Numerical and experimental assessment of PV/Solar Chimney

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Abstract. One of the main obstacles facing solar chimney systems is their low efficiency which contributed to the decrease in the construction of solar chimneys in the world. The current article presents a novel proposal to enhance the efficiency of solar chimneys by using solar panels. In this new system, the solar cells are fixed in the mid-distance between the chimney base and the glass cover. Therefore, the air can move above and below the solar cells to accelerate the photovoltaic cells' cooling and obtain higher air velocity. The results also showed that the photovoltaic cell location determines its temperature, where high temperatures characterized the solar panels fixed in the middle. In contrast, the solar cells that are placed on the ends were at lower temperatures. The outcomes also confirmed that the air velocity in the new design still depends on weather conditions, and the results show that the chimney base is the ideal location for the turbine, and the air velocity rises during the day to reach its maximum value at 1 p.m. The highest recorded air velocity was 1.8 m/s in February at 1 p.m. High-efficiency values were recorded in the early morning because of the solar cells' low temperatures for the tested months. The highest recorded electrical efficiency value was 17.8% in December. In contrast, the lowest recorded electrical efficiency was 10.6% in February at 1 p.m.

Keywords. Solar chimney, Photovoltaic cell, Performance, Experimental, Assessment.

Introduction

The increase in conventional fuel prices and the resulting environmental emissions have led researchers to look for a sustainable and non-polluting environmental source[1][2]. Solar energy has been one of the most powerful energies scientists have sought to take advantage of because it is available and needs no specialized technology, and does not pollute the environment[3][4]. However, low performance is inappropriate with solar energy systems, and researchers have tried to increase their efficiency[5][6]. There are many systems for generating electricity using solar energy, and solar chimneys or solar updraft towers are one of the technologies used for this purpose[7]. The solar chimney contains a circular glass region positioned at a certain distance from the ground's surface, and there is a high chimney close to the chimneys used in electrical power stations in the middle of this circle, as shown in Figure. (1)[8][9].
The solar radiation heats the air trapped between the glass layer and the ground which painted black to work as the solar collectors' absorbing plate. The air density below the glass cover decreases because of its high temperature and moves up towards the

chimney to rotate special turbines similar to wind turbines. In 1982, the first solar chimney was built in Manzanares, Spain[10]. The chimney had a height of 195 m with a collection area with a diameter of 244 m.

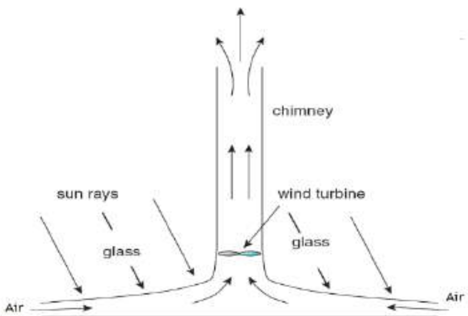


Fig. 1 The working principle of the solar chimney

One of the major disadvantages of solar chimneys is their low efficiency[11]. Several researchers and scientists have performed studies to enhance solar chimneys' efficiency by adding other technologies and means to improve solar chimney performance[12]. Photovoltaic-Solar Chimneys (PV/SC) are proposed designs to increase solar chimneys' efficiency. This technique relies on the use of solar chimneys to cool solar panels. Several studies and designs have been presented in recent years to assess these hybrid solar chimney systems[13][14]. Eryener et al.[15] presented a novel type of solar chimney called a transpired solar chimney, as shown in Fig. (2). The transpired solar chimney utilized transpired metal sheets in place of the conventional solar chimney's glass cover. The air enters the upper metal surface instead of the perimeter. A laboratory model for this type was built at Trakya University in Edirne-Turkey. Several tests were conducted during the summer and winter seasons to study the modified solar tower's performance design and operational parameters. The new solar chimney's efficiency was increased by three times the efficiency of the conventional solar chimney.

