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Ambient temperature and solar radiation effects on absorber and collector mean temperature in a solar chimney

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Abstract

The growing interest in solar chimneys stems from their simple design and wide-ranging applicability, offering a sustainable solution for energy efficiency and climate adaptation. However, optimizing their thermal performance in various environmental conditions remains an area of active research. This study aimed to address this gap by experimentally analyzing the thermal behavior of a solar chimney prototype with a 1-meter collector diameter in an arid climatic setting. Ten temperature sensors, evenly distributed on the absorber and collector, recorded data alongside ambient temperature and solar radiation at one-minute intervals. Results revealed that solar radiation and ambient temperature exert a significant impact on the thermal performance of the absorber and collector, with their average temperatures showing a strong correlation to these variables. A polynomial model was developed to predict the mean temperature variations of the absorber and collector as functions of solar radiation and ambient temperature, offering a reliable analytical tool for system optimization. These findings contribute to the understanding of solar chimney dynamics and provide a foundation for enhancing their design and performance, particularly in arid regions where solar energy potential is abundant.

Keywords: Absorber; ambient temperature; collector mean temperature; solar chimney; solar radiation

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1. INTRODUCTION

Today, clean and renewable energy technologies are receiving more attention in scientific research. Among the most promising is solar energy (Cuce, 2024). Numerous devices have been created to harness this energy and convert it into electrical power. Researchers have recently become interested in solar chimneys, which are less common than PV systems and have poor efficiency. Due to their ease of use and extensive application possibilities, solar chimneys have seen a significant rise in exploitation and use in recent years (Shi & Zhang 2024).

The collector, chimney, and turbine are the three structural components that make up a solar chimney, and because of their simple form, they are appealing solar power generation systems. The collector is the crucial component; it gathers sunlight via the roof's transparency. Because of the density difference, the air beneath the glass ceiling heats up and begins to ascend. The chimney is the main part through which the hot air rises and expands into the atmosphere. Turbines may be located at the top or close to the base of the chimney, where a suitable mechanism converts the rotary action of the turbine into electrical energy.

The three parameters that have an overall impact on the performance of solar chimneys are climatic, geometric, and design (Padhi et al., 2021; Das & Velayudhan Parvathy 2022; Semai & Bouhdjar 2021). The two climatic characteristics are solar radiation intensity and ambient temperature (Cuce et al., 2020). The solar chimney performance is positively impacted by solar radiation (Dai et al., 2003; Larbi et al., 2010; Asnaghi & Ladjevardi 2012; Ayli et al., 2021).

An exact model illustrating a linear correlation between output power and solar radiation intensity was created using computational fluid dynamics (Cuce et al., 2020). Its high correlation coefficient (R^2=0.9914) indicates that electricity output increases as solar radiation increases.

Based on research on how ambient temperature influences solar chimney performance, two distinct points of view have been established. The solar chimney performance is negatively impacted by the ambient temperature, according to the first opinion (Cuce et al., 2020; Kasaeian et al., 2017; Dhahri et al., 2014; Cuce et al., 2021; Ihaddadene et al., 2023), while the second opinion (Asnaghi & Ladjevardi 2012; Ayli et al., 2021) indicates the opposite. The geometric factors are collector diameter, collector height, chimney diameter, and chimney height. The collector diameter has a positive impact on the performance of solar chimney (power output, efficiency, temperature in the collector, airspeed, and mass flow) (Toghraie et al., 2018; Karimipour-Fard & Beheshti 2017; Yapıcı et al., 2020; Şen et al., 2021).

The collector height hurts solar chimney performance (power output, efficiency, temperature, and pressure distribution) (Toghraie et al., 2018; Cuce et al., 2022; Ayadi, Bouabidi et al., 2018). The chimney diameter affects the solar chimney output power and efficiency. Nonetheless, there's an optimal value for better performance parameters (Ayadi, Bouabidi et al., 2018; Guo et al., 2015).

