Experimental Study of Performance of Solar Chimney

A A Hassan, Omer Khalil Ahmed and E F Abbas

Technical college, Kirkuk, Northern technical university, Iraq
E-mail: afnan_hwj@ntu.edu.iq

Abstract. In this paper, a practical study was conducted with and without solar panels to show their effect on the performance of the hybrid solar chimney in the city of Kirkuk in Iraq. Six cells were placed between the base of the collector and the glass cover, which gives freedom to the air to move up and down the cells. Also, it is showed that the speed is higher when using PV until it reaches 1.8 m/s while the air leaving the collector and the energy coming out of the chimney and the efficiency of the solar collector and the efficiency of the chimney. The practical results showed that the chimney base is the ideal location for the turbine, as the air velocity is higher than other locations, and the air velocity increases during the day to reach its highest velocities at 1 pm. The maximum kinetic and electrical power and the amount of heat reached 37, 950, and 280 watts, respectively, in February at 1 pm. The results also showed that the location of the photovoltaic cell determines the degree of its temperature, as the solar cells that are in the middle are characterized by high temperature, while the solar cells that are on the ends are at a lower temperature and the solar cell temperature also depends on the surrounding weather conditions. High-efficiency values are observed for all months in the early morning hours due to the solar cells’ low temperature. The highest recorded electrical efficiency values were 17.8% in December.

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

1. Introduction
The increase in the traditional fuel prices and the resulting environmental pollution led the scientists to search for renewable and non-polluting sources of the environment [1]. Solar energy was one of the most vital energies that scientists tried to take advantage of because solar energy is available and does not need advanced technology and not polluting the environment [2]. However, what is wrong with solar energy systems is the low efficiency, and the researchers tried to improve these systems’ efficiency. There are currently many systems for generating electricity using solar energy, and solar chimneys or solar updraft towers are one of the technologies used for this purpose [3]. The solar chimney includes a circular area of glass placed at a certain distance from the Earth’s surface, and in the center of this circle, there is a high chimney similar to the chimneys utilized in electrical power stations. The solar radiation heats the air trapped between the glass layer and the ground, which is painted black to work as the absorbing plate in the solar collectors. 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 in Spain. The chimney had a height of 195 m and a radius of 5 m with a collection area with a diameter of 244 m, and one of the major disadvantages of solar chimneys is its low efficiency [4]. Scientists and researchers have conducted several studies to enhance the efficiency of solar chimneys by integrating...
and adding other technologies and means to improve the performance of the solar chimney [5]. Photovoltaic-Solar Chimneys (PV/SC) are one of the proposed designs to increase the efficiency of solar chimneys. 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 the performance of these hybrid solar chimney systems [6]. Eryener et al.[7] presented a novel type of solar chimney, which is called a transpired solar chimney. The transpired solar chimney utilized transpired metal sheets in place of the glass cover, which is used in the conventional solar chimney. 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 design and operational parameters on the performance of the modified solar tower. The efficiency of the new solar chimney was increased by 3 times the efficiency of the conventional solar chimney. Eryener and Kuscu [8] suggested a new concept of the solar chimney which called a hybrid transpired solar chimney and consists 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%)

2. Methodology
Solar energy systems are characterized by their low energy density and low efficiency. The research trends in the current period aim to enhance the efficiency of solar energy systems using different methods. This paper aims to assess the performance of an innovative system of the PV/solar chimney under Iraqi weather conditions. The experiments were conducted in Kirkuk city in Iraqi (35.47 N°, 44.39 °E). The experimental data were recorded from 9 am to 4 pm. The experiments were conducted in December-2019 and in January, February, and March-2020. The paper includes the following sections: the practical work is clarified in Section 3; in Section 4, the calculations of the performance and efficiencies estimation are clarified; the outcomes are presented and discussed in Section 5; finally, the conclusions and recommendations are presented in Section 6.

3. Practical study
To study the performance of this solar photovoltaic chimney, a pilot model was constructed, as shown in Figure (1). The system was placed on the roof of the Technical College/Kirkuk building, at the height of 12 m above ground level. This system consists of the following parts:
1- Iron structure, 2- Six solar cells, 3- Glass cover, 4- Chimney, 5- Measuring devices, and 6- Electrical load.

