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Research Article

Experimental study of temperature changes in a solar chimney

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ABSTRACT

The purpose of the current study is to conduct an experimental investigation into the effects of ambient temperature and solar radiation on the mean temperature of the absorber and collector of the solar chimney. To achieve this goal, a solar chimney prototype with a collector diameter of 0.79 m, a collector height of 0.105 m, a chimney diameter of 0.075 m, and a chimney height of 1.39 m was constructed at M'sila University. The experiments were conducted in a arid climate at the Biskra University. The results show that the mean absorber temperature was higher than the mean collector temperature. The absorber and collector temperatures are correlated by a polynomial law**.** The ambient temperature and solar radiation have a significant impact on the mean temperature changes of the absorber and collector. Mathematical models that depict how the mean collector and mean absorber temperatures change with respect to solar radiation and ambient temperature have been proposed.

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INTRODUCTION

With the increase in population and the advancement of living standards, energy has become more and more necessary. The shift towards clean (renewable) energies can be attributed to their clean nature, limitless supply, and growing competitiveness [1, 2]. These energies differ primarily from fossil energies in that they are abundant, diverse, and have global application potential. Likewise, renewable energies produce neither polluting emissions nor greenhouse gases responsible for climate change [2-4]. Their expenses are likewise going down at a reasonable rate. Currently scientific research is now focusing more on clean and renewable energy technologies. Solar energy is one of the most promising ones. Several technologies have been developed to use and turn this energy into electricity [2, 5, 6]. Some of these technologies have achieved great commercial success, such as photovoltaic [2, 5]. The IEA (International Energy Agency) predicts that the proportion of renewable energy in the world's electricity supply will rise from 28.7% (2021) to 43% (2030) [7]. Likewise, two-thirds of

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this increase in electricity demand during this period will be ensured by the development of wind and photovoltaic technologies) [7]. Another technology using solar radiation for electricity generation is the solar chimney [2, 4, 6]. The solar chimney has particular benefits, such as not requiring additional energy sources like gas or water, and having the ability to generate power both during the day and at night [8-10]. Researchers have recently become interested in the solar chimney, which is less common than PV system and have a poor efficiency. The solar chimney and photovoltaic systems are both applications of solar energy used for electricity production. The photovoltaic systems convert solar energy directly into electrical energy. However, the solar chimney produces electricity in an indirect manner by converting solar radiation into kinetic energy by air, which is subsequently converted into electrical energy in a turbine generator. The solar chimney has the advantage of being able to store solar energy during the day and thus produce energy during the day and at night, whereas the PV system produces it only during the day. Solar chimney has a little maintenance fees [11]. It is seen as a realistic and economical choice that can help developing nations with their energy demands [12]. Recently, the exploitation and use of solar chimneys have grown significantly due to their simplicity and wide application potential [4].

The three main components of the solar chimney are the collector, the chimney, and the power conversion unit (one or several turbines). Solar radiation passes through the transparent cover of the collector and heats the absorber, thus increasing its temperature. When the absorber is heated, the temperature of the air increases following thermal convection, which leads to a reduction in its density, and thus the air circulates towards the chimney through the turbine generator and produces electricity. The resulting air escapes into the atmosphere through the top of the chimney.

The Manzanares prototype, which was the first solar chimney prototype built, produced 50 kW of electricity for 8 continuous years, confirming the possibility of this technology. Haff et al. [13-14] evaluated the experimental and early test results of this system. Then the analysis and numerical modeling of this power plant with features of heat transmission under the collector were performed by Bernardes et al. [15]. With more research done on this topic, there has been a trend in the recent years to study of the effects of geometric and environmental parameters on the solar chimney using theoretical, experimental and CFD studies.