Eryener and Kuscu[16] suggested a new concept of the solar chimney called a hybrid transpired solar chimney and consisted of photovoltaic panels and transpired solar collectors. The photovoltaic panels cover 42% of the area of the transpired solar chimney. The efficiency of the solar chimney is ranging between 16–18%. Ahmed and Hussein[14][17] introduced two new solar chimney designs based on integrating solar panel technology with solar chimneys. In the first design, solar cells replaced the glass cover in the traditional solar chimney (Fig. 3-a). As for the second design, the floor of the solar chimney was replaced by solar cells, as in Fig. (3-b). The result appears that the first model's overall Power was more extensive than that produced from the second model.

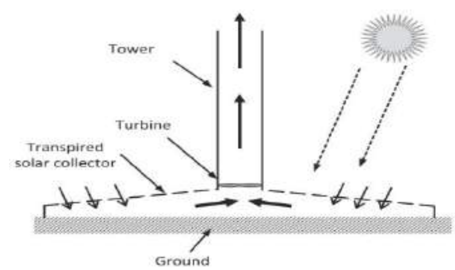
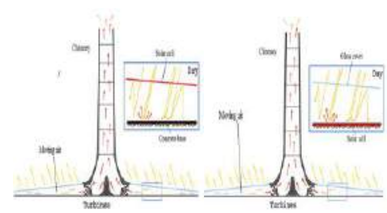


Fig. 2 Transpired solar chimneys[15]



(a) The first model (b) Second design
Fig. 3 The novel designs were presented by Ahmed and Hussein[14][17]

Liu.[18] presented a mathematical model to analyze the PV/solar chimney's performance in Northwest China. The results confirmed that the PV panel's temperature rise had a significant impact on its performance. Rahbar and Riasi[19] proposed two classical solar chimney designs with a transparent photovoltaic panel and solar to boost the classical solar chimney's efficiency. Mathematical models were built for each design. In the first design, the glass cover was replaced by solar cells. The second design is similar to the first design, except replacing the floor with a solar distillation containing saltwater to evaporate it and convert it into fresh water. The results showed that the first and second systems' efficiency increased by 55.97% and 71.8% relative to the traditional solar chimney's efficiency. The thermal and economic assessment was presented by Jamali et al.[20] to analyze the semi-transparent photovoltaic solar chimney's performance. A mathematical model based on the heat transfer between three main components of a solar chimney. The findings verified economic gains by using the framework proposed were 11% and 5% for Shiraz and Tabriz, respectively. Jamali et al.[21] enhanced the efficiency of the solar chimney using the solar cell. The results showed the possibility of reducing the temperature of solar cells up to 15 oC. Also, it is observed that the efficiency of the PV/solar chimney depends on the radiation intensity and the design parameters. For this method, an improvement in power generation of about 29% was achieved. Fadaei et al.[22] studied the effect of the phase change materials on the performance of the solar chimney. Two models of the solar chimney (with and without phase change material) were achieved. Different parameters such as temperature and velocity were measured to assess the performance of the solar chimney. The results confirmed that using phase change material used increases the solar chimney's performance. Boutina et al.[23] presented CFD simulation to analyze the turbulent free convection for solar panel cooling in a new hybrid PV/solar chimney design. The results confirmed that the rise in the tower's height increases air velocity. That could cause an increase in the kinetic Power and accelerates the cooling process of the solar panels. Therefore, that will increase the efficiency of the solar panels integrated with the solar chimneys. The low performance of these systems is one of the most significant challenges solar chimney technology faces[24]. Therefore, scientists and researchers started improving solar chimney systems' performance by making adjustments to the chimney design and suggested ways to increase solar chimneys' efficiency. In previous designs, solar cells were used as a solar chimney floor, and in other designs, solar cells were used instead of the glass cover. The current article provides an assessment of the efficiency of an advanced photovoltaic solar chimney system. In this design, the solar cells are fixed in the mid-distance between the chimney base and the glass cover. Therefore, the air can move over and below the solar cells to accelerate the solar cells' cooling and obtain the air's highest velocity. This PV/solar chimney is called as the Interlayer Photovoltaic Solar Chimney (IPV/solar chimney).

