https://erjm.journals.ekb.eg
ISSN: 1110-1180

DOI: ---------

ERJ
Engineering Research Journal
Faculty of Engineering
Menoufia University

Experimental Investigation of Solar Chimney Performance

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ABSTRACT
A solar chimney is a passive device that utilizes solar and wind energies for cooling, heating, and ventilation of closed spaces. In this study, an experimental investigation of the thermal performance of solar chimneys under the meteorological conditions of El-Arish, North Sinai, Egypt is presented and discussed. The experimental measurements were performed under different solar intensities, different geometric conditions, and storage heat techniques. The experimental investigation was conducted using two test rigs of the solar chimney with the same dimensions. One of them has a fixed configuration and was used as a reference, while the other one was modified at each stage of the measuring process. The experimental study was concerned with the effect of changing the gap width, integrating a layer of sensible heat storage material into the chimney, and integrating a phase change material. The experimental results showed that the solar chimneys (SCs) with gap widths of 2.5, 5, and 10 cm achieved an average daily efficiency of 21.1%, 24.1%, and 16.3% respectively. It also showed Integrating the SC with concrete and bitumen increased the air mass flow rate through the SC with a daily average value of about 24% and 32% respectively.

Keywords: *Solar chimney, ventilation, heat storage, solar energy.*

1. Introduction

The environment has been largely damaged due to the fact of overuse of fossil energy. The share of the buildings sector in energy consumption is the highest, which consumes about 42% of global energy consumption [1]. Most of this energy goes to heating, cooling, and ventilation purposes. Therefore, researchers looking for developing environmentally friendly building designs that reduce energy consumption and have satisfying thermal comfort. Early, solar chimneys (SCs) plays the main role to achieve a comfortable atmosphere inside buildings. The two main configurations of SC (wall and rooftop) mainly consist of glazing transparent to solar radiation, a cavity gab containing the air, a black wall called an absorber, that absorbs solar radiation and heats the air by natural convection, and inlet and outlet opening. The airflow inside the chimney is driven by two main forces, stack effect and pressure difference. These forces pull out undesired warm air and contaminants from the space and replace them with ambient fresh air from outside. SC chimney with its different configurations could be also used for cooling or heating purpose.