The chimney height has a positive effect on solar chimney performance (power output, efficiency, pressure differential, and mass flow) (Toghraie et al., 2018; Ayadi, Driss, et al., 2018).

The collector and chimney design (convergent, vertical, and divergent) are also an important factor that affects the system's performance. The performance of the solar chimney is affected by the collector slope, whether it is positive or negative. However, more vortex formation on steeper slopes tends to increase losses and decrease efficiency. Down to a certain level, positive slopes have been shown to enhance performance (Cuce et al., 2021). Numerous researchers have identified an optimal divergent angle and, they indicated that the divergent form is the best one (Nasraoui et al., Hassan et al., 2018).

Nomenclature

G	solar radiation
T_{Colm}	mean collector temperature
T_{Absm}	mean absorber temperature
$T_{Absm(a)}$	mean absorber temperature before 13:04 p.m.
$T_{Absm(b)}$	mean absorber temperature after 13:04 p.m.
T_{amb}	ambient temperature
R^2	coefficient of determination

1.1. Purpose of study

All the works cited in the literature are based on the fluid temperature itself, and the effects of ambient temperature and solar radiation intensity on the solar chimney have been carried out mainly using mathematical or CFD studies due to the experimental limitations of having desired temperature and radiation values. Note that the fluid temperature is affected by both collector and absorber temperatures. This experimental research paper is focused on how mean collector and mean absorber temperatures are affected by solar radiation and ambient temperature (climatic conditions). Mathematical formulae have been used to quantify these impacts. There are four parts to this paper. An introduction is followed by a materials and methods section that regroups the solar chimney prototype, data-gathering system, and experimental protocol. The results and their discussion are the subject of the third section, and the study closes with a conclusion.

2. MATERIALS AND METHODS

The prototype used in this study is a small solar chimney with a radius of 50 cm and a chimney (PVC plastic) length of 1 m (Figure 1). The upper disk made of Plexiglas is called the collector, and the lower disk made of steel is called the absorber. The distance between the collector and the absorber is 10 cm. The solar chimney is equipped with ten D518B20 temperature sensors, each with a measurement range of 55°C to 125°C with an accuracy of ±0.1 °C. Five temperature sensors are positioned on the collector, and an additional five are located on the absorber in the same plan. The first sensors are positioned at a radius of 13.75 cm, the second at 20.81 cm, the third at 31.87 cm, the fourth at 40.94 cm, and the last at 50 cm. Additionally, there is an additional temperature sensor to measure ambient temperature and a pyranomètre (489020) with a measurement range of 0 - 1999 W/m² and ±5% accuracy to measure solar energy received on the collector's surface. These solar radiation temperature sensors are connected to Arduino systems to preprocess the measurements every minute.

On February 21, 2023, tests were taken in Biskra (Algeria) to examine the impact of solar radiation and ambient temperature on the mean temperature of the collector and absorber. The ten temperature values were recorded each minute, along with the amount of solar radiation and ambient temperature.

3. RESULTS

Figure 1 shows the Solar chimney setup. The solar radiation throughout the clear day of the experiment follows a bell shape; as shown in Figure 2, it increases during the day to reach the maximum value of 667.5 W/m^2 at 1:04 p.m., then decreases to reach the minimum value of 114.5 W/m^2 at 3:50 PM. On the other hand, the ambient temperature shows a rising trend during the experience, peaking at 23.5°C (3:20 p.m.).