A solar chimney's performance is influenced by a number of factors, which can be divided into three categories: climatic factors, geometric factors, and design-related factors. The climatic factors such as solar radiations, ambient temperature and wind speed are unique to the study's region [16]. Two different points of view have been documented based on research done on how ambient temperature affects the performance of solar chimneys. The first opinion shows that the ambient temperature has a negative impact on the solar chimney's performance [17-20], whereas the second opinion confirms a favorable impact [21-23]. Using a novel three-dimensional axisymmetric computational fluid dynamics (CFD) method, adapted to the Manzanares solar chimney, Cuce et al. (2020) [20] look at how ambient temperature affects the power produced by the solar chimney. The produced power decreases as the temperature rises (for a constant solar radiation intensity of 1000 W/m^2) according to a linear regression (R^2=0.998). Similar results were presented by other studies [24-25]. It has been observed that power generation rises as radiation and ambient temperature rise [21]. The solar radiation has a positive effect on solar chimney performance [17, 21-23, 26]. Using the Manzanares solar chimney, Cuce et al. (2020) [20] introduced a novel three-dimensional axisymmetric computational fluid dynamics (CFD) approach. This study looks at how solar radiation intensity affects solar power plants that produce electricity. A precise model was developed that demonstrated a linear relationship between output power and solar radiation intensity. It had a high correlation coefficient (0.9914), and with an increase in solar radiation, power output rises. Furthermore, the performance of a chimney solar system is positively impacted by wind speed [27]. In general, the solar chimney performance depends on various geometric factors, including collector diameter, collector height, chimney diameter, chimney height. Based on these factors, researchers performed out comprehensive studies to change solar chimney systems, with a focus on optimizing the system geometry [9, 28-37]. The effect of the change in the collector radius on the system's performance parameters, such as temperature, air flow rate, efficiency, and power output, has been repeatedly analyzed by many researchers [9, 28-30]. The majority of the time, mathematical modeling or numerical simulation is used in studies on how the collector radius affects the solar chimney's performance [32]. Recently Sen et al. [30] presents a complete study on the effect of collector diameter on the temperature rise in the collector, maximum velocity, masse flow rate, power output and efficiency. This study was performed on Manzanares geometry using a CFD model. The findings show that the temperature rise in the collection and the collector diameter have a linear connection. As the collector radius increases, the power output increases exponentially. A linear relationship between collector radius and temperature rise in the collector was presented. Collector radius tends to increase mass flow and maximum air speed. Another crucial geometric factor that influences the performance of a solar chimney is the collector height. It influences the surface of the air flow and the amount of solar energy that reaches the ground [31]. A CFD model was developed by Ayadi et al. [32] to study the impact of collector height on temperature, pressure, and velocity distribution. The results indicated a negative effect of increasing the collector height (at a constant ambient temperature and solar radiation) on the chimney inlet velocity and the power output. Likewise, Toghraie et al. [9], using a simulation study, presented a negative effect of increasing the collector height (at a constant ambient temperature and solar radiation) on the power output, efficiency, pressure, and temperature change of the system. The chimney diameter is also considered

as an important factor that affects the output power and efficiency of the solar chimney. It has been observed that better performance was typically achieved with larger diameters. However, there is an optimal value for increasing the chimney diameter [32-34]. The chimney creates a pressure difference due to its height. This increase in chimney height reduces air pressure, increases air velocity, and therefore increases flow. Increasing the air flow increases the power delivered by the solar chimney and the system efficiency. Since the chimney is the system's motor, raising the chimney height enhances solar chimney performance [9, 35-37]. A CFD model was created by Shahi et al. [37] using Manzanares' geometry. They highlighted that raising the system's chimney height would raise the power output, mass flow, turbine pressure drop, and turbine input speed. A CFD model for two distinct collector radiuses was created by Toghraie et al. [9]. They demonstrated that raising the chimney height while maintaining a constant ambient temperature and radiation intensity will boost power output, efficiency, pressure differential, and mass flow. Recently, Cuce et al. [25], using a CFD model, quantifies the effect of stack height on system efficiency by studying the Manzanares pilot plant. They developed mathematical models relating the height of the solar chimney to the pressure difference, maximum speed, mass flow, power output and efficiency of the solar chimney.

The last parameter is related to the design (convergent, vertical and divergent) of the collector and chimney of the power plant. The chimney design has been considered as a parameter that affects the chimney performance. Different configuration was reported in the literature; cylindrical, convergent, and divergent. The divergent-shape was reported to be the best one and an optimum divergent angle was considered by many researchers [38, 41]. The collector slope (negative or positive) has an impact on the chimney performance. Nevertheless, higher slopes tend to result in more vortex formation, which raises losses and lowers efficiency. It has been reported that, down to a certain level, positive slopes improve performance [32, 42-45].

Following all the works cited in the literature, all the studies are based on the temperature of the fluid itself. In this study, our research focuses on the changes in the absorber and collector temperatures, which raise the air's temperature and cause it to move in the direction of the chimney. Likewise, the effects of climatic conditions (solar radiation and ambient temperature) on the mean temperature of the collector and the mean temperature of the absorber are studied. Mathematical models that describe the variation of the mean temperature of the absorber and the collector as a function of both solar radiation and ambient temperature were proposed. This study presents an experimental investigation of a solar chimney prototype with a data acquisition system that was developed at the University of M'sila. This paper is divided into four sections. The first presents an introduction, followed by materials and methods, which describe the prototype of the solar chimney, the data acquisition system, and the experimental procedure. The third section focuses on the results and their discussion, and finally, a conclusion closes this study.

