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Experimental Study of Solar Chimney Power Plant

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ABSTRACT

Solar chimney power plants are passive thermal systems that use the greenhouse effect to produce electricity from solar radiation (SR). The performance of these devices varies from one climate to another. Indeed, the building site of the SCPP is a particular parameter for its total effectiveness. The aim of this work was to present an experimental investigation of a solar chimney prototype under the climatic conditions of Sfax, Tunisia. In fact, Sfax is characterized by its arid and sunny climate. The impact of the climatic conditions of Sfax city on the aero-thermal characteristics of the considered prototype is carried out. Particularly, the variations of the fluid temperature and velocity are carried out under different times. The present outcomes show that the solar chimney power plant is an applicable device in the Tunisian region of Sfax.

1. Introduction

The limitation of the quantity of these reserves, the successive oil crisis in 1973 and the increase in the demand for energy in all countries of the world have led industrialized countries to seek and develop new sources of supply. The nuclear industry was already launched, but its choice on a large scale can lead to serious consequences, especially for the environment, due to pollution and also nuclear accidents [1].

The researchers have developed another form of energy known as "renewable energy" [2-7]. These renewable energies all have the immense advantage of being of natural origin, inexhaustible and non-polluting since they do not emit greenhouse gases, CO_2. The use of these non-renewable energies has had harmful consequences on the climate, the environment and continues to do so. Greenhouse gas emissions, the main causes of global warming, increased by 0.5% in 2019 compared to an average of 1.1% per year over the last decade, resulting in particular in the imbalance of ecosystems and the destruction of land quality.

Today, more than 85% of the energy used in the world comes from fossil fuel deposits (coal, oil, gas) or uranium, formed over time and geological evolution [8].

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Renewable energy is a source of energy that renews itself rapidly enough to be considered inexhaustible on a human time scale. Renewable energies are the result of regular or constant natural phenomena caused by the stars, mainly the Sun but also the Moon [9].

Among these renewable energies, we can mention the production of electricity of solar origin by the photovoltaic effect (solar cells or photovoltaic cells). The conversion of light into electricity (photovoltaic conversion) occurs in semiconductor materials. Photovoltaic can play an important role in the transition towards a sustainable energy supply system for the XXI century and is likely to cover a significant part of the electricity needs of several countries [10].

Tunisia is a Mediterranean arid region located in the north of Africa. It is characterized by a high level of average solar radiation (SR). The solar energy technologies are suitable to be applied in Tunisia especially in the south desert [11]. The Solar Chimney Power Plant (SCPP) is an attractive solar energy setup, which provides the environmental conditions of the surrounding air to produce electricity. Its simple principle is based on both the natural convection and the buoyancy of the air. Several researchers had interested in optimizing SCPP in order to reduce overall investment. The first prototype of the SCPP, built-in Manzanraes Spain, is conducted by Schlaich [12] to reveal the application of agricultural greenhouses in electricity production. This prototype was operated for eight years with overall electrical power of about 50 kilowatts [13]. Since the successful technology of the Manzanraes prototype, many small prototypes of the solar chimney systems have been installed in different regions around the world; in China, Brazil, Turkey, India, Northern Mongolia, Syria, Egypt, Jordan, USA and Algeria [16-29]. Al-Kayiem *et al.,* [30], presented a novel solar chimney layout, which is installed over the roof of a small room. Sangi [31] evaluated the impact of different environmental conditions and structural dimensions on the performance of the SCPP in Iran. Abdelmohimen and Algarni [32] performed a numerical study of the SCPP overall the year for the metrological data of six regions of Saudi Arabia. They incorporated the Manzanares prototype as a case study to validate their numerical models. They reported that the south of the kingdom presents a benefit region to install the SCPP. However, their study did not present a real experiment on the system. Wei and Wu [33] A new mixed solar generating station has been built in the Wuhai Desert in Inner Mongolia, China, which receives solar and wind energy. This technology uses solar and wind power to generate electricity. The designers used multiple north-facing air intakes for naturally absorbing wind. The solar system is characterized by an area of collection of 5300 square meters, a chimney height of 53 meters, a chimney diameter of 10 meters, and an output power of 200 kilowatts. Najmi *et al.,* [34] conducted a feasibility study on a small solar chimney built in Kerman, Iran. They checked at the effect of certain metrics on SCPP performance. As a result, they found that double glazing on the collector roof and the installation of cones at the entrance to the chimney could increase power generation. However, limited works involving Tunisia regions affect the feasibility of the SCPP technology. Jemli *et al.,* [35] conducted an experimental study of an SCPP prototype at the Research and Technology Centre of Energy, Borj Cedria, northern Tunisia. They analyzed the impact of the ambient temperature and the solar radiation intensity on the SCPP efficiency while they changed the chimney height and the collector diameter. Other works have been reported by the numerical and the preliminary study of the SCPP for Tunisia weather.