![Figure 1. PV/Solar chimney pilot model.](image-url)
Specifications of these cells are shown in Table 1. The six solar cells were linked in series. The current design differs from the previously studied designs, such as in [9], because the air moves below and above the solar cells to absorb the most considerable possible amount of heat that causes low efficiency of the solar cells, Figure 2.

| Parameters                          | 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 |
| Maximum Power voltage               | 35 V       | Operating Temperature               | 25 °C      |
| Maximum Power Current               | 15 A       | Dimensions (m)                      | (1.64×0.990×0.04) |

Figure 2. Dimensions of the experimental model.

4. Performance calculations

The thermal efficiency of the solar chimney can be calculated as [10]:

\[
\eta_{th} = \frac{Q_u}{A_{co} I} \tag{1}
\]

\(A_{co}\) is the total area of the solar cells, and it is a square area of 10.8 m².

\(I\) is the total solar radiation on a horizontal surface (W/m²).

\(Q_u\) represents the heat gained by the chimney and calculated as [11]:

\[
Q_u = \dot{m}_{air} C_p \ (T_{outlet \ air} - T_{air}) \tag{2}
\]

Where \(T_{outlet \ air}\) is the temperature of outlet air and measured by the thermocouples at the exit of the chimney.

\(T_{air}\) is the ambient air temperature and also measured by a thermocouple

\(C_p\) is the air specific capacity of the air and evaluated as [12]:

\[
C_p = \left[1.007 + 0.000004(T_{air} - 300)\right] \times 10^3 \tag{3}
\]

Also, \(\dot{m}_{air}\) represents the mass flow rate of air and calculated as [6]:

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

\(\rho_{air}\) is the density of moving air at the inlet of the chimney and calculated by [13]:
\[ \rho_{\text{air}} = 1.1614 - 0.00353(T_{\text{air}} - 300) \]  

\( V_{\text{air,exp}} \) is the average of the air velocity, which is calculated experimentally by hot-wire anemometer along with the chimney height. 

\( A_{\text{chimney}} \) is the cross-sectional area of the chimney and equal to (81 cm\(^2\)). 

The electric efficiency of the new solar chimney was evaluated as [14]: 

\[ \eta_{\text{ele}} = \frac{P_K + P_{PV}}{I_{c} A_{co}} \]  

\( P_K \) represents the electrical energy generated by the turbine at the base of the solar chimney [15] 

\[ P_K = P_W \eta_{wt} \]  

Where: \( \eta_{wt} \) the efficiency of the used turbine and its value (85 \%) [15]. 

\( P_W \) represents the kinetic power produced by the system and calculated experimentally from the following relation [16]: 

\[ P_W = \frac{1}{2} \rho_{\text{air}} A_{\text{chimney}} (V_{\text{air,exp}})^2 \]  

While \( P_{PV} \) represents the electric energy produced by solar cells. It is well known that the electric energy produced depends on the temperature of the solar cell and calculated as[17]: 

\[ P_{PV} = V . I \]  

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

The error analyses are one of the essential criteria that determine the suitability of a novel solar chimney to produce electric power. Table (2) shows the uncertainty of the instruments utilized in the practical work, then the uncertainty of the obtained results is evaluated by the following equation [18]: 

\[ \omega_{R} = \sqrt{\left( \frac{\partial \phi}{\partial x_1} \times \psi_1 \right)^2 + \left( \frac{\partial \phi}{\partial x_2} \times \psi_2 \right)^2 + \ldots \ldots \left( \frac{\partial \phi}{\partial x_n} \times \psi_n \right)^2} \]  

**Table 2.** Specifications of the instruments.  

| Equipment            | Measurement     | Error       |
|----------------------|-----------------|-------------|
| Hotwire Anemometer   | Wind Velocity   | ± (2\%)     |
| Multi-meter          | DC Current      | ± (0.7\%)   |
| Digital Thermometer  | Temperature     | ± (0.5 \ laissez)
| Multi-meter          | DC Voltage      | ± (0.4\%)   |

5. Results and discussions 

Figure (3) shows the variation of the ambient air temperature and solar radiation values during the test months. The recorded temperatures ranged between 4 °C in December and 23 °C in February. In contrast, the highest recorded solar radiation value was 707 W/m\(^2\) at 1:00 pm in February.
5.1. Air velocity