Many studies have been performed to investigate the thermal performance of SCs under various conditions. These conditions include the shape and geometric parameters of SC and study the effect of various meteorological conditions. Ong [2] proposed a steady-state mathematical model of a Tromb wall. By comparing the obtained results with published experimental data it was found that the model predicted the thermal performance of SC with good accuracy. To evaluate the usage of phase change materials (PCMs) in solar chimneys as thermal energy storage, Rashidi et al. [3] performed a survey on the usage of PCMs in solar chimneys, in addition to the discussion of the various techniques used in thermal energy storage. The main conclusion from the review is that integrating PCM in the solar chimney is effective in night and evening ventilation because it can provide higher values of ventilation rates. In addition, the phase change temperature has a significant impact on the thermal efficiency of SC. Finally, paraffin PCMs usage in solar chimneys is a cost-effective option. While in an experimental investigation, Chen et al [4] studied the buoyancy-driven airflow induced by SC under uniform heat flux. The study was performed with different chimney gap-to-height ratios, inclination angles, and different heat fluxes. The study revealed that the maximum airflow was obtained at 45° inclination angle, 200 mm gap, and 1.5 m height which is higher than it is at a vertical chimney by 45%. Cisse et al. [5] performed an experimental investigation on the effect of adding reflectors for an inclined SC. The study was performed on two tested models of SCs with and without reflectors, under the climatic conditions of Dakar, Senegal. Results showed that the absorber of the SC with concentrated collector achieved a higher surface temperature of 65.3℃ against 50.8℃ for the other absorber. It also concluded that adding the reflectors affected the air velocity at the inlet of SC and improved the air ventilation in the building. In a numerical study, Cao et al. [6] assisted with the impact of integrating PCM into a hybrid solar chimney and photovoltaic panel. The study focused on the influence of the physical properties of PCM on electricity production and ventilation capacity. Results showed that increasing the heat capacity and the enthalpy of PCM decreases the air outlet temperature and mass flow rate. It also was found that increasing the melting point increases the ventilation capacity while rising the thermal conductivity of PCM doesn't affect the SC performance. Mathur et al [7] experimentally investigated SC with various combinations of chimney heights and air gaps. The results showed that the relationship between airflow and solar radiation is a linear relationship and the ventilation rate is influenced by the inlet-to-outlet area ratios. In a mathematical investigation, Hamdy and Fikry [8] examined the effect of the tilt angle of SC on its performance. The study area was the north coast of Egypt (latitude 32̊). The study results showed that a 60º slope angle yields the optimal performance in the study area. To determine the impact of solar chimney energy, Lee and Strand [9] examined several design parameters that influence the ventilation rate. The results showed that solar absorbance, transmittance, and stack height influence natural ventilation more than the air gap. Also, the results showed that SC is more efficient for cooling than heating purposes and the climatic conditions of the location have a slight effect on the chimney performance. Sivalakshmi et al. [10] proposed an experimental investigation to study the thermal performance of a wall solar chimney integrated with a room under warm and humid conditions. Different gap widths were applied to the chimney with multiple room openings. The study revealed that increasing the gap width increases the flow rate and air velocity. It also was found that integrating a chimney with a 15 cm gap width achieved a decrease in the indoor temperature of the room by 1-1.9℃. Vazquez-Ruiz et al. [11] performed an experimental and numerical investigation of the airflow and heat transfer in a scaled room integrated with a double-channel vertical roof SC. The numerical study was performed using the CFD, ANSYS Fluent 15 software. Results showed that the model with the nearest position of SC to the air inlet achieved the highest value of air change per hour (ACH) of 30.24 for the model with a heated wall and 16.2 ACH for the model without a heated wall. The study also, revealed that the position of SC on the roof has a significant influence on the performance of the chimney and air conditions in the room. A numerical study of the reversal flow effect on airflow in SC induced by buoyancy was presented by Khanna and Lee [12]. The study revealed that the presence of reversal flow at the channel exit strongly affects the ventilation rate achieved by the chimney while the penetration depth of the reverse flow is dependent on the Rayleigh number. Zha et al. [13] performed experimental and numerical studies during the period from April to October 2018 in China. The results showed that integrating SC in buildings can save about 12.9% of annual consumed energy in buildings. The experimental study investigated the effect of solar radiation intensity and gap width on the performance of different chimneys by Ong and Chow [14]. From the results, it was concluded that solar radiation of 650 $W/m2$ could induce air velocities between 0.25 m/s and 0.39 m/s, and even at large gap width of 0.3 m there is no reverse flow was observed. Barozzi et al. [15] conducted an experimental and numerical study to investigate the thermal performance of a prototype of a bio-climatic building with a roof performing as an SC. Results showed the effectiveness of the SC concept to induce airflow although the cooling effect is weak. Arce et al. [16] experimentally studied a full-scale model of SC under real operating conditions. The result presented the dependence of the airflow rate through the chimney on the pressure difference between the inlet air opening and outlet air opening. The concept of SC investigated with a wind tower to create natural ventilation has been studied analytically by Bansal et al. [17]. It's revealed that the high wind speed reduces the SC effect. It also was found that the mass flow rate produced by the proposed system doubled the mass flow rate produced by a conventional wind tower at 700 $W/m2$. A numerical and theoretical study of the performance of a small SC installed in a building was presented by Arce et al. [18]. The study results showed that when the solar radiation increases from 100 to 700 $W/m2$, the maximum efficiency of the chimney increased from 28% to 37% and the volumetric flow rate increased from 61 to 147 $m3/h$. Li and Liu [19] performed a numerical study on the thermal behavior of SC integrated with organic phase change material (PCM). The study has been carried out under various heat fluxes from 100 to 800 $W/m2$. Numerical results showed that during the initial period of solidification, a sharp drop in air temperature difference and the flow rate takes place. It also found that, the mass flow rate and air temperature difference at the inlet and outlet of the chimney decrease very slowly when the PCM reaches the melting temperature. Marti-Herrero and Heras-Celemin [20] presented a mathematical model to evaluate the energy performance of SC with a concrete wall as a storage surface of solar radiation. The results showed that the concrete wall reached its higher temperature 2 hours later and remain at that high temperature after the absence of solar radiation. Moreover, for a 2 m chimney height and 14.5 cm width at 450 W/$m2$ the air mass flow rate was 0 .011 kg/s. An experimental investigation on the thermal performance of wall-type solar chimneys integrated with PCM was carried out by Li and Liu [21]. The study revealed that integrating the PCMs in the system can extend the ventilation period by 13 h and 50 min for different cases of heat fluxes. It also can be concluded that average airflow rates of 0.04 kg/s, 0.039 kg/s, and 0.037 kg/s are obtained during the phase change period. An unexpected phenomenon occurred that the air outlet temperature is the lowest for the case of 700 $W/\ m2$. The study cleared that the PCM-based solar chimney has satisfying performance and recommended more studies with different cases of low heat fluxes. Zhang et al. [22] investigated the performance of the solar chimney attached to the multi-zone building. The aim is to inspect the characteristics of the airflow through a solar chimney and the attached zones in addition to the performance of the solar chimney under various configurations and operational conditions. Wang et al. [23] investigated the thermal and ventilation performance of the solar chimney under three heating modes, one of them sealed heating and the other fresh air heating. The study revealed that the fresh air heating mode is applicable for cool and cold climates conditions. While the sealed heating mode is only applicable for conditions where fresh air is not required.