Methodology

Solar energy systems are characterized by their low energy density and low efficiency. The research trends in the current period are aiming to enhance solar energy systems' efficiency using different methods. This paper aims to assess the performance of an innovative system of the IPV/solar chimney at the Iraqi weather conditions. The experiments were conducted in Kirkuk-Iraq (35.47 N^{o}, 44.39 ^{o}E). The data were recorded from 9 a.m. to 4 p.m. The experiments were done in December-2019 and in January, February, and March-2020. The study included the following items: explain of the practical work is clarified in section 3. In section 4, the calculations of the performance and efficiencies estimation are clarified.

Experimental study:

A pilot model was constructed, as shown in Fig. (4). The system was placed on the roof of the building at the Kirkuk Technical College/Northern Technical University, at 12 m above ground level. This system consisted of the following parts:

a) Steel structure,
b) Six solar cells,
c) Glass cover,
d) Chimney,
e) Measuring devices and electrical load.

The experimental system's base was made of wood, and a layer of cork was installed to reduce the amount of heat transferred from the system to the roof of the building. The wooden base dimensions were 3.485 m in length and 3.1 m width, and the base area 10.8 m2. The distance between the system base and the building roof was 8 cm, as shown in Fig. (5). Six solar cells were installed at 3 cm from the solar chimney's metal base—specifications of these cells as shown in Table 1. The six solar cells were linked in a series. The current design differs from the previously studied designs, such in[21][14][20] by the fact that the air moves below and above the solar cells to absorb the largest possible amount of heat that causes low efficiency of cells. Fig. (6) shows the arrangement of the solar panels on the chimney base.

Fig. 4 PV/Solar chimney pilot model

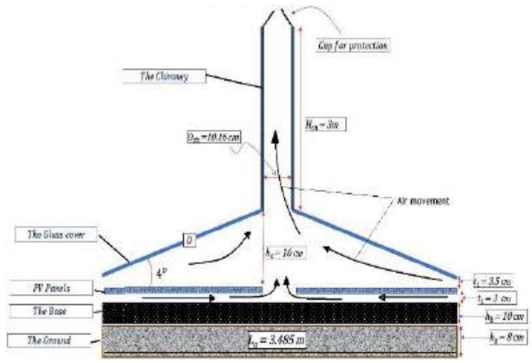


Fig. 5 Dimensions of the experimental model

Table 1. PV/cell specifications

Parameter.	Unit	Parameters	Unit
Open Circuit Voltage (Voc)	21.9 V	Short Circuit Current (Isc)	9.01 A
Maximum Power at the standard condition	250 W	Cell Type	Multicrystalline
Max. PV	35 V	Ambient Temperature	25 °C
MPV.	15 A	Dimensions (m)	(1.64*0.990* 0.04)

A layer of glass with a thickness of 6 mm and an angle of 4° was installed over the solar cells to accelerate the air movement, increase the amount of solar radiation absorbed by the solar cells, and reduce the heat losses. A chimney with a diameter of 10.16 cm and a height of 3 m was placed above the glass cover to increase the system's air movement. To measure the air velocity inside the chimney, two round holes of 2 cm in diameter were made in the chimney wall. The first hole is at the base of the chimney and the second hole is at 1.5 m height from the base of the chimney. Fluid velocity and temperature were measured using a hot wire digital anemometer type (GM8903) with an error ratio (± 0.03 m/s).

11 thermocouples (K type) were fixed and utilized to measure temperature in different experimental system locations. Three thermocouples are installed to measure the temperature of the three solar panels. The method of arranging the solar cells was symmetrical as the thermocouple was installed in the center of the upper solar panel. Also, six thermocouples were installed to measure the temperature of the glass cover. Where two thermocouples are installed above and below the glass cover fixed over three symmetrical solar panels. A thermocouple was utilized to sense the base system's temperature and another thermocouple was to measure the ambient air temperature. The electricity generated by the solar panels was stored in deep cycle batteries, as shown in Fig. 7. The voltage and current of the PV cell were measured using a multimeter (Type Victor-VC890D). The weather station was used to measure solar radiation, wind speed, and ambient air temperature. Three DC lamps (21 W) were connected to a three-button switch and a solar cell, as shown in Fig. (7).

