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Building and Experimenting Solar Chimney Power Plant

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Abstract

Recently several resources of sustainable and clean energy have been developed, such as solar panels, wind turbines, and others. The Solar Chimney Power Plant (SCPP), which is among those harnessing solar power where a stream of air is induced by adding heat through solar irradiation using the greenhouse effect, is rarely utilized for generating power. The hot air flows through the chimney under the effect of buoyancy force which in turn drives a vertical axis wind turbine. Although this technique is investigated by many reports, unfortunately, it is still in the laboratory phase. However, it might be an optimal solution for zones where operating other techniques is not efficient for various reasons. In this project, an SCPP prototype was built and tested in Anbar, a central province in Iraq. The impact of various design parameters on power generation was assessed. The experimental results prove the feasibility of SCPPs for generating electricity at low costs and the suitability of building SCPPs in countries technologically less developed with specific weather conditions and scarcity in water resources that are normally needed for cleaning solar panels, for example.

Keywords: Clean Energy, Renewable, Solar Chimney, Sustainability, Solar Collector.

1. Introduction

The working principle of Solar Chimney (SC) relies on heating up the air inside a vertical tower, due to the rising temperature, the air becomes lighter generating a buoyancy force which, in turn, induces airflow through the tower and fresh air is drawn from a room causing passive ventilation [1–4]. The history of SC for natural ventilation dates back to several centuries ago [5].

Researchers found an additional application for this machine which is producing electricity by installing a turbine at the base of the chimney. This application was exploited when the Germany Ministry of Research and Technology built the first prototype of a Solar Chimney Power Plant (SCPP) in Spain in 1982 [6]. Since then, the SCPP has not been commercialized and is still at the investigation stage. Even in diverse regions, the acceptance and transition to solar energy practices reveal socio-spatial inequalities, as observed in the Hague, The Netherlands [7]. Similarly, studies have highlighted the key role of developers in advancing solar energy acceptance in areas like the Golestan province in Iran [8]. The heat in SCPPs is added to the system through a collector which has a conical shape and is made of a transparent material allowing the solar irradiation to heat up the air using the greenhouse effect. The top of the collector is connected to a tower where the hot air flows under the effect of buoyancy force due to the fact that hot air has lower density compared to the ambient density.

At the base of the tower, a vertical axis turbine is installed which is driven by the airflow, which in turn drives an electrical power generator [1,9–11].

A great deal of research has focused on SCs for natural ventilation such as [12–15] while other reports were focused on it being a subsystem of SCPPs such as [9–11,16–21].

Other studies investigated the dual purposes of the SC such as generating power and ventilating at the same time such as [22], generating power in addition to cooling solar panels [3], power generation and water desalination [23], or a solar updraft tower combined with solar panels [24]. Most researchers relied on a numerical simulation to analyse the flow inside the chimney using sophisticated finite element packages such as [3,9-13,22,23,25].

Furthermore, novel techniques have been introduced to improve the efficiency of solar energy systems. For instance, a three-dimensional model was developed to study solar energy reflection from mirrors in circular orbits, presenting a unique perspective on optimizing solar energy capture [26]. Another significant stride is the utilization of machine learning algorithms to forecast solar energy production, emphasizing the intersection of technology and renewable energy [27].

A smaller number of studies relied on analytical modelling in order to analyse the performance of the SC and seek major designing parameters such as [18–20,28]. Other research adopted mixed-approach, for example, a numerical and analytical method was used in [16], and [11], while analytical results were compared with experimental ones in [29]. The analytical iterative procedure with field measurements was found in [17]. While others relied only on an experimental analysis such as [14,15,24]. In spite of the large number of experimental evaluations of SCPP, the investigations were not enough to convince firms or institutions to invest in the commercialization of this machine.

However, in those studies, the investigations were focused partially on the effect of some parameters on the overall performance. For example, static pressure, driving force, power output, efficiency, airflow velocity, height, chimney radius, and the ratio of collector radius to gap height, were among those parameters studied separately using analytical and/or numerical approaches, with very few using experimental measurements.