MATERIALS AND METHODS

Description of the Solar Chimney Prototype

At the University of M'sila in Algeria, a small-scale solar chimney prototype was built in order to conduct research on solar energy chimneys. As seen in Figure 1, it consists of two fundamental parts: the chimney tower and the collector. The collector is made up of two parallel disks with the same diameter (79 cm), and the distance between the two disks is 10.5 cm. The lower disk is made of steel and presents the absorber, and the upper disk is made of Plexiglas (with an opening) to capture the most solar radiation. With a height of 1.39 m and a diameter of 7.5 cm, the solar tower is embedded in Plexiglas. It is constructed of PVC plastic tube.

A number of ten (10) temperature sensors were used to measure the temperatures on the collector and absorber at various locations shown in Figure 2. They are placed exactly 7.15 cm from one sensor to the next one on the absorber and collector, respectively. As shown in Figure 2, the five sensors placed in the collector are situated at different diameters: 3.75 cm (S5), 10.90 cm (S4), 18.05 cm (S3), 25.20 cm (S2), and 32.35 cm (S1), respectively. Five additional temperature sensors are positioned on the absorber in the same plane and locations as the collector.

Figure 1. The solar chimney prototype.

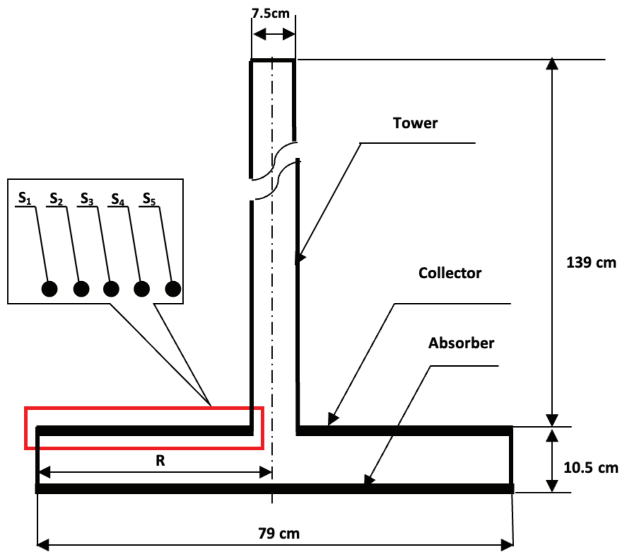

Figure 2. Temperature sensor placement in the solar chimney.

Data Acquisition System

Ten temperature sensors (Type D518B20) measuring the temperature in the range of -55° to 125°C with an accuracy of 0.1°C were used to measure temperatures at the different points mentioned above. Two digital acquisition systems composed mainly of Arduino boards and five temperature sensors were designed (Fig. 3). They allow temperature values to be recorded every minute. They are used to capture the temperature values on the collector and on the absorber.

Figure 3. Temperature acquisition system.

The wind speed is measured using an anemometer (PCS X Wind Speed Sensor), as seen in Figure 4. It moves at 0.1 m/s in resolution. Similarly, the amount of solar energy collected on the collector surface is measured using a hand pyranometer (489020 type pyranometer), as illustrated in Figure 4. It has an accuracy of ± 5% and a measuring range of 0–1999 W/m^2. In addition, an additional temperature sensor of the same kind as the one mentioned earlier is used to measure ambient temperature. An Arduino board was used to record the ambient temperature, wind speed, and sun radiation values every minute during the test period.

Experimental Procedure

The experiments were carried out at the University of Mohamed Khider in Biskra (Algeria). The city of Biskra

Figure 4. The used pyranometer and the anemometer.

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is located in the north of the Algerian Sahara, at the foot of the Aurès massif and the Zab Mountains. It is situated at 34°51‘ North, 5° 44’ East, and at an altitude of -120 m. Biskra has an arid climate. The climate of Biskra is hot desert, with long, intense summers and moderate winters [46]. In Biskra, the average temperature is 21.1°C. There is 125 mm of precipitation on average every year. [46].

On May 9, 2022, tests on the solar chimney were conducted to determine the change of the mean temperatures of the collector and the absorber as a function of climatic variables (T_{amb} and G). Using the suggested acquisition techniques, the values of ambient temperature, solar radiation, and ten temperature measurements (five on the collector and five on the absorber) were taken once every minute.