From the literature, it can be concluded that limited research was performed on integrating heat storage materials into the SC, and a few types of material were investigated. Therefore, this study presents an experimental investigation of SCs under the meteorological conditions of (El-Arish, North Sinai, Egypt). The effect of different operating and geometrical conditions on solar chimney performance will be discussed to obtain the highest efficiency of SC.

2. Experimental Set-Up

Two similar SCs are designed and fabricated as shown in Fig. (1). The two test rigs have the same component which mainly consists of the main body made of wood to ensure thermal insulation. An absorber made of 0.2 cm thick, 100 cm wide, and 100 cm height iron sheet coated with black paint to maximize solar radiation absorbance and for glazing, a glass slap of 0.5 cm thick, 100 cm and 100 cm height was used.

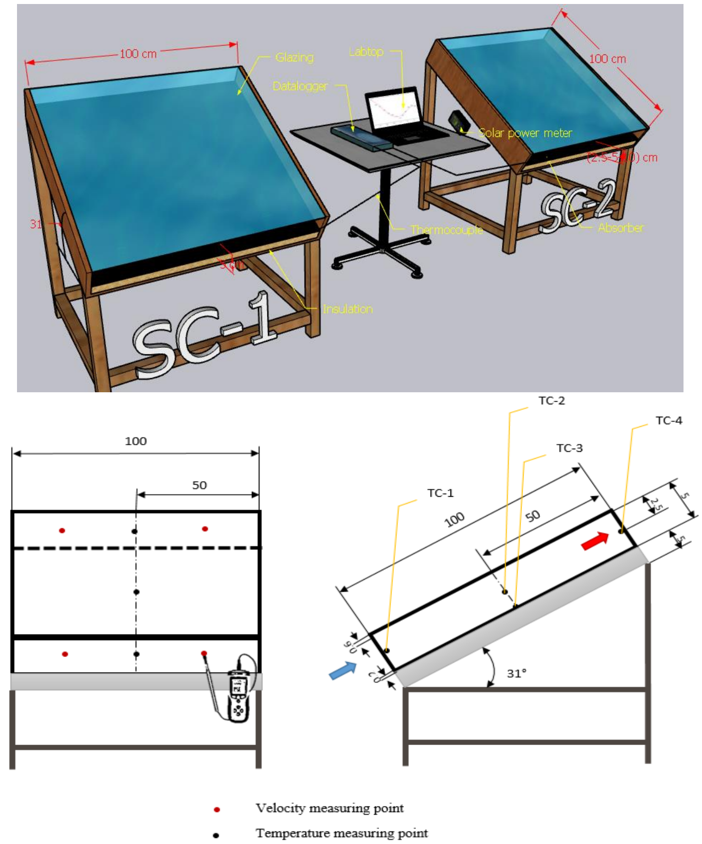

Fig. 1. Layout of the test model (Dimensions in cm).

An insulation layer of sawdust with 5 cm thickness is set behind the iron sheet (absorber) of the first test rig (SC-1) to reduce the heat loss from the chimney and to ensure that most storage heat is emissive to the air enclosed between the absorber and glazing, as shown in Fig. (2-a). While in the second test rig (SC-2), the heat storage material takes place adjacent to the back surface of the absorber then insulation material is placed as shown in Fig. (2-b). The experimental SC models have internal dimensions of 100 cm wide and 100 cm long. The SC-1 has a fixed gap width of 5 cm, but the SC-2 has variable gap widths (i.e. 2.5, 5, and 10 cm). The inclination angle of the models is 31° according to Al-Arish latitude to obtain higher solar radiation throughout the year.

Temperature distribution along the centerline of the chimney and absorber temperature were measured with the aid of eight thermocouples (type- K) with an accuracy of ± 1 °C. These thermocouples are located at the specified points as shown in Fig. (3) of the two test rigs. Each thermocouple is connected to a data logger type "TC-08 PicoLog" which is connected to a display and storage unit (Personal computer). A vane