Figure 1

Solar chimney setup

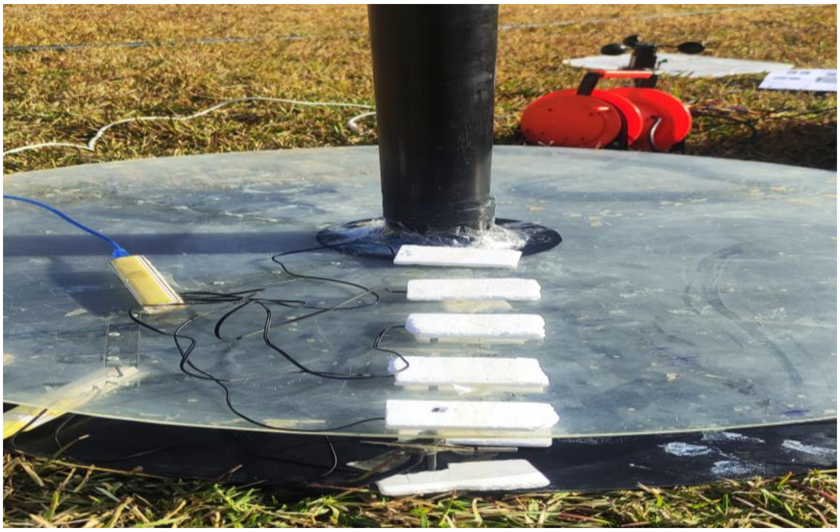


Figure 3 shows the evolution of the collector's and absorber's mean temperatures. The mean temperature on the collector (T_{Colm}) (or absorber (T_{Absm})) is the mean of the five temperatures recorded on the collector (or absorber). The two temperatures have the same tendency; their minimums are noted at 10 a.m., where they are 22.64 °C (T_{Colm}) and 28.42 °C (T_{Abm}), and their maximums are registered at 12:08 a.m. 44.48°C (T_{Abm}) and 28.42°C (T_{Colm}). Because of the heat transfer that occurs at the absorber's level (the absorption of solar radiation that is transmitted and emitted by the collector), the absorber's temperature is higher than the collector's. The maximum temperature difference between the T_{Abm} and T_{Colm} was recorded at 11:46 a.m. and is 11.62 °C. Other works, like Aurybi et al., (2018); Mustafa et al., (2015); and Ihaddadene et al., (2024), have documented the same tendency of the T_{Abm} and $T_{Colm.}$

The variations of the T_{Colm} and T_{Abm} based on ambient temperature are carried out as shown in Figure 4 to visualize the impact of ambient temperature on the evolution of these two temperatures. It is observed that in both cases, the mean collector temperature and the mean absorber temperature rise in response to an increase in ambient temperature, following a polynomial function as follows:

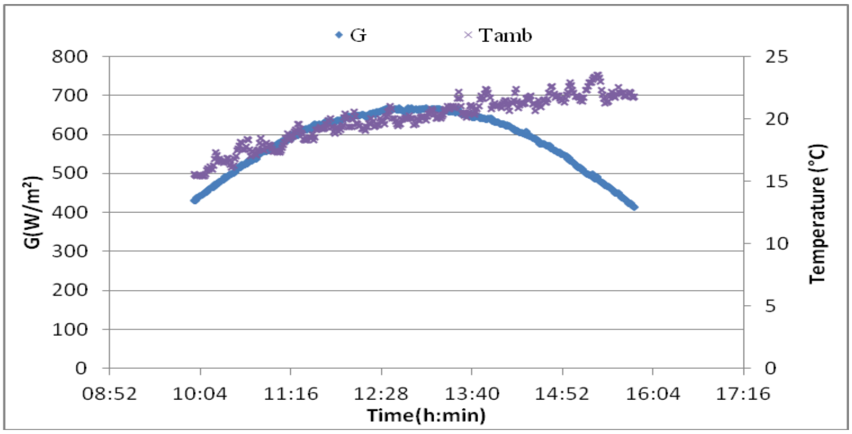
$$T_{Colm} = -0.2658 T_{amb}^{\ 2} + 11.432 T_{amb} - 90.36 \quad (R^2 = 0.8552) \qquad (1)$$

$$T_{Abm} = -0.4953 T_{amb}^{\ 2} + 20.325 T_{amb} - 166.45 \quad (R^2 = 0.775) \qquad (2)$$

It is noted that the T_{Colm} is more affected by ambient temperature than the $T_{Abm.}$ The collector's immediate contact with the surrounding temperature makes this evident. So, as the ambient temperature increases, the absorber and collector temperatures increase. It should be mentioned that increasing the ambient temperature raises the temperatures of the absorber and collector, which in turn raises the air temperature between the two. As a result, the power and efficiency of the solar chimney grow as the temperature differential between the collector's input and output increases.