For example, geometric parameters and ambient conditions on the performance were studied by [28], while geometrical parameters and thermal boundary condition using 3D CFD simulation were conducted by [9].

While, solar radiation and ambient temperature on pressure drop were investigated by [11]. Some studies focused on evaluating the performance of the SC in certain countries, such as in Algeria [19,30], Nigeria [2], and Spain [31]. Nevertheless, this literature review reveals that experimental investigations on the effect of major parameters such as structural dimension, solar irradiation, and atmospheric conditions on the performance of an SCPP at the middle of Anbar, Iraq, have not been conducted yet. This zone of the world was selected due to the lack of electricity in spite of abundant sunlight and meeting many other conditions outlined by [6]. This choice of using SCPP in Iraq, and in particular in Al-Anbar, is highly recommended since Iraq suffers from water scarcity and, unlike other mechanisms, water is not necessary for SCPP. Additionally, this selection is beneficial due to the availability of cheap building material for the chimneys [6].

To assess the performance of SCPPs in this region and the effect of major parameters on the overall performance, a small-scale SCPP prototype was built using locally available materials and devices, and then measured using a customized configuration of an Arduino circuit. Additionally, the effect of using a thermal isolator at the bottom of the collector was evaluated. The results of the investigation, as shown later in this report, demonstrate SCPPs can contribute to solving the present power problem in Iraq by relying on this sustainable, clean, and economical source of energy.

2. Theoretical Background

The power generated through a turbine is proportional to the pressure drop of the flow stream. The experiment and the analytical analysis shows that the value of the pressure drop functions to the densities difference, which can be approximated by the following integration [16]:

$$\Delta P = g \int_0^H \left(\rho_{o,z} - \rho_{i,z}\right) dz \,, \qquad \textbf{(1)}$$

where, $\rho_{o,z}$ and $\rho_{i,z}$ are the ambient and internal air density, respectively, H, is the chimney height, g is the acceleration of gravity.

Assuming constant density for small chimney, the integration can be approximated as follows:

$$\Delta P = g(\rho_o - \rho_i).H \qquad \textbf{(2)}$$

The density difference is created by the effect of heat difference, therefore, it can be approximated [16] as

$$(\rho_o - \rho_i) = \beta.\rho \ \Delta T, \qquad \textbf{(3)}$$

where, ΔT is the air temperature difference due to the added heat can be approximated by heat balance equation:

$$\Delta T = \pi.\frac{q}{C_p.\dot{m}}(R_{coll}^2 - r^2), \qquad \textbf{(4)}$$

where, q is the added heat to the air flow, C_p Specific Heat for air as an ideal gas at constant pressure, and $\dot{m}$ is mass flow rate of air. The added heat is proportional to the solar irradiation.

Part of the total pressure drop is subject to pressure loss due to friction inside the chimney which can be evaluated as [16]

$$\delta P_{loss} = f\frac{H}{D}g.\frac{\rho_i}{2}v^2 \ , \qquad \textbf{(5)}$$

where, D is the chimney radius, v is flow velocity, f is friction factor which depends on the Reynold's number of the flow and the material nature internal surface of the chimney.

The amount of absorbed power by turbine can be evaluated using

$$Power = \delta P_{turbine} . Q \,, \qquad \textbf{(6)}$$

where, $\delta P_{turbine}$ is pressure drop over the turbine [N/m^2], and Q is the flow rate in [*kg/s]*.

Clearly, the equations show that the power increases as the cross-section, and the driving pressure drop increase. Equation [2] shows that the driving force increases as the density difference increases. The density difference increases as the radius of the collector, the heat flux, and the temperature difference increase. Thus, increasing the power output of SCPP requires bigger volume of chimney and larger area of collector and higher intensity of solar irradiation.