RESULTS AND DISCUSSION

Variation of Solar Radiation and Ambient Temperature

Figure 5 shows the change of both ambient temperature and solar radiation during the length of the experiment on May 9, 2022. The solar radiation changes from the beginning of the experiment, with a value of 416.51 W/m^2 recorded at 10:30, to its highest value of 959.76 W/m^2 recorded at midday (12:30). The ambient temperature rises during this time; it reaches a maximum value of 32.67°C at 14:50 and a minimum value of 23.1°C at 8:30.

Change of Collector and Absorber Temperatures as a Function of Time

The temperature variations on the collector and the absorber as a function of the diameter are illustrated,

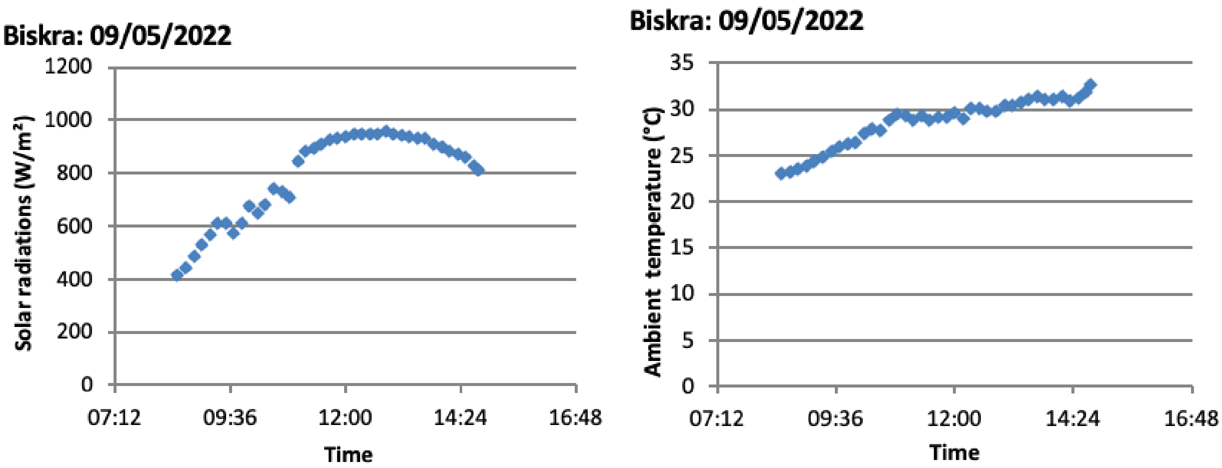

Figure 5. Solar radiation and ambient temperature change.

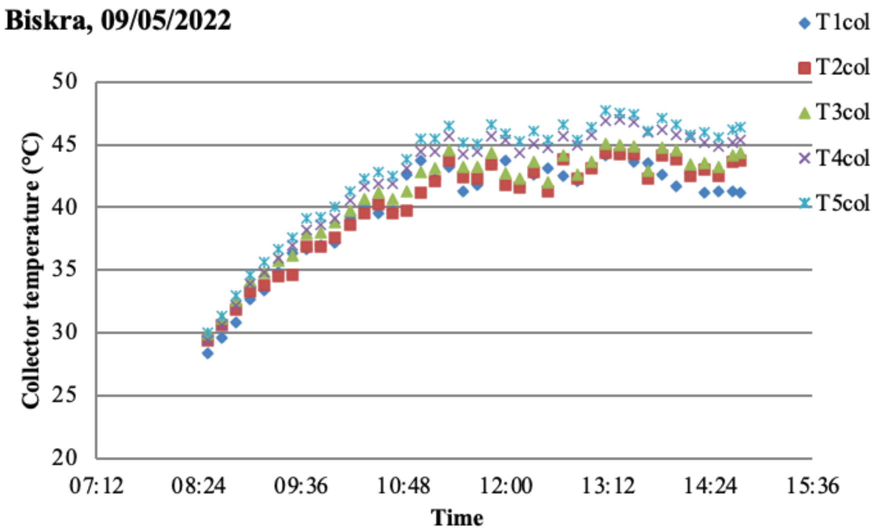

Figure 6. Collector temperatures change.