Fig. 6 Arrangement of solar cells

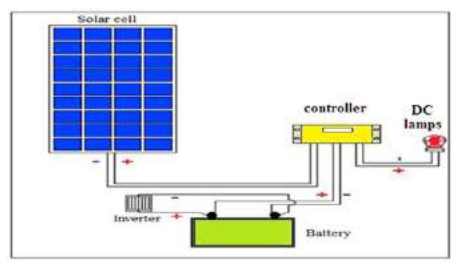


Fig. 7 The electrical connection of the solar cells and their accessories

Performance calculations:

The thermal efficiency of the solar chimney calculated as[25]:

$$\eta_{th} = \frac{Q_u}{A_{co} I_t} \quad (1)$$

Where:

A_{co} is the total area of the solar cells shown in Fig. (6), and it is a square area of 10.8 m^2.

I_t: is the total solar radiation on a horizontal surface (W/m^2).
Q_u represents the heat gained by the chimney and calculated as[26]:

$$Q_u = \dot{m}_{air}\ Cp_{air}\ (T_{outlet\ air} - T_{ambient}) \tag{2}$$

Where, $T_{outlet\ air}$ is the temperature exit air and measured by the thermocouples at the exit of the chimney.
$T_{ambient}$ is the ambient air temperature and also measured by a thermocouple.
Cp_{air} is the air specific capacity of the air and evaluated as[27]:

$$Cp_{air} = [1.007 + 0.00004(T_{air} - 300)] * 10^3 \tag{3}$$

Also, $\dot{m}_{air}$ represents the mass flow rate of air and calculated as[13]:

$$\dot{m}_{air} = \rho_{air} V_{air,exp} A_{chimney} \tag{4}$$

ρ_{air} is the density of moving fluid at inlet chimney and calculated by[27]:

$$\rho_{air} = 1.1614 - 0.00353\ (T_{base,air} - 300) \tag{5}$$

$T_{base,air}$ is the temperature of the chimney base.
$V_{air,exp}$ is the average of the air velocity, which is calculated experimentally by hot-wire anemometer along with the chimney height.
$A_{chimney}$ is the area of the chimney and equal to (81 cm^2).

The electric efficiency of the new solar chimney was evaluated as [28]:

$$\eta_{ele} = \frac{P_K + P_{PV}}{I_t A_{co}} \tag{6}$$

P_K represents the electrical energy generated by the turbine at the base of the solar chimney[29]:

$$P_K = P_W\ \eta_{wt} \tag{7}$$

Where: η_{wt} the efficiency of the used turbine and its value range (50-90 %)[30].

P_W represents the kinetic Power produced by the system and calculated experimentally from the following relation[19]:

$$P_W = \frac{1}{3} \rho_{air} A_{chimney} (V_{air,exp})^3 \tag{8}$$

While P_{PV} represents the electric energy produced by solar cells[31]:

$$P_{PV} = V.I \tag{9}$$

V and I represent the voltage and current of the solar cells, respectively.

The error analyses can be calculated by Eq. (10)[32]. Table (2) represented the uncertainty of the instruments utilized in the article.

$$\omega_R = \sqrt{\left(\frac{\partial\varphi}{\partial x_1} \times \psi_1\right)^2 + \left(\frac{\partial\varphi}{\partial x_2} \times \psi_2\right)^2 + \cdots\cdots \left(\frac{\partial\varphi}{\partial x_n} \times \psi_n\right)^2} \tag{10}$$

Table 2 Specifications of the instruments

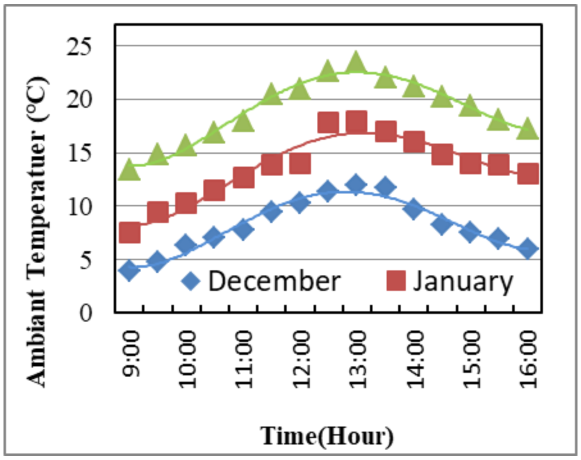
Devices	Uses	Errors
Hotwire Anemometer	Wind Velocity	± (2%)
Multimeter	D-C Current	±(0.7%)
Dig-ital Thermo-meter	Temperat ure	± (0.5 °C)
Multimeter	DC Voltage	±(0.4%)

