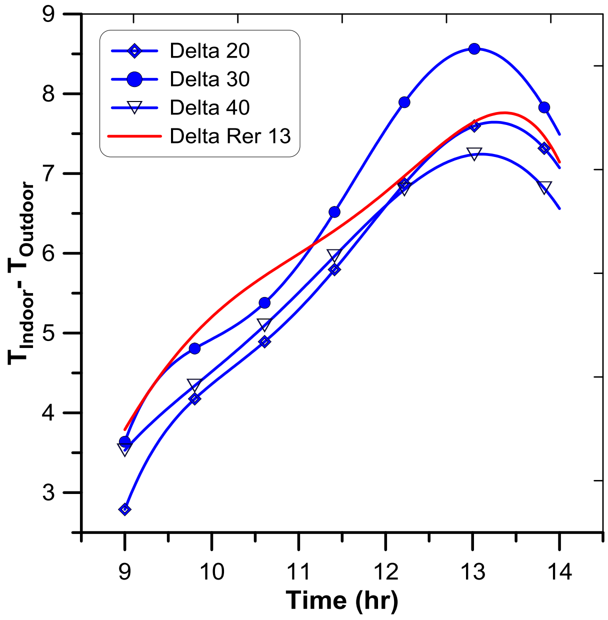


Fig.18. Comparing the experimental results of present study with experimental results of **Ref 13.**

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