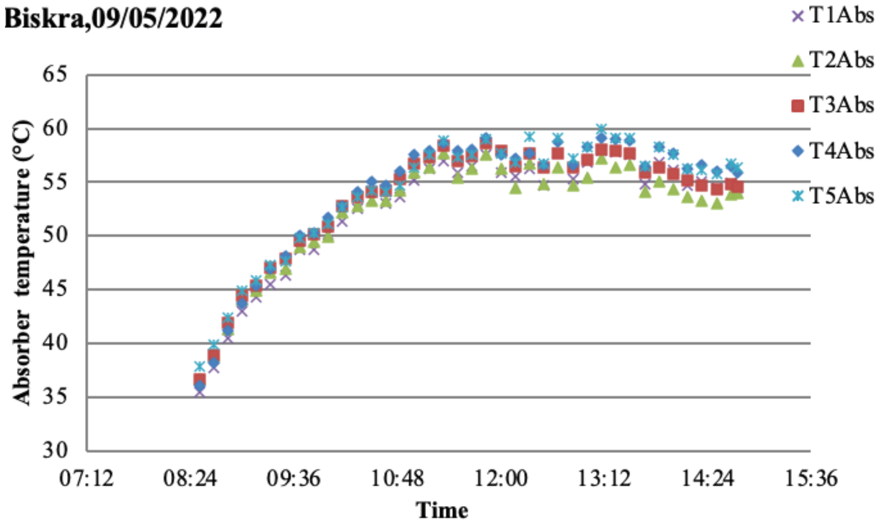

Figure 7. Absorber temperatures change.

respectively, in Figures 6 and 7. In both cases (collector and absorber), all temperatures (T1, T2, T3, T4, and T5) have the same form. As a result of solar radiation passing through the collector and being absorbed by the absorber, the absorber temperature values are higher than those indicated on the collector, as illustrated in Figures 6 and 7. The highest temperatures on the absorber and collector are presented for the greatest solar radiation intensity. The collector (or absorber) temperatures are a function of the radius of the collector (or absorber); they increase with decreasing radius, as shown in Figures 6 and 7. T1 temperatures have the lowest values, and T5 temperatures have the highest values. T4Abs and T5Abs temperatures are almost identical.

Relationship Between the Mean Collector and Absorber Temperatures

The variation of the mean temperatures on the collector and on the absorber over the tested period is presented in Figure 8. It should be considered that the mean temperature is the mean of the temperatures presented for each case (collector and absorber). The mean temperature change of the collector and absorber follows the same pattern as solar radiation. The maximum values are recorded at 12:10 p.m.: 45.64°C for the collector and 58.44°C for the absorber, respectively. Over the duration of the experiment, the mean absorber temperature is always higher than the mean collector temperature. The temperature difference between the absorber and collector varies with time, reaching

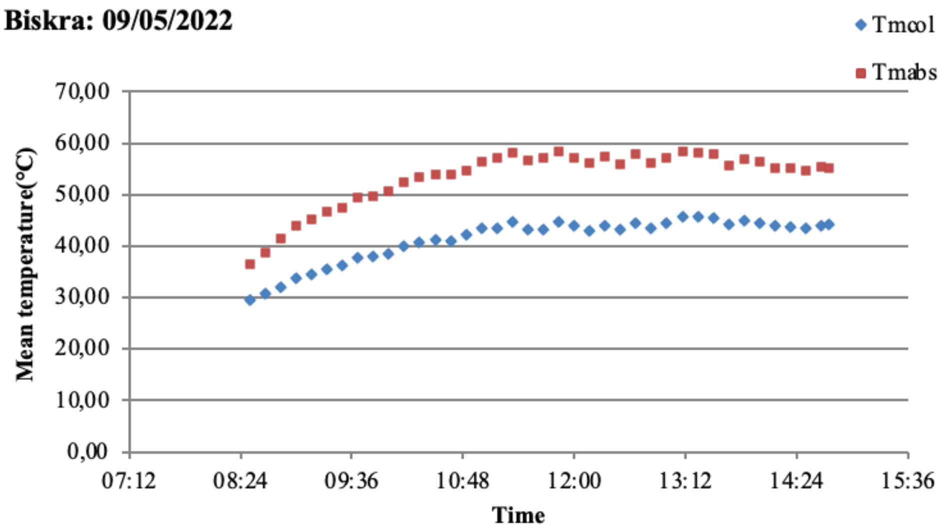

Figure 8. The mean temperatures (collector and the absorber) over time.

a maximum of 13.98°C at 11:10 a.m. and a minimum of 07.08°C at 8:30 a.m.