3. Methodology

To evaluate the performance of the SCPP, several prototypes with different sizes and configurations were designed, fabricated, and experimented at the same ambient conditions in Anbar, the largest province in Iraq, which is located in western Iraq, with longitude 44,39 E and latitude 35,36N, during the month of May 2020. This zone was selected because it suffers from a lack of electricity in spite of the abundance of solar irradiance. The SCPP was built using affordable locally available materials. The machine was built for investigation purposes only, and was pictured as shown in Figure 1.

Figure 1. In-house- built a prototype of a SCPP.

The bottom part was made of a transparent film from Nylon of 1mm thick with an open periphery. The height of the inlet was 30 [cm] above the ground. The chimney part was made from a Polyvinyl Chloride (PVC) tube of 4-inch diameter and a wall thickness of 1.5 mm. in order to study the effect of structural geometry, the height of the chimney, and the diameter of the collector were changed several times as it will be detailed in the experiment section. A simple turbine was installed inside the tower at the base section, the turbine was also connected to DC-generator. The load was a simple Ohm's resistance allowing to measure the applied voltage and the consumed ampere.

The used instruments and rigs:

The following devices and tools were used to perform various measurements

1- To measure the intensity of solar irradiation at the location of experiments, Lutron SPM-1116SD Solar Energy Meter with data logger capabilities had been used. The recorded data could be logged to a SD-cart or to a pc through RS232 or USB PC computer interface; the measurement resolution of the meter was 0.1 mW/m^2 for intensities less than 1000 W/m^2 and 1 mW/m^2 for intensities bigger than or equal to 1000 W/m^2 [32].

2- To log the temperature at various locations, a dedicated Arduino circuit was configured and connected to five thermal sensors. All thermal sensors were LM35 which has an accuracy of 0.5°C and suitable for remote application and has a linearity of +10.0 mV/°C scale factor [33]. The Arduino circuit was connected to a PC through a USB cable which was sending the readings of temperatures in real-time.

3- The speed of the air flow through the tower was measured using an anemometer device, the handheld anemometer was HP-817A Digital Anemometer 30m/s LCD from HoldPeak; wind speed ranges from 0.3 to 30m/s with an accuracy of ±5% and Resolution of 0.1m/s.

4- In order to measure the output electrical power, a simple device capable of measuring the voltage and ampere simultaneously was used. The volts and amperes were recorded manually.

Four different experiments were conducted as follows.

4. The Experimetnal Results

4.1. The First Experiment

This experiment investigated the effect of ambient temperature and the intensity of solar irradiation on the amount of electricity produced. The collector diameter was 2m, while the tower height was 3m.

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The measured parameters were solar irradiation, ambient temperature, and the produced electricity. Figure 3 shows the power in milliwatt plotted against the ambient temperature in Celsius for three different cases of solar irradiance (800, 100, and 1200 W/m^2). The chart shows that the amount of produced electricity depends on two factors; solar irradiation and ambient temperature.

At a solar irradiance of 1200 w/m^2, the generated power is at its highest, and it increases as the temperature increases and reaches the highest value of 142 mw at a temperature of 32^{o}C.

Conversely, the generated power at solar irradiance of 800 and 1000 w/m^2 reduces as the temperature increases. Furthermore, regardless of the ambient temperature, the amount of produced electricity increases as the solar irradiance increases.

4.2. The Second Experiments

This experiment aimed to investigate the effect of adding thermal insulation to the collector of the SCPP on the productivity of the machine. Therefore, two experiments were carried out.

In the first experiment, the measurements were made without installing any insulator, while in the second experiment, a layer of thermal insulation of polystyrene of the thickness of 15mm and heat load coefficient of 0.03 W/(m.K) was installed on the ground beneath the collector in order to prevent any heat loss through the ground.