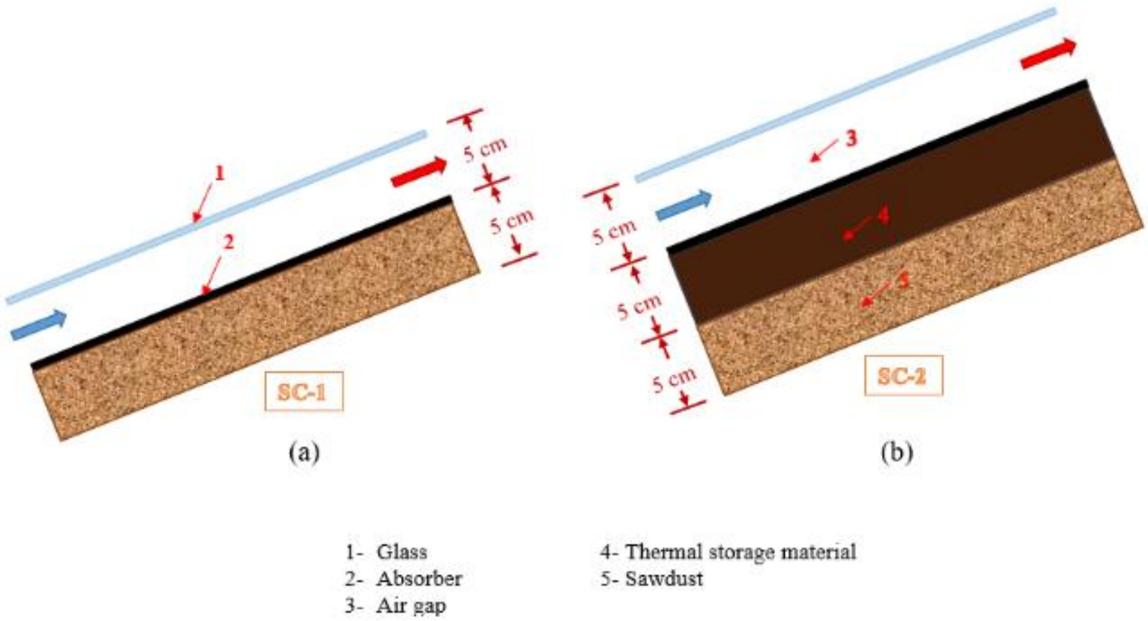

Fig. 2. Schematic layout of (a) reference and (b) modified test rigs.

anemometer type “Testo 410-1” is used to measure local air velocity. It has a measuring range of 0.1 to 20 m/s and a resolution of 0.1 m/s. While the velocity of the air stream enclosed between the absorber and glazing at the inlet and the outlet of the chimney is measured by hot-wire probe. The hot wire probe type is “Testo 405-V1” with a range from 0 to 10 m/s and an accuracy of ± 0.05 m/s. The solar radiation intensity is measured by the “TENMARS TM-206” solar power meter which has a maximum range of 2000 W/m^2, resolution of 0.1 W/m^2, and accuracy within ±10 W/m^2 and greater in sunlight.

Fig. 3. Photograph of the two test rigs.

3. Experimental Procedure

Experimental results are recorded in three stages. In each stage, a specified modification was applied to SC-2. All measured data were repeated for three days to ensure the reproducibility of the measurements.

3.1 The first stage of measurements (Changing the gap width)

In this stage, the absorbers of the two SCs models [SC-1 and SC-2] were insulated with a 5 cm back layer of sawdust. During this stage of measurements, the gap width of SC-2 is changed (2.5, 5, and 10 cm), while the gap width of SC-1 is fixed at 5 cm. During this measurement, the effect of gap width was determined and discussed.

3.2 The second stage of measurements (Adding sensible heat storage material)

In this stage, the gap width of the two test rigs is fixed at 5 cm and SC-1 is equipped with a back layer of insulation below the absorber (layer of sawdust with 5 cm thickness). While in SC-2 the back layer of the absorber surface is replaced with sensible heat storage (SHS) material and then a layer of insulation material. The concrete layer mixture consists of 40% stone, 20% of sand, 20% of cement, and 20% of water. According to a study conducted by Haghi et al. [24], the density of concrete typically ranges from 2200 to 2500 kg/m^3. Additionally, the thermal conductivity of concrete can vary based on the type of aggregate used and the moisture content, but generally ranges from 0.8 to 1.7 W/mK [25].

3.3 The third stage of measurements (Adding latent heat storage material)

In this stage, the layer of concrete in SC-2 is replaced with latent heat storage (LHS) material also known as phase change material (PCM) which is Bitumen

(Asphalt) with the same thickness and volume as the concrete layer. The Bitumen specific gravity is about 0.99 while the softening point is between 50 and 62 °C [26].

4. Results and Discussion

The results of experimental work will be presented graphically and discussed in an attempt to investigate and analyze the behavior of airflow throughout the heated cavity of the chimneys. Also, the analysis would demonstrate the parameters that affect the flow properties to determine the best operating conditions and design values for the solar chimney.

Figure (4) shows the variation of solar radiation over three days of the first stage of measurement which was recorded during the period from the 15th to the 24th of September 2020. From the figure, it can be seen that there is a small fluctuation in the solar radiation curves which means that the measuring processes were stable. The solar radiation varies along the day and it reaches the maximum value at noon and then gradually decreases in the afternoon until sunset.