Results and discussions:

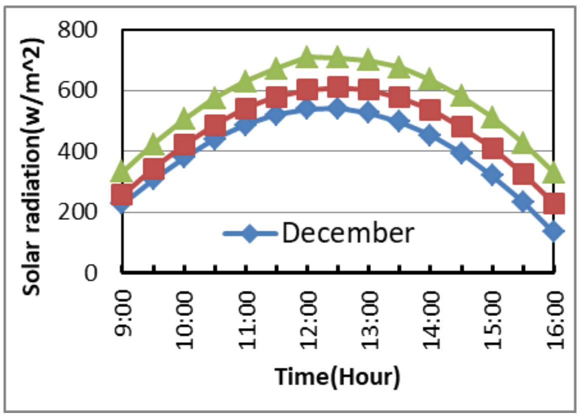
The tests were achieved in Kirkuk city (35° 28' N, 44° 24' E). The series of experiments were conducted in December 2019 and January and February 2020. The daily system effectiveness was analyzed systematically for all test conditions. These included the solar cell temperature, air temperature at different locations, air velocity along the chimney, and the electrical and thermal efficiencies. In the early morning, the solar cells are cleaned of dust and accumulated dirt before experiments start. Measurements of different parameters are measured every half an hour. Fig. (8) shows the variation of the ambient air temperature and solar radiation values during the test months. The recorded temperatures ranged between 4 °C for December and 23 for February. In comparison, the highest recorded value of solar radiation was 707 W/m2 at 1:00 p.m. in February.

Air velocity:

Solar chimneys transform solar energy into kinetic energy in all their designs. Then it uses this kinetic energy to rotate special turbines that produce electricity. Fig. (9) shows the variation of the air velocity at the chimney base for different months. The first impression of the change in air velocity at the base of the chimney shows the escalation of air velocity values to reach the highest speed at 1 p.m. for all months, and it decreases after that.



(a) Ambient air temperature



(b) Solar radiation

Fig. 8 Variation of the ambient air temperature and solar radiation

This increase in air velocity is due to an increase in solar radiation values, which has caused an increase in the air temperature trapped under the glass cover due to the greenhouse phenomenon. The increase in temperature reduces its density, which causes the air to move towards the chimney [33]. It is also noted that the measured air velocity rate for February is higher than for the other two months due to the high values of solar radiation, which is the main driver of the movement of air in solar chimneys. The highest recorded air velocity was 1.8 m/s for February at 1:00 p.m. As mentioned previously, the air velocity was measured at the inlet, middle, and chimney outlets. Fig. (10) shows that the air velocity at the chimney inlet is higher than the air velocity in the middle and the chimney outlet due to the friction effect and the decrease in air temperature while passing through the chimney. This behavior is consistent with the published literature[34][35].

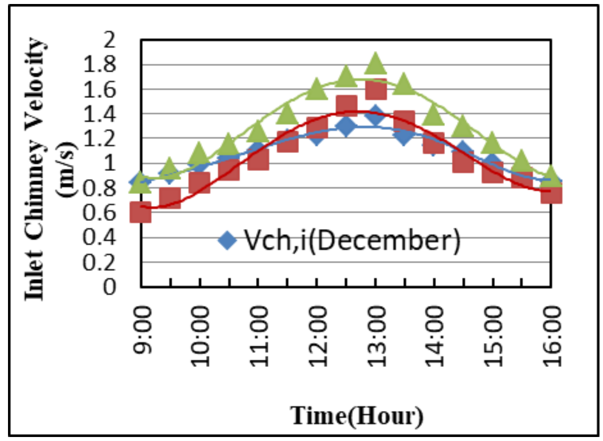


Fig. 9 Variation of the air velocity at the chimney base (chimney inlet) for different months.