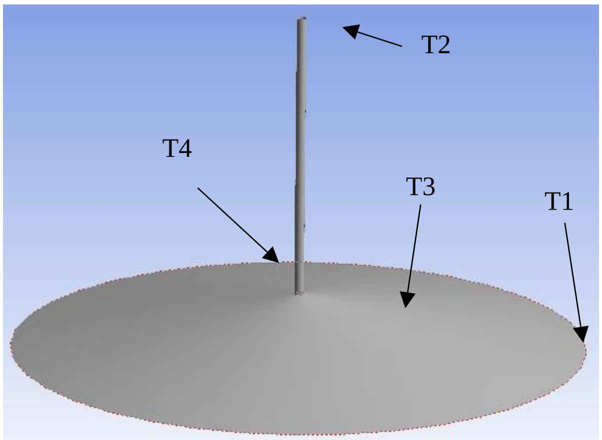

Figure 2. Schematic diagram of the machine and thermal sensors distribution.

In both experiments, the collector diameter was 2m. the tower height was 3m**.** the temperatures were measured at four different locations on the SCPP as shown in Figure 2. The first location, T1, was at the inlet of the collector while the second location, T3, was at the central point of the collector. The last two locations, T4 and T2 were at the bottom and the top ends of the tower, respectively.

The temperature was measured every hour by the Arduino circuit using the thermal sensors LM35, over 24 hours for several days.

The average values of the temperatures over seven days were calculated. The results of the first case, non-isolated, were plotted as shown in Figure 4; while the results for the insulated case were plotted as shown in Figure 5.

In the both cases, the trendline of the temperature is changing according to the time period of the day. In the period from 05:00 to 10:00 O'clock, there was a sharp increase in temperature at the four locations. Almost all locations reached maximum values in the period from 10:00 to 15:00 O'clock. The highest value was recorded at the centre of the chimney as high as 44 C^o at 13:00 O'clock for the non-isolated case while it recorded 67 C^o at the same period of time. Noticeably, all-temperature degrees of the isolated case are higher than those for the non-isolated case indicating the feasibility of using the thermal insulator. Furthermore, to quantify the impact of using a thermal isolator on power productivity one more experiment was conducted by measuring the resulting power for the isolated and non-isolated cases.

4.3. The Third Experiments

This experiment investigated the effect of thermal insulation on electricity production by comparing the produced power for two cases, in the first case, the isolator was not installed while in the second case the insulator was installed. The experiment conditions were the same, the solar irradiation was 1200 w/m². The used insulator was made from polystyrene with a heat load of 0.03W/(m.K). In this experiment the measured produced power, and ambient temperatures were recorded. The results were plotted as shown in
Figure **6**.

The chart in Figure **6** shows that the produced power decreases as the ambient temperature increases this is due to the fact that the SCPP relies on temperature differences between inner and ambient air. Furthermore, it shows that the thermal insulation increases the produced electricity. The highest power's increment was reached to 3.5% when the ambient temperature was 7^{O}C. All in all, clearly the insulation improves the power productivity and increases the temperature differences between inside and outside of the chimney.

4.4. The Fourth Experiment

This experiment investigates the effect of the dimension of the SCPP on power production. Therefore, the tower's height was altered regularly six times from 0.5 m to 3.0 m by a step of 0.5m; the diameter of the collector was also changed three times 0.5, 1.0, and 2.0 m allowing to test 18 different cases. Under the same ambient conditions and the same solar irradiation of 1200 w/m2, all measurements were recorded and plotted as shown in Figure 7.