Figure 2

Solar radiation and ambient temperature variation during the experiment



As illustrated in Figure 2, the solar radiation has a bell shape during the experimental test. So, to study the effect of solar radiation on the T_{Colm} and T_{Abm} evolution, the solar radiation must be divided into two intervals: from the beginning to the maximum value and from the maximum value to the end of the test.

The solar radiation affects the T_{Colm}; it increases as the solar radiation increases in the morning (until 1:04 p.m.) as noted in Figure 5(Collector(a)). It follows a polynomial evolution as noted by equation (3). It presents a high determination coefficient (R^2) value of 0.935. After 1:04 p.m., the T_{Colm} decreases as the solar radiation increases as represented in Figure 5(Collector (b)). It follows also a polynomial evolution (equation (4)) with 0.909 (R^2). This effect is more significant in the early part of the day.

$$T_{Colm(a)} = -9 \times 10^{-5} G^2 + 0.1363\, G - 20.467 \qquad (R^2 = 0.9349) \tag{3}$$

$$T_{Colm(b)} = -0.0003\, G^2 + 0.3221\, G - 48.543 \qquad (R^2 = 0.9085) \tag{4}$$

In the absorber's case and before 1:04 p.m., T_{Abm} increases by solar radiation increases according to a polynomial law (equation (5)) with 0.9468 (R^2). After 1:04 p.m., the same behavior was noted (equation (6)) with 0.664 (R^2).

$$T_{Abm(a)} = -0.0002\, G^2 + 0.2488\, G - 46.729 \quad (R^2 = 0.9468) \tag{5}$$

$$T_{Abm(b)} = 2 \times 10^{-5}\, G^2 - 0.012\, G + 39.593 \quad (R^2 = 0.6637) \tag{6}$$

Note that before 1:04 p.m., T_{Colm} and T_{Abm} follow the same pattern based on variations in solar radiation as illustrated in Figure 5 and Figure 6. It is noted that the range of values is larger in the case of the absorber than the collector, which is attributed to the thermal properties of the materials used (metal and plexiglass) (thermal conductivity and absorptivity). However, after 1:04 p.m., T_{Colm} and T_{Abm} evolve differently; T_{Colm} increases as solar radiation decreases. This can be related to the increase in the ambient temperature as noted previously. T_{Abm} decreases as solar radiation decreases. But with a lower