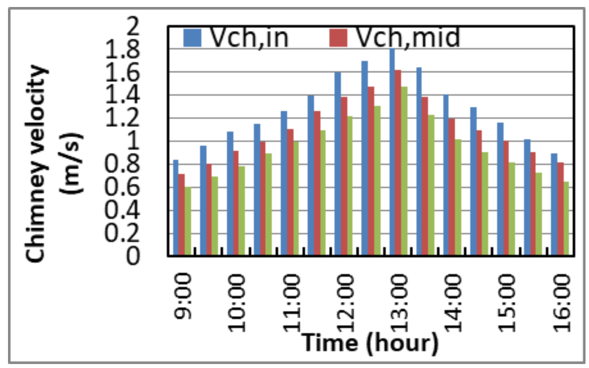


Fig. 10 Variation of the air velocity inside the chimney at different locations for February

Temperature of the solar cells:

Six solar panels were used and distributed symmetrically, as shown in Fig. (11). The thermal sensors are fixed to three plates on one side, and they are named in the left, middle, and right cells to show their temperature. Fig. (12) shows the change of temperature for the three solar cells for the three months (December, January, and February). It is found that the temperature of the solar panels increases to reach the highest temperature at 1 p.m. for the three panels and other months and then decreases. It also turns out that the central solar cell was at a higher temperature than other panels because its presence in the middle of the model reduces the external wind's impact on the solar panels. Therefore, it reduced the solar panels' temperature in the ends (left and right solar cells). It is also shown that the temperatures of the solar cells measured in February are higher than in December and January due to the high values of solar radiation and the high ambient air temperature of February at the study site[36][37].

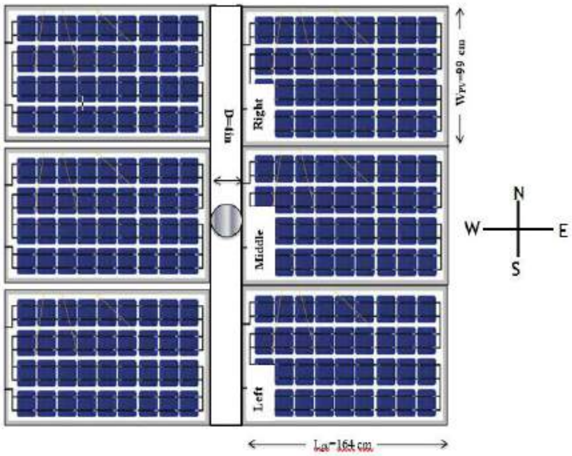
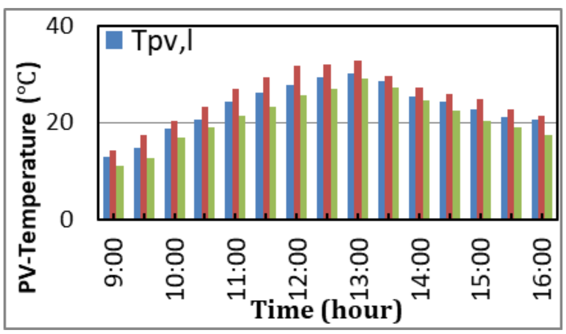
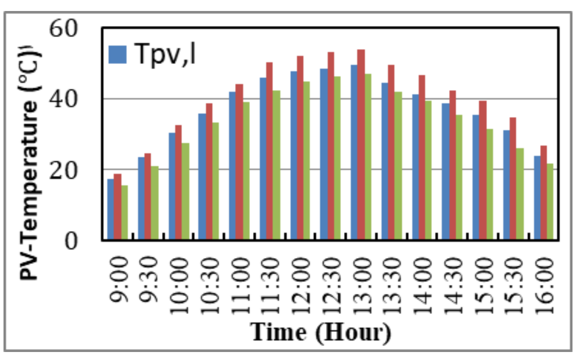