Generally, the designs of solar chimneys are based on converting solar energy into kinetic energy and then use this kinetic energy to rotate special turbines that generate electricity. Figure (4) 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 pm for all months, and then it decreases after that. This escalation in the air’s speed is due to the increased solar radiation values, which caused an increase in the air temperature trapped under the glass cover because of the greenhouses’ phenomenon. The increase in temperature reduces its density, which causes air to move towards the chimney [19]. It is also noted that the measured air velocity rates for February are higher than the other two months due to the high values of solar radiation, which is the primary driver of air movement in solar chimneys. The highest recorded air velocity was 1.8 m/s for February at 1:00 pm. As mentioned previously, the air velocity was measured at the inlet, middle, and chimney outlet. Figure 5 shows that the air velocity at the chimney inlet is higher than the air velocity in the middle and the chimney outlet because of the effect of friction and the decrease in air temperature while passing through the chimney. This behavior is consistent with the published literature [20].
5.2. Temperature of the solar cells
The high temperature of the solar cells causes a decrease in their efficiency, and therefore one of the most important goals of the current article is to cool the solar cells and take advantage of the excess heat to generate electricity by the technology of the solar chimney. Six solar panels were used and distributed symmetrically. 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. Figure (6) shows the change of temperature for the three solar cells for the three months (December, January, and February). It is noted that the temperature of the solar panels increases to reach the highest temperature at 1 pm for the three panels and other months and then decreases. The increase and decrease in the cell temperature are related to the increase in solar radiation values during the first half of the day and its decrease in the second half of the day [21]. It also turns out that the central solar cell was at a higher temperature than other panels, and the reason is that its presence in the middle of the model reduces the impact of the external wind on the solar panels, which contributed to reducing the temperature of the solar
panels installed in the ends (left and right solar cells). It is also noted 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 temperature of February at the study site [22].

Figure 6. PV temperature for different months.

5.3. Kinetic Power
The kinetic power of the system was calculated using Equation (8). Figure (7) shows the variation of the kinetic power. It is noticed that the kinetic power rates increased in February due to the increase in solar radiation [23], and the highest kinetic energy of 35 W was recorded at 1 pm in February. Also, it is noticed that the increase of solar radiation led to an increase in the kinetic power during the day.
5.4. Electric Power and Thermal power

The solar cells are connected in series, and the total electrical power produced is calculated using Equation (9). Figure (8) shows the change in the electric power produced during the day for various months. It appears clearly that the rates of electrical power were at their highest levels in January due to the decrease in 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 energy produced [24].

![Figure 7. Variation of the kinetic power.](image1)

![Figure 8. Variation of the electric power during the day for different months.](image2)

The results also showed that increasing the values of solar radiation leads to an increase in the amount of thermal power in the system, which is calculated using Equation (2) and these results are shown in Figure (9), and 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 pm. Simultaneously, the lowest value for thermal efficiency during the day was in December, which is identical to the results published in [25].
Figure 9. Variation of the heat power during the day in different months.

5.5. Efficiency of the system

The electrical efficiency of photovoltaic systems is the most crucial factor in determining the suitability of these systems for different uses. The electrical efficiency of the PV/solar chimney is calculated using Equation (6). Figure (10) shows the change of the hourly electrical efficiency during the day. It is noted that the shape of the change in electrical efficiency is concave up. In all the considered months, high-efficiency values are observed in the early morning hours due to the low temperature of the solar cells. The highest recorded electrical efficiency value was 17.8% in December. This behavior is normal and has been observed in previous research that deals with the study of PV/T solar systems, such as in [26]. Figure (11) shows the change of the 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 in December, which is identical to the results published in [27].

Figure 10. The change of the hourly electrical efficiency during the day.
Figure 11. The change of the hourly thermal efficiency during the day.

6. Conclusions and recommendations

From the results obtained, the following observations were concluded:

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

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

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

4- In all the considered months, high-efficiency values are observed in the early morning hours due to the low temperature of the solar cells.

5- The highest recorded electrical efficiency value was 17.8% in December.

7. References

[1] O K Ahmed 2018 A Numerical and Experimental Investigation for a Triangular Storage Collector (Sol Energy) vol 171 pp 884–892

[2] H Nasraoui, Z Driss, A Ayedi and H Kchaou 2019 Numerical and Experimental Study of the Aerothermal Characteristics in Solar Chimney Power Plant with Hyperbolic Chimney Shape (Arab J Sci Eng) vol 44 no 9 pp 7491–7504

[3] C B Maia, F V M Silva, V L C Oliveira and L L Kazmerski 2019 An Overview of the use of Solar Chimneys for Desalination (Sol Energy) vol 183 no 3 pp 3–8

[4] Zou Z, Gong H, Wang J and Xie S 2017 Numerical Investigation of Solar Enhanced Passive Air Cooling System for Concentration Photovoltaic Module Heat Dissipation (J. Clean. Energy Technol) vol 5 no 3 pp 3–8