Figure 3

Collector and absorber mean temperature variation

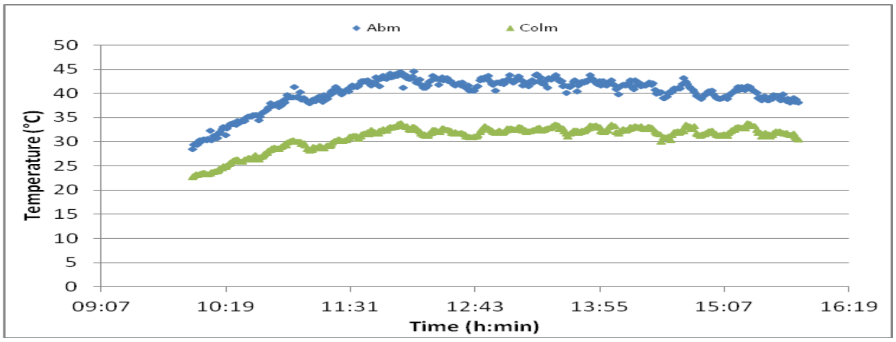


Figure 4

Effect of ambient temperature on mean collector and mean absorber temperatures

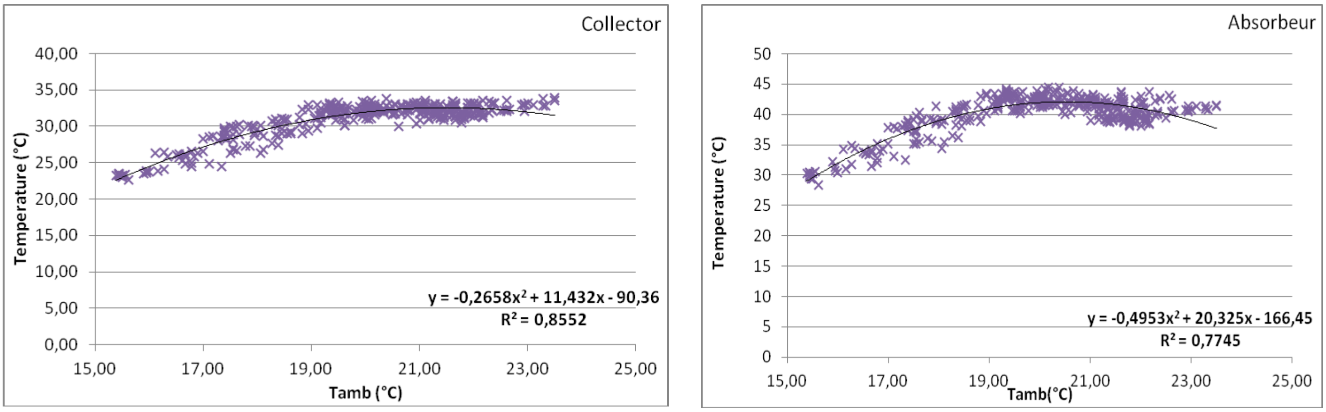
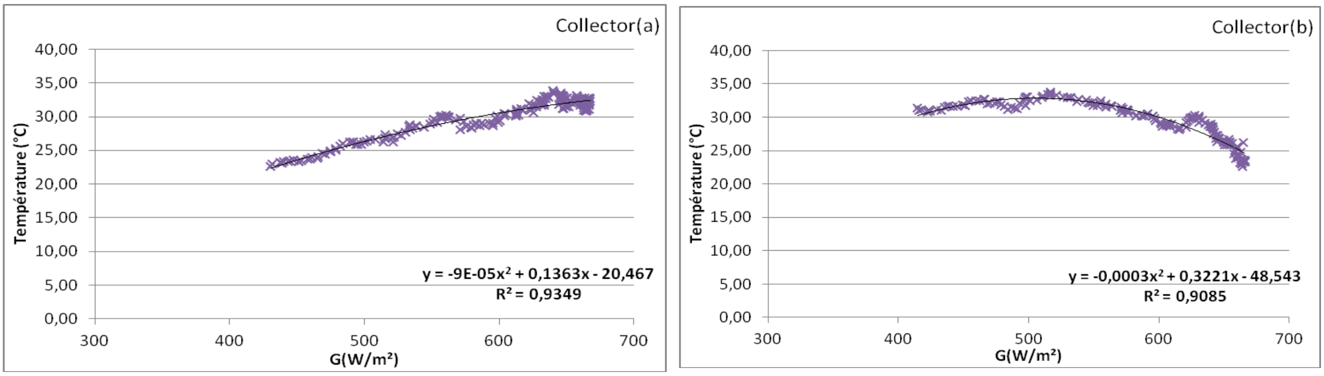