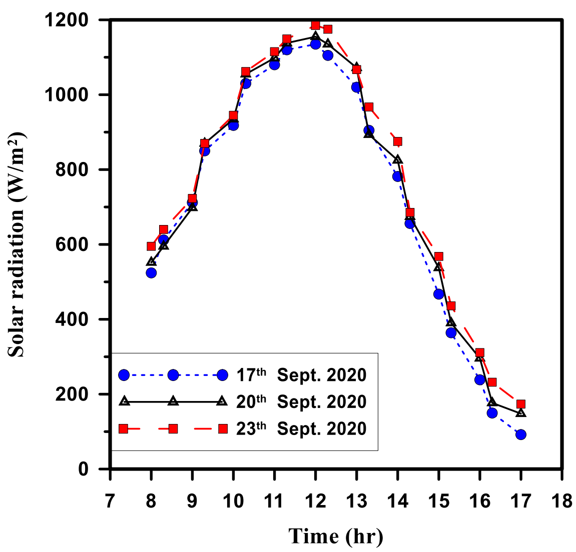

Fig. 4. Solar radiation variation along the days of the first stage of measurements.

While the solar radiation along the days of the second and the third stages of measurement was recorded during the period from the 5th to the 12th of June 2021 as shown in Fig. (5). From the figure it can be observed that the solar radiation curve takes the shape of the bell as usual. The solar radiation varies along the day and it reaches a maximum of about 935 W/m^2 at noon on the 6th of June 2021. The effect of gap width and heat storage materials on the solar chimney performance will be presented and discussed in the following sections.

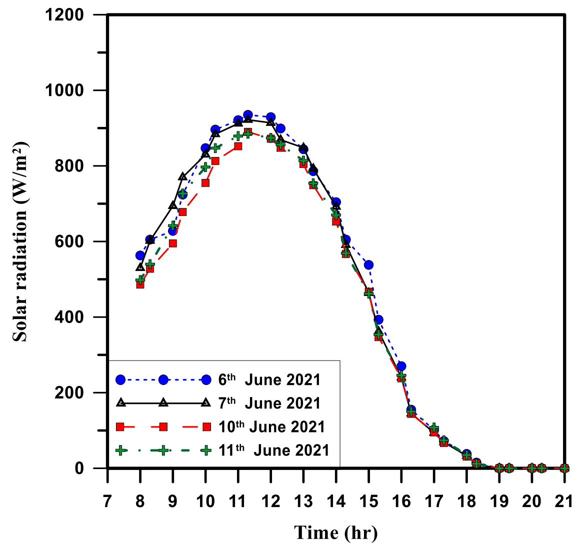

Fig. 5. Solar radiation variation along the days of the second and third measurements.

4.2 Effect of integrating thermal storage material

Figure (6) shows the variation of absorber temperature (at the middle of cavity length) along the solar time of day for the different gap widths. From the figure, it is noticed that the maximum absorber temperature is 82 °C at a gap width of 2.5 cm, and its decreases at a gap width of 10 cm (i.e. 62 °C). Also, it can be noticed that the temperature of the absorber along solar time of day tends to decrease by increasing the gap width.

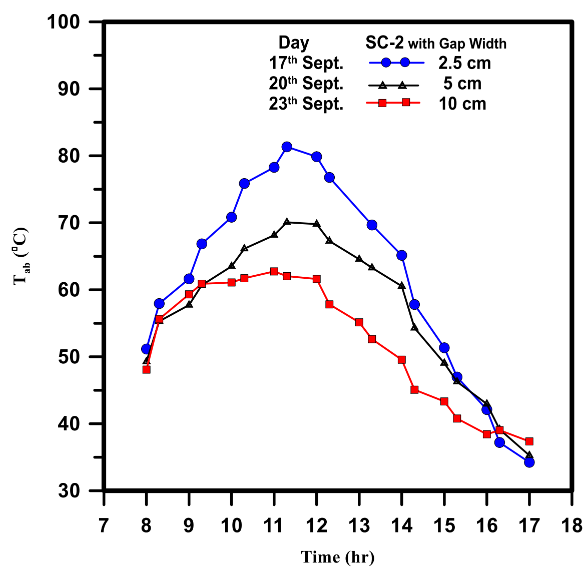

Fig. 6. The effect of different gap widths of SC-2 without thermal storage materials on the absorber temperature.

This may be the reason that, at higher gap width, a higher amount of airflow passes through the chimney which increases the amount of heat transferred from the absorber by convection and radiation. It also can be concluded (from 20th Sep.) that, the two test rigs at the same conditions of measurement and geometrical parameters give almost identical results which ensure the soundness of comparisons between the two test rigs at different geometrical parameters.