The absorber mean temperature (T_{mabs}) increases with the increase in the collector mean temperature (T_{mcol}), and they are correlated according to a polynomial law as presented in Eq. 1, with a coefficient of determination of 0.98.

$$T_{mabs} = -0.0321 \times (T_{mcol})^2 + 3.7266 \times T_{mcol} - 45.324 \quad (R^2 = 0.9832) \tag{1}$$

Operating Conditions Effect of the Mean Temperatures of the Collector and the Absorber

The effects of ambient temperature and solar radiation on the mean temperature of the collector are illustrated in Figures 9 and Figure 10. As presented, the mean temperature of the collector increases with increasing ambient temperature. (T_{amb}) according to the following relation:

$$T_{mcol} = -0.1659 \times (T_{amb})^2 + 10.77 \times T_{amb} - 129.78 \quad (R^2 = 0.9632) \tag{2}$$

This mathematical model has a very good coefficient of determination of 0.96. This justifies the effect of ambient temperature on the mean collector temperature. Likewise, the increase in solar radiation (G) received on the surface of the collector increases the mean temperature of the collector; it follows a law similar to the effect of ambient temperature as presented in Eq.3, with a coefficient of determination of 0.954. The calculated R^2 value confirms the impact of solar radiation on the mean collector temperature and provides a suitable illustration of the model that is suggested for the collector's mean temperature progression.

$$T_{mcol} = -5 \times 10^{-5} \times (G)^2 + 0.094 \times G - 2.27893 \quad (R^2 = 0.9542) \tag{3}$$

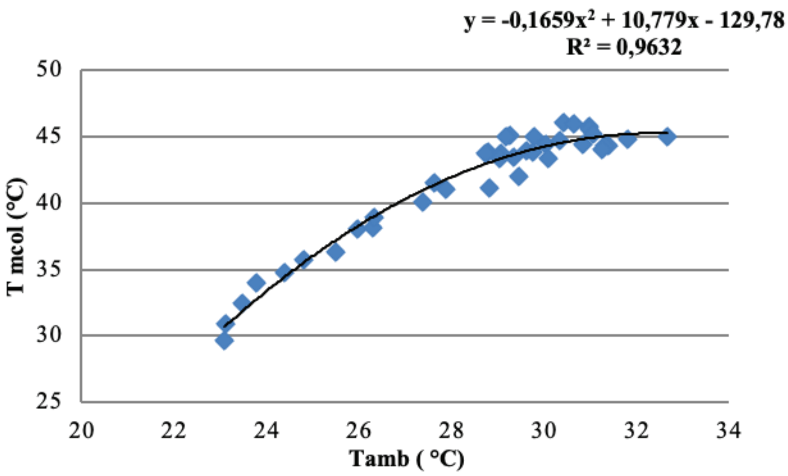

Figure 9. Ambient temperature effect on the mean collector temperature.

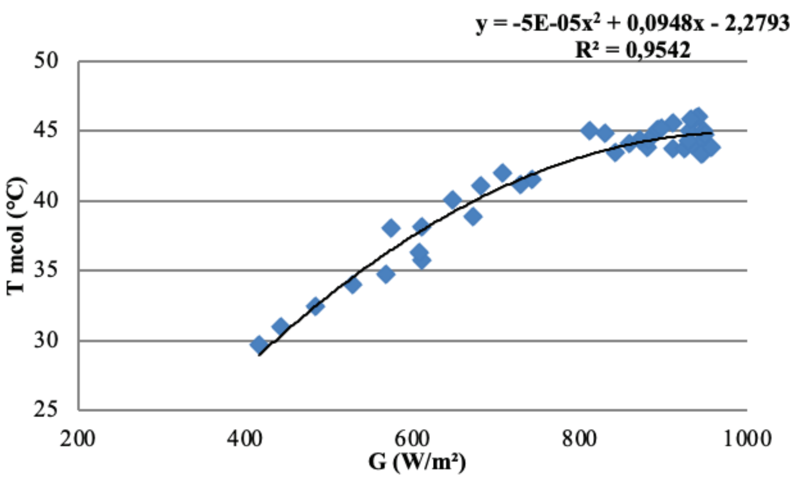

Figure 10. Solar radiation effect on the mean collector temperature.

As mentioned previously, two models of the change of T_{mcol} as a function of T_{amb} and G respectively have been proposed. Another model of the change of T_{mcol} as a function of these two variables (T_{amb} and G) is proposed using Matlab software. It is of the form:

$$T_{mcol} = -60.84 + 1.412\times10^{-5}\times(G)^2 + 0.03216\times G - 0.07856\times(T_{amb})^2 + 5.281\times T_{amb} \; (R^2 = 0.9811) \quad (4)$$

This model has a very good coefficient of determination (0.981) and a root mean square error (RMSE) value of 0.61°C, which validates this model for the prediction of the mean collector temperature as a function of ambient temperature and solar radiation. The modeled values for the mean temperature of the collector agree with the experimentally recorded values, as shown in Figure 11.