According to these anterior published works, we could conclude that there are many solar chimney configuration sizes. This could be interpreted by the variation of meteorological and geographic conditions. The main objective of this work is the revealing the effectiveness of the SCPP in Sfax, Tunisia.

Indeed the thermal characteristics and the generated electric power were hourly investigated during the month of May 2016. This Work is identified as important to experimentally comprehend the behavior of an existing solar chimney power plant.

2. Method

The commercial city of Sfax is cited in the South East of Tunisia. The geographic data of Sfax are 34.72 of latitude and 10.72 of longitude. The prototype is exactly built at ENIS. Figure 1 shows a photographic photo of the experimental solar chimney for power generation. The schematic view and the dimensions of the different compounds of the prototype are represented in Figure 2. The experimental prototype consists of a plastic transparent collector that is constructed from a polyethylene film and a chimney pipe of inelastic PVC. The collector has a radius of R=1375mm and a height of h=50mm. Furthermore, the height of the chimney equal to H=3 m and the chimney has a diameter equal to 160 mm. Polyethylene is characterized by its high transmission of the visible and ultraviolet waves of solar radiation. The transitivity factor of the collector roof is equal to 0.88. The pipe is fixed on the wooden platform by steel support.

Fig. 1. Prototype

The turbine generator is installed at the chimney entrance. It presents a six-blade turbine coupled with an electric generator. The generator is asynchrony machinery with efficiency equal to 0.9.

The absorber is a combination of a wooden platform with 8 mm thickness with a black layer of paint. The wooden platform is painted black to promote a good absorption of sunlight. In this study, it can be assumed that the absorptivity of the black wood is equal to 0.8.

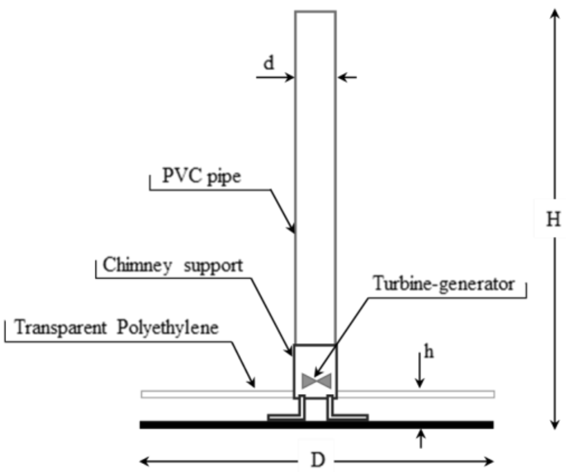

Fig. 2. SCPP schematic

To study the thermo-aerodynamic characteristics of the airflow within the proposed solar chimney prototype, four main parameters were tested such as solar radiation, temperature, velocity, and the electric power of the turbine-generator. The experimental data directly depend on the measuring instrument's accuracy. Therefore, the choice of different devices is required. The adequate device is generally the Hot-wires Anemometer to control the air velocity. It is a simple sensor that required a high resolution for low air speed applications. An anemometer is an instrument for measuring air velocity either in a contained stream, such as airflow in a duct, or in unconfined streams. To determine the speed, an anemometer detects the change in certain physical properties of the fluid or the effect of the fluid on a mechanical device inserted in the flow.

The available instruments used during the experimental tests were shown in Figure 3. This figure shows the different devices used for testing the ambient characteristics of the prototype zone and the local experimental results. A digital thermometer (Figure 3(a)), the Uni-Trend Model UT325 Digital Thermometer Temperature Meter Tester USB Interface T1-T2 Dual Input with High/Lower Alarm & Auto Calibration is used. An anemometer is a thermal transducer which has been widely used to measure instantaneous flow velocity in several times (Figure 3(b)) with a precision of ±0.01 $m.s^{-1}$ is used. A pyranometer generally is a type of actinometer used for measuring solar irradiance on a planar surface and it is designed to measure the solar radiation flux density (W/m^2) (Figure 3(c)). In our work was used to measure the solar radiation at any test time. The local temperature and velocity are measured along the collector centerline in seven points.

A digital multimeter (Figure 3(d)) is a test tool used to measure two or more electrical values. However, the air temperature was simultaneously measured in many spots under the solar collector. Using a plot temperature change over time. This device is based on a microprocessor and is designed to use external J, K, T, E, R, S, and N type thermocouples as temperature sensors. It has a Software and USB data cable, which allow the data transfer by the connection of the different sensors with a computer.