Fig. 11 Arrangement of solar panels



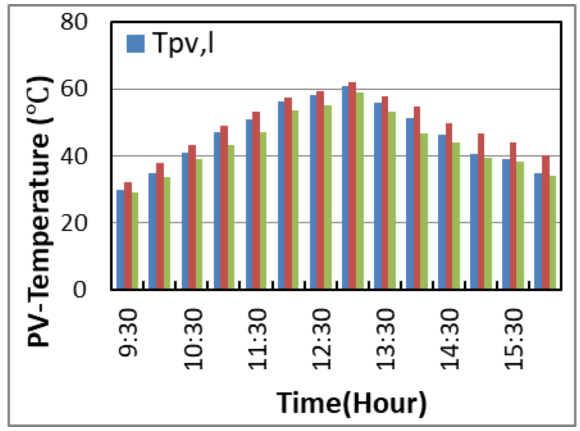
(a) PV temperature for December



(b) PV temperature for January

Kinetic Power:

The kinetic Power of the system was calculated using eq. (8). Fig. (13) shows the variation of the kinetic Power. It is noticed that the kinetic power rates increase in February due to the increase in solar radiation[38], and the highest kinetic power of 35 W was recorded at 1 p.m. in February. Furthermore, it is observed that the increase of solar radiation led to an increase in the kinetic Power during the day.



(c) PV temperature for February

Fig. 12 PV temperature for different months

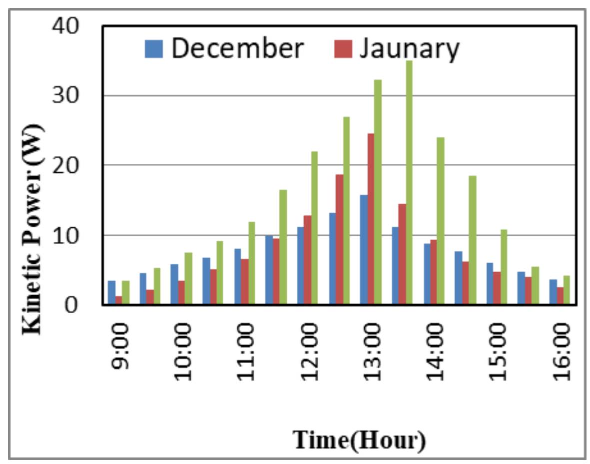


Fig. (13) Kinetic Power Variation.

Electric Power and Thermal Power:

The solar cells are connected in series, and the total electrical power produced is calculated using eq. (9). Fig. (14) shows the change in the electrical power produced during the day for several months. It is clearly appear that the production of electrical power was the highest level in January due to the decrease in the solar cell temperature and the increase of solar radiation. As the published literature indicates, the increase in the amount of incident solar radiation and the decrease in the solar cell temperature at the same time leads to an increase in the electrical power produced[39].

The results also showed that increasing the solar radiation values leads to an increase in the amount of thermal power in the system. The thermal power amount was calculated using eq. (2)

Moreover, these results are shown in Fig. (15). Therefore, this heat can be used for home uses such as heating, water heating, etc. The thermal Power in February was higher than the other months due to the high values of solar radiation, and the maximum value for the thermal Power was 284 W at 1 p.m. In comparison, the lowest value for thermal efficiency during the day was in December, which is identical to the results published in[40].