Figure (7) presents the percentage of changing the air mass flow rate between the SC-1 ($\dot{m}_{SC-1}$ with a fixed gap width of 5 cm) and the SC-2 ($\dot{m}_{SC-2}$ with different gap widths 2.5, 5, and 10 cm respectively).

$$\Delta\dot{m}\ \% = \frac{(\dot{m}_{SC-2} - \dot{m}_{SC-1})}{\dot{m}_{SC-1}} \times 100 \qquad (1)$$

The air mass flow rate is calculated by the following equation, Bansal et al. [16].

$$\dot{m} = \frac{C_d \rho_f A_e}{\sqrt{\left(1+\frac{A_e^2}{A_i^2}\right)}} \sqrt{2gL_s(T_f - T_a)/T_a} \qquad (2)$$

In which A_i and A_e are the inlet and the exit area of the chimney and ρ_f is the average density of the air inside the chimney. C_d is the discharge coefficient and is taken as 0.57 for the sharp edge inlet and outlet, g is the gravitational acceleration, L_s is the stack length, T_f is the average temperature of the air inside the chimney cavity (the arithmetic mean of the air temperature at the inlet, middle, and outlet of the chimney) and T_a is the temperature of the ambient air. From the figure, it can be observed that the amount of airflow in the smaller gap width is lower than in the larger one.

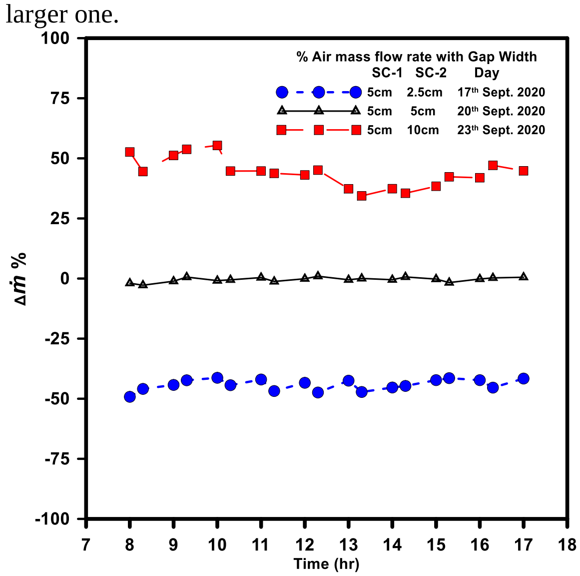

Fig. 7. Variation of the percentage of air mass flow rates at SC-1 and SC-2 for different gap widths.

The maximum delivered mass flow rate is increased by 55% at a chimney gap width of 10 cm at 10:00 a.m. Generally, with increasing the gap width from 5 cm to 10 cm, the amount of mass flow rate is increased between 30% and 50% along the solar time of day. On the other hand, decreasing the gap width from 5 cm to 2.5 cm decreases the air mass flow rate by 44% approximately as shown in the Figure.

The efficiency of the solar chimney, which is the ratio of the amount of absorbed heat by the air to the incident solar radiation on the absorber, is calculated from the following equation presented by Duffie and Beckman [17]

$$\eta_{SC} = \frac{\dot{m}C_p(T_o - T_i)}{qA_{ab}} \qquad (3)$$

The efficiency of the SC at different gap widths (i.e. 2.5, 5, and 10 cm) along the measuring hours is presented in Fig. (8). The figure shows that the efficiencies are almost identical at the first and last period of the day, this is due to the low solar radiation at this period which makes no apparent differences. It also can be seen that the SC with 10 cm achieved the lowest efficiency and the SC with 5 cm gap widths achieved the highest efficiency from 11:00 to 15:00 with a maximum value of about 45% at noon. The results can be proved that the select a suitable gap width between small width (with a high effect of thermal buoyancy and small flow rate) and large width (with a low effect of thermal buoyancy and high flow rate) played the main role to improve the efficiency of solar chimney.

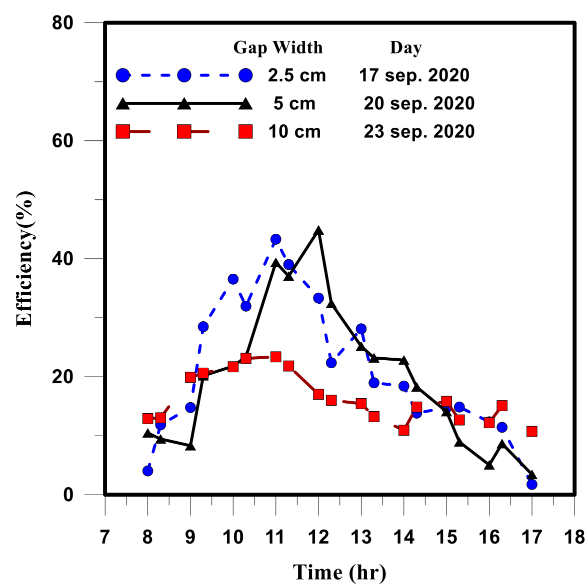

Fig. 8. The effect of gap width on the solar chimney efficiency.