From the literature, it is known that the solar collector is the responsible compound for the air heating by the greenhouse effect. In this study, many sensors are fixed along the collector centreline in order to control the air temperature. The air temperature was measured by J type thermocouples. Six standard points from (L1 to L6) in the collector have been verified. The distance from one point to another is 0.3 m in the east section through the middle axis. With this prototype, the researcher can freely adjust the sensor heights. The position L5 is installed to measure the maximum velocity which is located at the chimney inlet.

(a) (b) (c) (d)

Fig. 3. Experimental devices; (a) Digital thermometer, (b) Anemometer, (c) Pyranometer and (d) Digital multimeter

3. Results
3.1 Solar Radiation

One of the advantages of the SCPP is its operation mode. In fact, this type of thermal system is able to capture both direct and diffuse solar radiations. Therefore, solar radiation is an important parameter in our experimental study and it is essential to calculate the power output. To measure the solar radiation values and to record these values, the metrological data of Sfax is taken into account. Figure 4 shows the hourly variation of the average solar radiation during the experimental test times. The global radiation for different days of May and June is shown in Figure 4(a). According to these results, it is clear that solar radiation presents the same evolution during the day for the different cases. The maximum radiation value appears at 12:00 h for all days. However, the weakest values are shown at the beginning and the end of the day. Besides, the global radiation values on May 1, and May 23 and is slightly superior to the values on June 02. For this reason, May 23 is chosen as a typical day for further studies.

Environmental parameters such as global, diffuse, direct solar radiation and ambient air temperature are given for a typical day on May 23, 2016. Figure 4(b) shows the relationship between global, diffuse, and direct solar irradiance and ambient air temperature for a typical day of May 23, 2016. From these results, it can be concluded that the global irradiance at 12:00h is equal to G=991 $W.m^{-2}$ and the maximum diffuse SR is equal to G=146 $W.m^{-2}$.

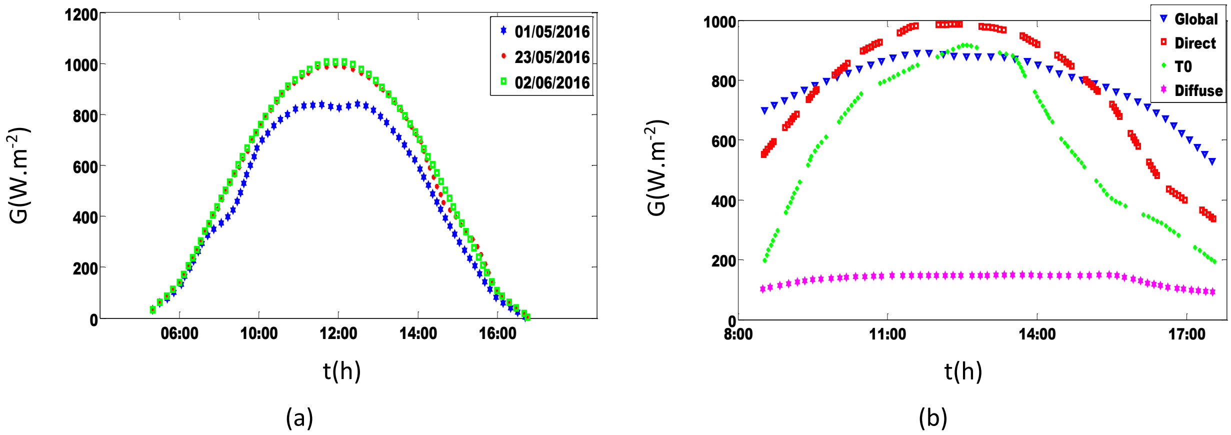

Fig. 4. Hourly solar radiation; (a) Solar radiation during the experimental test times, and (b) Relationship between global, diffuse, and direct solar irradiance

3.2 Temperature

The temperature rise in the collector is the first parameter responsible for the creation of the airflow in the system due to the greenhouse phenomenon. For the first time, the daily temperature values in different locations along the collector centerline are controlled on the same days of May and June 2016. A second time, the temperature is measured at the collector outlet position on the considered typical day. The experimental data of the air temperature under the solar collector is recorded on May 01, May 05, May 11, May 17, May 23, May 28, June 02, and June 05. Figure 5 shows the daily evolution of the air temperature within the collector. Figure 5(a) depicted the daily variation of the temperature for different positions in the collector that was carried out at 12:00 h. Figure 5(b) shows the temperature variation in the location L5 consisting of the collector outlet for the considered days from 08:00 h to 16:00 h. Based on these results, it was noticed that the air temperature at L5 peaked on May 23 during the day. In addition, the maximum value appears at 12:00 h, due to the increase of solar radiation at this time. The air temperature presents the same profiles for all positions. In fact, these values are maximum on May 23. Indeed, the air temperature increases in the direction of flow to reach its maximum at the chimney inlet.