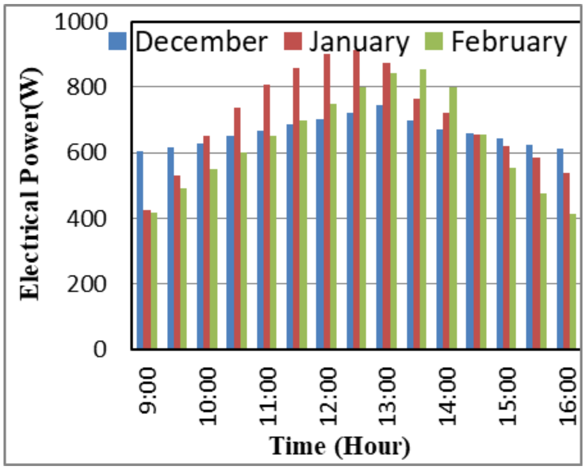


Fig. 14 Variation of the electric power during the day for different months

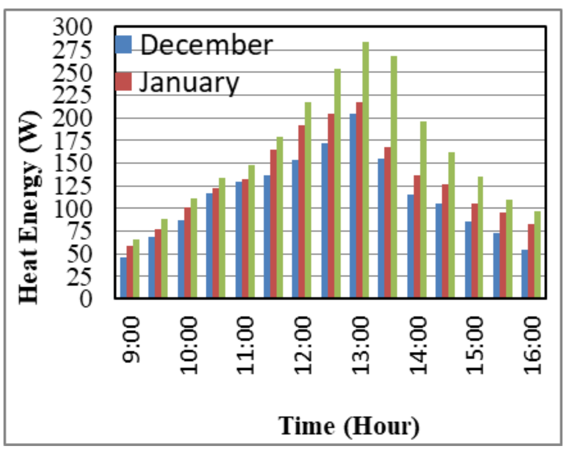


Fig.15 Variation of the heat power during the day for different months

Efficiency of the system:

The electrical efficiency of the PV/solar chimney is calculated using eq. (6).Fig. (16) shows the change in the hourly electrical efficiency during the day. It is noted that the shape of the change in electrical efficiency is concave up. High-efficiency values were observed in the early morning hours due to the solar cells' low temperature for all months. The highest recorded electrical efficiency values were 17.8% for December. In contrast, it was the lowest recorded electrical efficiency of 10.6% for February at 1 p.m. due to the increase of the cell temperature. This behavior was expected and observed in previous research, which dealt with the study of PV/T solar systems such as[23][41]. Fig. (17) shows the change in hourly thermal efficiency during the day. The thermal efficiency in February was higher than the other months due to the high values of solar radiation, and the maximum value for this efficiency was 68% at 12:30 noon. In comparison, the lowest value for thermal efficiency during the day was for December, which is identical to the results published in[42][43].

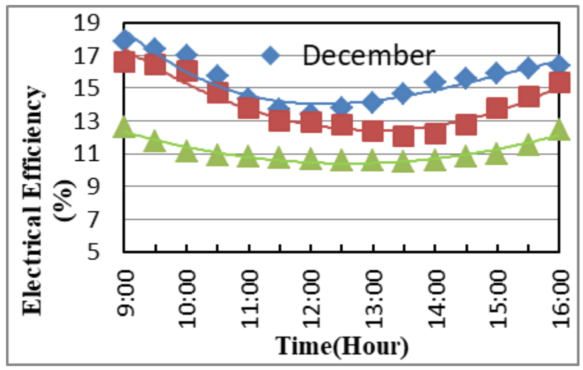


Fig. 16 The change of the hourly electrical efficiency during the day.

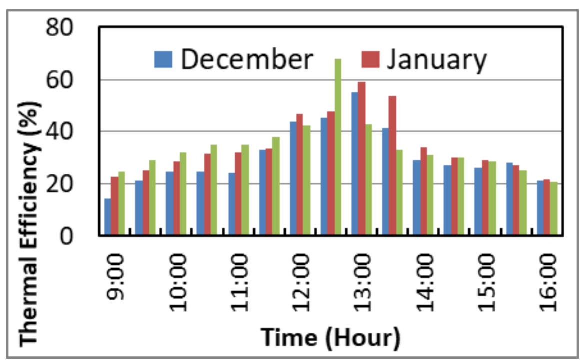


Fig. 17 The change of the hourly thermal efficiency during the day

Conclusions and recommendations:

From the results obtained, the following observations were concluded:

1- The air velocity at the chimney inlet was higher than that in the middle and the chimney outlet. The highest recorded air velocity was 1.8 m/s for February at 1:00 p.m.

2- The results indicated that solar cell location determines the degree of its temperature, as the solar cells in the middle were characterized by high temperatures, while the solar cells that are on the edges were at a lower temperature.

3- The air velocity inside the chimney and the solar cell temperature depended mainly on the surrounding weather conditions.

4- For all months, high-efficiency values were observed in the early morning hours due to the solar cells' low temperature.

5- The highest recorded electrical efficiency value was 17.8% for December. In comparison, the lowest recorded electrical efficiency was 10.6% for February at 1 p.m.

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