Figure 5

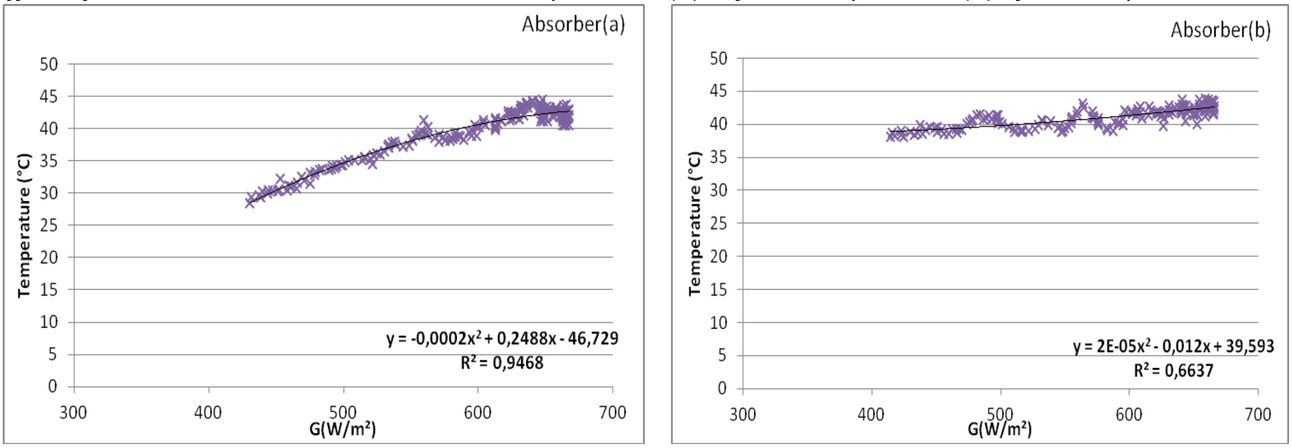
Effect of solar radiation on mean collector temperature ;(a) before 1:04 p.m. and (b) after 1:04 p.m.



Intensity in the morning can be linked to the thermal capacity of the absorber (metal). As a conclusion, the study of the ambient temperature and the solar radiation effect on the collector mean temperature and the absorber mean temperature was carried out experimentally in an arid climate (Biskra, Algeria). The results show that these two parameters are of great importance in the variation of the average temperatures of the collector and the absorber. This directly affects the power and efficiency of the solar chimney.

Figure 6

Effect of solar radiation on mean absorber temperature; (a) before 1:04 p.m. and (b) after 1:04 p.m.



4. DISCUSSION

The experimental analysis of the solar chimney system revealed significant insights into the relationships between solar radiation, ambient temperature, and the mean temperatures of the collector (TColm) and absorber (TAbm). Solar radiation exhibited a bell-shaped curve, peaking at 667.5 W/m² at 1:04 p.m., while ambient temperature showed a steady increase, reaching a maximum of 23.5°C at 3:20 p.m. These environmental factors strongly influenced the thermal performance of the solar chimney components.

TColm and TAbm demonstrated similar trends during the early hours of the experiment, with their maximum values recorded at 12:08 p.m. (44.48°C for TAbm and 28.42°C for TColm). However, their behavior diverged post 1:04 p.m., as TColm increased slightly due to rising ambient temperatures, while TAbm decreased alongside declining solar radiation. This divergence highlights the distinct thermal properties and responses of the collector and absorber materials.

The study confirmed that TColm is more influenced by ambient temperature than TAbm, as the collector's immediate exposure to environmental conditions intensifies its thermal response. Both TColm and TAbm were positively correlated with solar radiation, following polynomial relationships, with TAbm exhibiting a more pronounced sensitivity due to the higher thermal absorptivity of its metallic surface.

5. CONCLUSION

The experimental findings underscore the pivotal role of solar radiation and ambient temperature in determining the thermal behavior of solar chimney components. These parameters directly influence the temperature differentials between the collector and absorber, which in turn govern the power output and efficiency of the system. The study demonstrates that during peak solar radiation, the absorber achieves significantly higher temperatures, enhancing heat transfer to the air.

The data also reveal that beyond peak radiation, ambient temperature becomes a critical driver for TColm, while the absorber’s thermal response diminishes. This highlights the importance of optimizing material properties and environmental conditions to enhance solar chimney performance. The results provide valuable insights for improving solar chimney designs in arid climates, where maximizing efficiency is crucial for sustainable energy solutions.

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Ethical Approval: The study adheres to the ethical guidelines for conducting research.

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