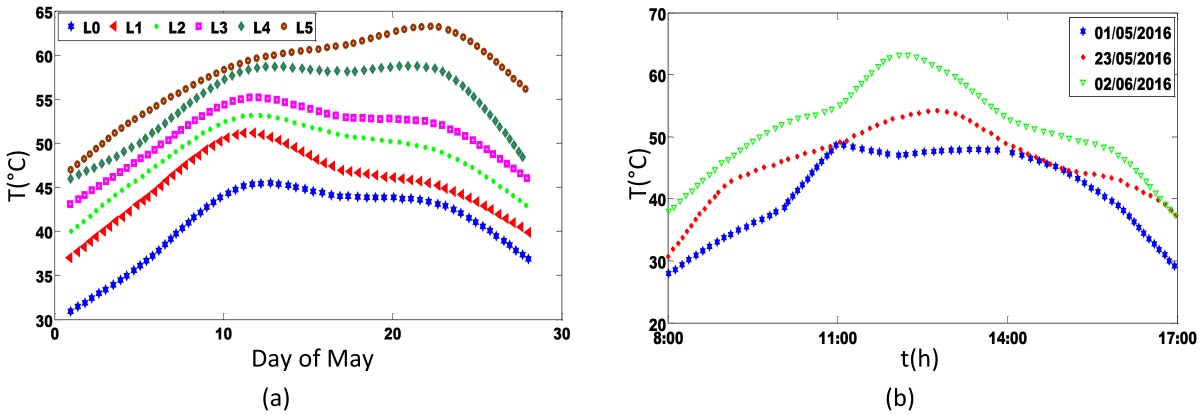

Fig. 5. Hourly temperature; (a) Depicted the daily variation of the temperature for different positions in the collector and (b) Temperature variation in the location L5

3.3 Air Velocity

Air velocity measurements are required to show the airflow kinetic energy of the entire solar chimney system. Figure 6 shows the daily course of air velocity in the collector outlet. Figure 6(b) shows the wind speed curves at different times of the month. Figure 6(a) shows the daytime air velocity development for three days; May 1, May 23, and June 2. From these results, it can be observed that the air velocity increases with the same temperature behavior on all days. Moreover, the temperature presents the highest values on May 23.

Indeed, the highest velocity value appears on May 23. The velocity presents the same distribution for all collector radius positions and it is maximum on May 23. According to these results, the velocity increases along the collector due to the greenhouse effect for all hours. This could be interpreted by the temperature difference. However, the minimum velocities are reached at 08h and the maximum values are reached at 12h.

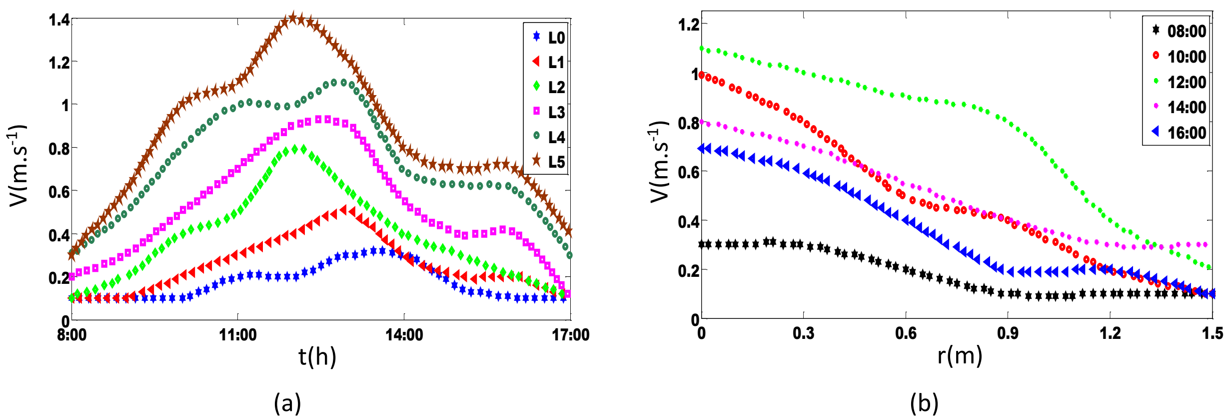

Fig. 6. Hourly velocity; (a) Daytime air velocity development for three days and (b) Wind speed curves at different times of the month

4. Conclusions

Solar chimneys are an interesting alternative to centralized electricity generation power plants. It's very important for the future, because our resources are limited, except our sun and the study of this technology has a topicality in the energetic fields. In this study, an experimental study of a solar chimney prototype is presented under the climatic conditions of Sfax, Tunisia. The impact of the climatic conditions of Sfax city on the aero-thermal characteristics of the considered prototype is carried out. The present outcomes show that the solar chimney power plant (SCPP) is an applicable device in the Tunisian region of Sfax.

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