The effects of ambient temperature and solar radiation on the mean absorber temperature are illustrated in Figures 12 and 13. It is considered that increasing solar radiation and ambient temperature increases the mean absorber temperature. The amount of radiation that passes through the glazing increases as solar radiation rises, increasing the amount of heat absorbed by the absorber. This results in an increase in the absorber's temperature. Increasing the ambient temperature increases the temperature of the collector and thus increases the heat exchange (radiation) between the collector and the absorber, and therefore the temperature of the absorber increases. Therefore, the absorber temperature increases with increasing solar radiation and ambient temperature, and thus the air temperature, the collector temperature difference, and the power and efficiency of the chimney increase. This is in agreement with the results of the literature [20, 22–23].

Noting that the T_{mabs} change as a function of T_{amb} and the T_{mabs} change as a function of G can be summarized in the form of a mathematical expression as follows:

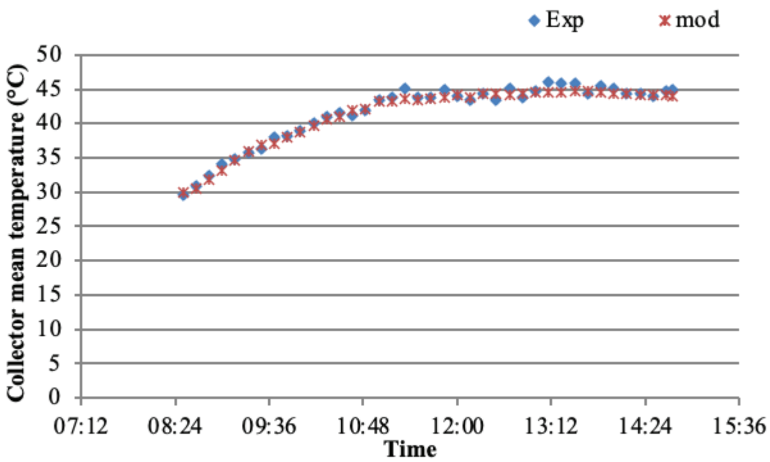

Figure 11. Comparison of experimental and modeled mean collector temperatures.

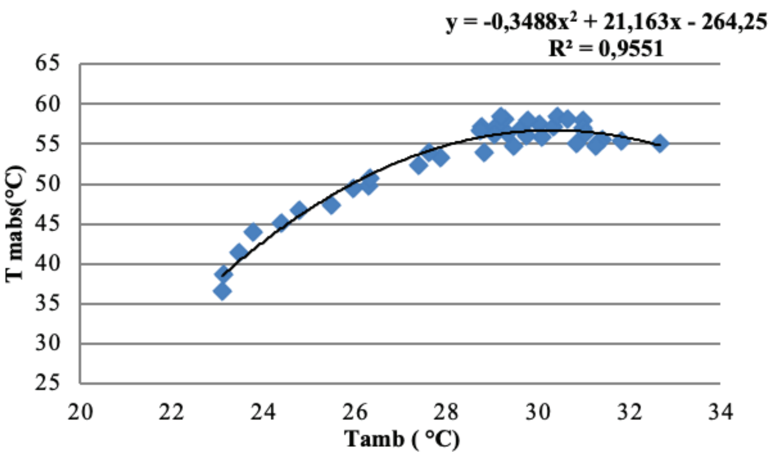

Figure 12. Ambient temperature effect on the mean Absorber temperature.

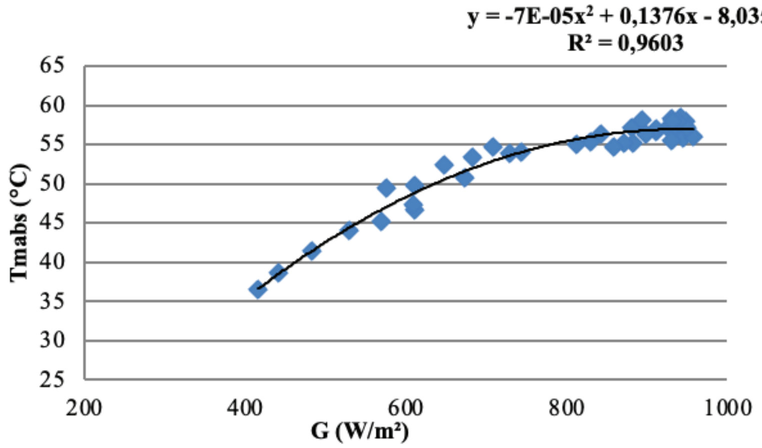

Figure 13. Solar radiation effect on the mean absorber temperature.