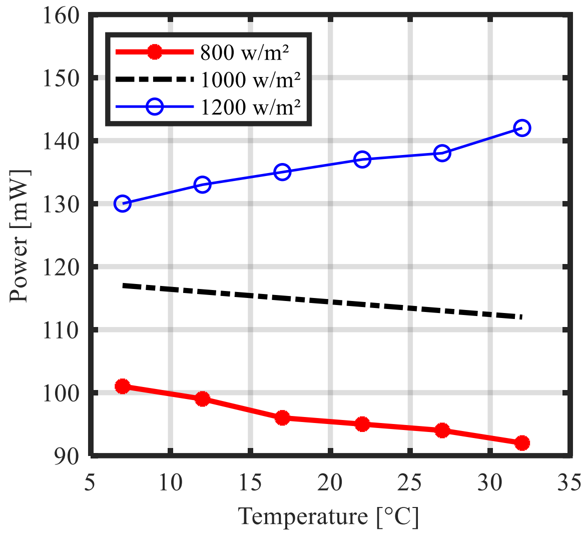

Figure 3. Power production versus ambient conditions.

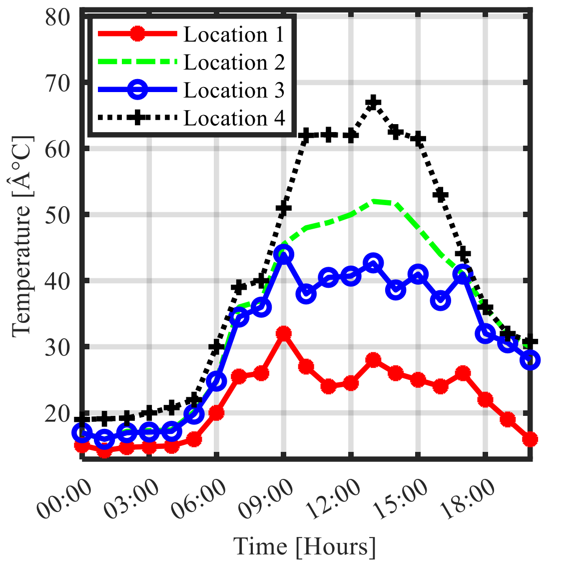

Figure 5. The variation of average temperature over 24 hours.

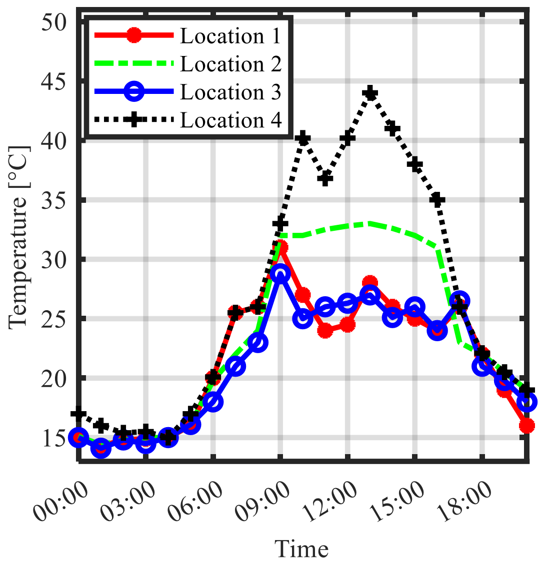

Figure 4. The variation of average temperature over 24 hours.

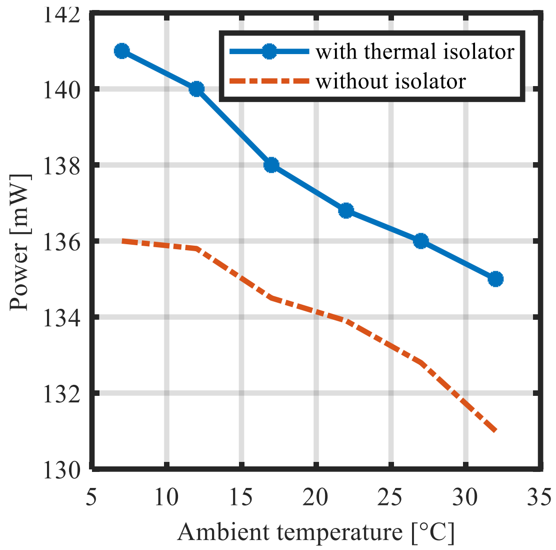

Figure 6. The effect of the thermal insulator on electricity production.