[5] A B Kasaeian, S Molana, K Rahmani and D Wen 2017 A Review on Solar Chimney Systems (Renew Sustain Energy Rev) vol 67 pp 954–987

[6] O K Ahmed, A S Hussein, R W Daoud and Z H Ali 2020 A New Method to Improve the Performance of Solar Chimneys (in AIP Conference Proceedings) vol 2213

[7] D Eryener, J Hollick and H Kuscu 2017 Thermal Performance of a Transpired Solar Collector Updraft Tower (Energy Convers Manag) vol 142 pp 286–295
[8] D Eryener and H Kuscu 2018 Hybrid Transpired Solar Collector Updraft Tower (Sol Energy) vol 159 pp 561–571
[9] N Fadaei, A Kasaeian, A Akbarzadeh and S H Hashemabadi 2018 Experimental Investigation of Solar Chimney with Phase Change Material (PCM) (Renew Energy) vol 123 pp 26–35
[10] L Boutina, A Khelifa, K Touafek, M Lebbi and M T Baissi 2018 Improvement of PVT Air-Cooling by the Integration of a Chimney Tower (CT/PVT) (Appl Therm Eng) vol 129 pp 1181–1188
[11] H H Al-Kayiem and O C Aja 2016 Historic And Recent Progress In Solar Chimney Power Plant Enhancing Technologies (Renew Sustain Energy Rev) vol 58 pp 1269–1292
[12] X Zhou, J Yang, J Wang and B Xiao 2009 Novel Concept For Producing Energy Integrating A Solar Collector With A Man Made Mountain Hollow (Energy Convers Manag) vol 50 no 3 pp 847–854
[13] O K Ahmed and Z A Mohammed 2017 Influence of Porous Media on the Performance of Hybrid PV/Thermal Collector (Renew Energy) vol 112 pp 378–387
[14] K S Ong and C C Chow 2003 Performance of a Solar Chimney (Sol Energy) vol 74 pp 1–17
[15] A Koonsrisuk and T Chitsomboon 2013 Mathematical Modeling of Solar Chimney Power Plants (Energy) vol 51 pp 314–322
[16] X Zhou, J Yang, B Xiao and G Hou 2007 Simulation of a Pilot Solar Chimney Thermal Power Generating Equipment (Renew Energy) vol 32 no 10 pp 1637–1644
[17] O K Ahmed, K I Hamada and A M Salih 2019 Enhancement of the Performance of Photovoltaic / Trombe Wall System using the Porous Medium: Experimental and Theoretical Study (Energy) vol 171 pp 14–26
[18] R S Figliola and D E Beasley 1996 Theory and Design for Mechanical Measurements (Meas Sci Technol) vol 7 no 7
[19] M A Al-Dabbas 2011 A Performance Analysis of Solar Chimney Thermal Power Systems (Therm Sci) vol 15 no 3 pp 619–642
[20] M O Hamdan 2011 Analysis of A Solar Chimney Power Plant in the Arabian Gulf Region (Renew Energy) vol 36 no 10 pp 2593–2598
[21] O K Ahmed, K I Hamada and A M Salih 2019 Performance Analysis of PV/Trombe with Water and Air Heating System: an Experimental and Theoretical Study (Energy Sources, Part A Recover Util Environ Eff) vol 86 pp 716–722
[22] O K Ahmed and Z A Mohammed 2017 Dust effect on the Performance of the Hybrid PV/Thermal Collector (Therm Sci Eng Prog)
[23] S Kiwan, M Al-Nimr and I Salim 2020 A Hybrid Solar Chimney/Photovoltaic Thermal System for Direct Electric Power Production and Water Distillation (Sustain Energy Technol Assessments) vol 38 p 100680
[24] N Gupta, A Tiwari and G N Tiwari 2017 A Thermal Model of Hybrid Cooling Systems for Building Integrated Semitransparent Photovoltaic Thermal System (Sol Energy) vol 153 pp 486–498
[25] K A Omer and A M Zala 2018 Experimental Investigation Of PV/Thermal Collector With Theoretical Analysis (Renew Energy Focus) vol 27 pp 67–77
[26] D Chemisana, J I Rosell, A Riverola and C Lammataou 2016 Experimental Performance of a Fresnel-Transmission PVT Concentrator for Building-Façade Integration (Renew Energy) vol 85 pp 564–572
[27] P Guo, Y Wang, Q Meng and J Li 2016 Experimental Study on an Indoor Scale Solar Chimney Setup in an Artificial Environment Simulation Laboratory (Appl Therm Eng) vol 107 pp 818–826