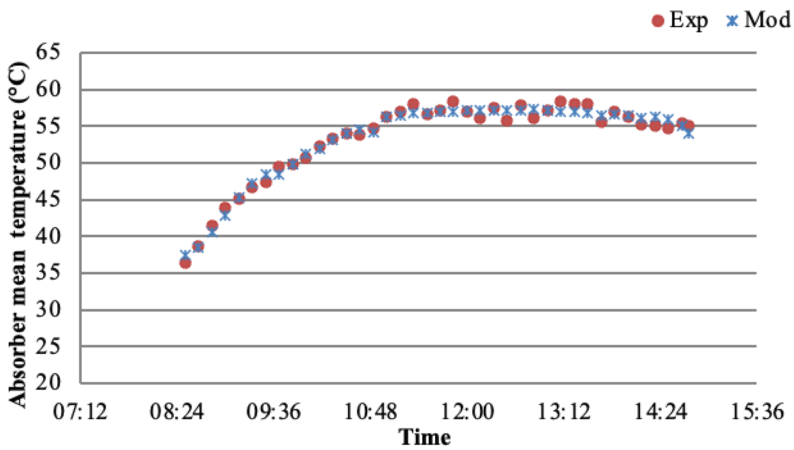

Figure 14. Comparison of experimental and modeled mean absorber temperatures.

$$T_{mabs} = -0.3488 \times (T_{amb})^2 + 21.163 \times T_{amb} - 264.25 \; (R^2 = 0.9551) \quad (5)$$

$$T_{mabs} = -7 \times 10^{-5} \times (G)^2 + 0.1376 \times G - 8.0354 \; (R^2 = 0.9603) \quad (6)$$

In a similar manner, a model of change of the mean temperature of the absorber as a function of environmental conditions (G, T_{amb}) is established:

$$T_{mabs} = -157 - 2.595 \times 10^{-5} \times (G)^2 + 0.0554 \times G - 0.2101 \times (T_{amb})^2 + 12.47 \times T_{amb} \; (R^2 = 0.979) \quad (7)$$

This model's coefficient of determination (0.979) and its root mean square error (RMSE) (0.664°C), making it valid for predicting the mean absorber temperature in relation to ambient temperature and solar radiation. Figure 14 shows a comparison between the model's values and experimental values for the mean absorber temperature. There is good agreement between these values, which supports the proposed model.

CONCLUSION

In this experimental study, the effects of ambient temperature and solar radiation on the mean temperature of the absorber (T_{mab}) and the collector (T_{mcol}) were examined. A solar chimney prototype has been constructed at the University of Msila in order to achieve this goal. This prototype has a collector diameter of 0.79 m, a collector height of 0.105 m, a tower diameter of 0.075 m, and a tower height of 1.39 m. Additionally, the ability to gather data every minute was developed through the use of data collecting devices (temperature, solar radiation, wind speed) coupled to Arduino boards.

The research conducted throughout this study allowed us to retain the following points:

1. There is dependence between T_{mab} and T_{mcol} temperatures; they are related with a polynomial law with a coefficient of determination (R^2) of 0.98.
2. The T_{mcol} is dependent on both ambient temperature and solar radiation. A mathematical model which describes the evolution of the mean collector temperature as a function of solar radiation and ambient temperature has been developed. It follows a polynomial law with a coefficient of determination (R^2) of 0.9811 and a root mean square error (RMSE) value of 0.61°C.
3. The T_{mab} is also affected by ambient temperature and solar radiation. A mathematical model has been established to explain how the mean collector temperature changes in relation to solar radiation and ambient temperature. It obeys a polynomial law with a coefficient of determination (R^2) of 0.979 and a root mean square error (RMSE) of 0.664°C.

The increase in the air temperature in the collector leads to an increase in: the air temperature difference (the outlet minus the inlet) in the collector; the air circulation speed in the solar chimney; and the power and efficiency of the solar chimney. It is essential to increase the absorber temperature to achieve this goal. As presented in this study, the increase in ambient temperature and solar radiation increases the temperature of the absorber and thus increases the performance of the solar chimney. Likewise, the materials used in the construction of the absorber and the collector also have an impact on the air temperature in the chimney and, thus, on the performance of the solar chimney.

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data that supports the findings of this study are available within the article. Raw data that support the finding of this study are available from the corresponding author, upon reasonable request.

CONFLICT OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

ETHICS

There are no ethical issues with the publication of this manuscript.

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