4.1 Effect of changing gap width

The effect of using a material as thermal storage under the absorber is tested at fixed gap width (5 cm). Figure (9) indicates the change that occurs to the absorber temperature when the absorber of SC-2 is equipped with a 5 cm back layer of thermal storage material (adherent with the absorber) while the absorber of SC-

1 is normally insulated without an adding layer of thermal storage. It can be noticed that at the time from 8 am to 12 pm the temperature of the SC-2 absorber (with adding thermal storage) is lower than the SC-1 absorber (without thermal storage) and that's because the concrete layer in SC-2 absorbs heat by conduction from the absorber while the layer of sawdust insulates the absorber. Afternoon and from 12 pm to 9 pm the SC- 2 absorber temperature is higher than it is at SC-1 due to the heat released from the concrete layer and transferred to the absorber by conduction. In the forenoon period from 8 am to 12 noon, the isolated absorber temperature is slightly higher than that for the absorber augmented with an LHS material (Bitumen layer). While in the afternoon, from 12 pm to 9 pm, when the solar radiation tends to decrease, the absorber temperature decreases too, and the LHS layer starts releasing heat to the absorber. Consequently, the absorber temperature for SC-1 is higher than the absorber temperature of SC-2. It can also be noticed that the rate of decrease in the absorber temperature is more rapid when no LHS is used. The use of LHS maintains a slower rate of decrease in absorber temperature.

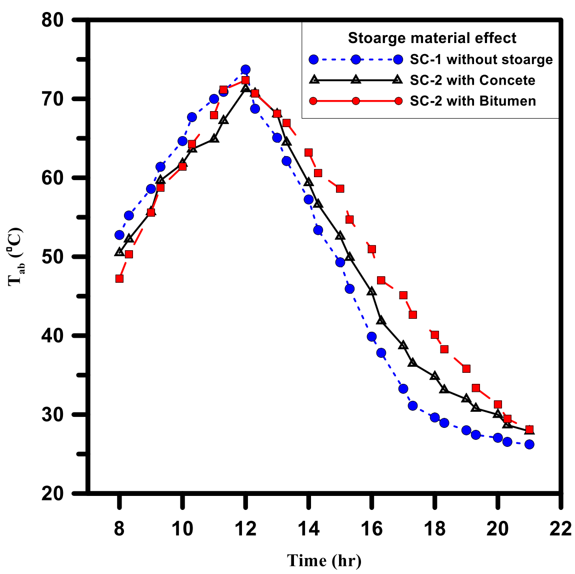

Fig. 9. Absorber temperature of SC-1 and SC-2 with different heat storage materials at a gap width, 5 cm.

Figure (10) shows the absorber temperature difference ($T_{ab\text{-}SC\text{-}2} - T_{ab\text{-}SC\text{-}1}$) achieved by SC with different heat storage materials. From the figure, it can be observed that LHS material (Bitumen) increases the absorber temperature concerning conventional solar chimney SC-1 (about 15 °C between 4.0 and 6 pm). Also, the absorber temperature with LHS material is higher than with SHS material. In general, it could be seen that the Bitumen layer has a better effect on the absorber temperature at night time than the concrete layer.

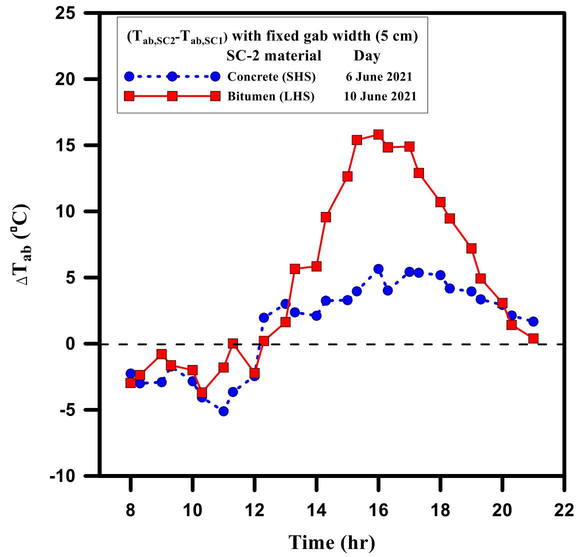

Fig. 10. The absorber temperature difference with different thermal storage materials.