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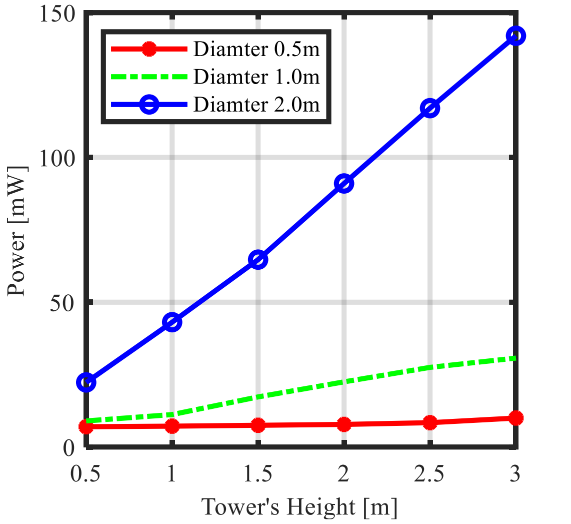

Figure 7. The effect of chimney's size on the generated power

The chart in Figure 7 shows that the power productivity increases as the tower's height and the collector diameter increase. This is in agreement with the analytical equation in the theoretical background section and the results of many researchers [2,6,34,35]. At a very small collector, the produced power is almost zero and the height of the tower has no impact. The impact of the height becomes more significant as the collector diameter increases. These results agree with the fact that the received energy is proportional to the area of the collector, and the pressure difference between the internal and the external of the tower is directly proportional to the elevation according to the hydrostatic pressure principle.

5. Conclusion

This project aimed to investigate the feasibility of SCPPs in producing electricity power in Al-Anbar, Iraq. For this purpose, an SCPP was built from locally available materials, the tower was made of a PVC tube of 4inch diameter and multiple heights from 0.5 to 3.0 meters. The base is connected to the collector which is made from transparent Nylon film, which is responsible for collecting the solar irradiation using the greenhouse effect, which was formed conically at multiple diameters 1.0, 1.5, and 2.0 meters. In some experiments, a thermal insulator of polystyrene was also installed at the bottom of the collector. In order to measure the generated power, a small system of a turbine-DC-generator, which was connected to an Ohm's resistance, was installed inside the tower allowing to measure the output power. By inspecting the experimental results, the following conclusion can be drawn:

The investigated zone of Iraq shows high intensity of solar irradiance ensuring that renewable solar energy is an appropriate choice, and harnessing solar irradiance by SCPPs is a feasible project and due to other factors, it is also low costs and low complexity.

The amount of produced electricity is directly proportional to the size of the SCPP, the chimney height, chimney and collector radius, the intensity of solar irradiance. The larger size the higher amount of produced electricity agrees others researches.

Producing energy using SCPP allows avoiding the drawback of other technologies. Specifically, it requires no water for cleaning, unlike the solar panel technology; besides, it does not affect the perspective and does not kill flying birds as the wind turbine does. In the SCPP technique, the power is collected at a low cost for a long period of the day even at night in addition to its relatively long lifespan.

Author's Contributions

Sohayb Abdulkerim:
Led the study's conceptualization, design, and data analysis, drafted the manuscript, and managed the literature review, playing a pivotal role in theoretical framework development.
Mohammed Qaddoori Hammoodi:
Responsible for manufacturing the testing machine, conducting the primary experiments, and contributing to data interpretation and experimental process refinement.
Mussaab Alshbib:
Focused on report preparation and revisions, ensuring clarity and coherence in documentation, and provided essential administrative support for the project.

Ethics

The research conducted in this study adhered to ethical guidelines and principles. All experiments and data collection were conducted in accordance with relevant laws, regulations, and institutional guidelines. Any potential ethical concerns related to human or animal subjects, data privacy, or other ethical considerations were carefully addressed and mitigated during the course of the research.

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