The variation of percentage air mass flow rates for the conventional SC-1 and modified solar chimney SC-2 is presented in Fig. (11). From the figure, it is observed that the mass flow rate in SC-1 is higher than that in SC-2 (Concrete and Bitumen) layers during the period from 8 a.m.to 12:30 pm. During this period the SC-1 achieved a higher air mass flow rate compared with the mass flow rate of SC-2. By absorbing some of the heat to the thermal storage layer, the air mass flow rate of SC-2 is decreased by -20% to -4% during the first time of sun day (8 am t 12:30 pm). While in the period from 12:30 p.m. to 9 pm., the air mass flow rate in SC-2 is higher than in SC-1. The storage heat increases the temperature through the chimney cavity and this reflects in the flow velocity and the air mass flow rate after solar noon. From the figure, it can be observed that the percentage of air mass flow rate of SC-2 increases and it reaches the maximum value (about 90 %) at 7 pm (sunset period). Then decreases with the night period from 7 pm to 9 pm. Generally, it can be concluded that the thermal storage materials increase the airflow rate during the solar chimney, and the use of LHS material is best than SHS material.

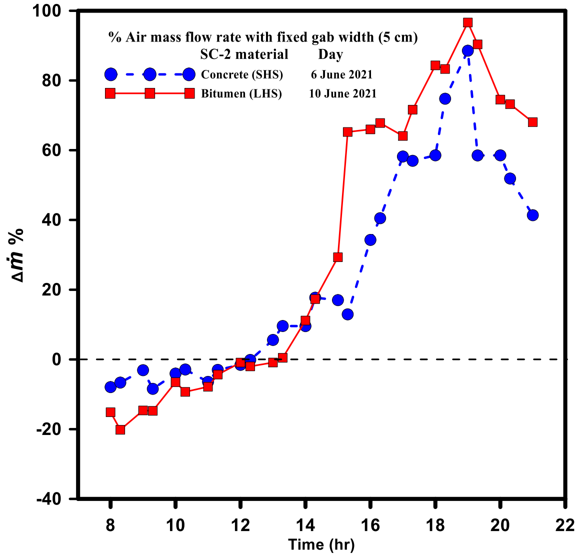

Fig. 11 The variation of percentage air mass flow rate difference between SC-1 and SC-2 with different thermal storage materials.

Figure (12) represents the number of air change per hour (ACH) variations for different chimneys' thermal storage materials, throughout the day. From the figure, it can be seen that the concrete layer has a better effect than bitumen, in the period from 8:00 a.m. to noon. While the period between 12 pm and 5 pm the performance of SHS material and LHS material is almost the same. On the other hand, the performance of the chimney equipped with Bitumen is better than concrete during the period from 17:00 to 21:00.

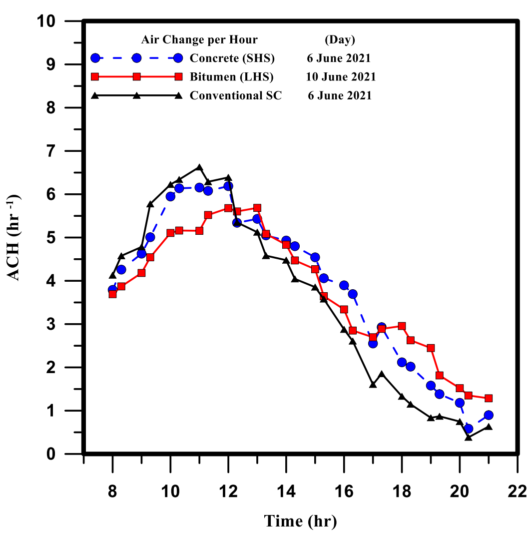

Fig. 12. ACH variation during the day for different thermal storage materials.

5. Conclusions

The current study presents an experimental investigation of the thermal performance of solar chimneys under various geometrical and operational conditions. The use of the solar chimney for night ventilation was also investigated by equipping the chimney with a new novel phase change material (bitumen). Based on the results, the following conclusions can be made for SC design:

1. The gap width has a direct effect on the air mass flow rate across the chimney, in which increasing the gap width increases airflow through the chimney even though it decreases the air temperature difference between the outlet and inlet of the chimney. It also was found that increasing the gap width value above 10 cm would cause a reverse flow at the chimney outlet. While the SCs with gap widths of 2.5, 5, and 10 cm achieved an average day efficiency of 21.1%, 24.1%, and 16.3% respectively.

2. Adding a 5 cm thick layer of sensible heat storage material (concrete) improved the thermal performance of the SC and prolonged the ventilation hours.
3. Backing the absorber with a 5 cm layer of latent heat storage material (bitumen) improved the solar chimney's performance better than the concrete layer.
4. Integrating the SC with concrete and bitumen increased the air mass flow rate through the SC with a daily average value of about 24% and 32% respectively.

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