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Research Article

Study of the variation of temperatures in a solar chimney

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ABSTRACT

In the present study, an experimental investigation was performed to study the effect of mean absorber and collector temperatures on the mean air and chimney temperatures. In the dry climate of Biskra University, experiments were carried out using a solar chimney prototype that presented the following characteristics: 0.50 m for the collector's radius, 10 cm for the collector's height, 10 cm for the chimney radius, and 1 m for the chimney's height. The temperature at the various study points has been measured using temperature measurement systems. The experimental results show that the temperatures of the absorber, collector, and air follow the same pattern. The temperature in the chimney follows the same pattern; it degrades following a linear law depending on the position. The absorber's mean temperature rises in accordance with the collector's mean temperature rise, according to a linear law with a coefficient of determination (R^2) of 0.94. The mean air temperature rises in tandem with the mean absorber and collector temperatures in a model that follows an exponential law (R^2=0.84). Additionally, the mean temperature of the chimney rises in tandem with the mean temperatures of the absorber and collector, according to a mathematical model following a polynomial law (R^2=0.87). So the absorber temperature is a key parameter that affects the solar chimney performance.

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INTRODUCTION

Throughout the world, the use of renewable energies as an alternative to easy energies has grown rapidly in recent years. Due to its ease of manufacture, ease of use, and availability of solar energy, the solar chimney presents an interesting technology. After photovoltaic technology, it is the second method for producing electricity from solar energy.

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The solar chimney functions as a device that converts solar energy into electrical energy. It is made up of three parts: the turbine, the chimney, and the collector. The way it operates is based on the air (between the absorber and the collector) heating as a result of solar energy passing through the collector. As a result, the absorber's temperature rises, raising the air's temperature by convection and lowering its density. The difference in density between the ambient and collector air is what causes the air circulation within the solar chimney. The air generates electricity as it passes through the turbine.

The solar chimney's efficiency is dependent on several climatic factors, including solar radiation, ambient temperature, wind speed, and humidity. Additionally, the geometry of the solar chimney itself involves the collector's radius and height (the distance between the collector and absorber), collector form, and chimney's radius, height and form. Noting also that the building materials used in its construction play a major role in their effectiveness.

The impact of solar chimney geometry and the influence of weather conditions have been the subject of several experimental, mathematical models and numerical simulation investigations.

Numerous solar chimneys have been designed in order to assess their effectiveness, for example: a 5 W pilot solar chimney was installed on a Chinese building's roof by Zhou et al. [1]. The 8 m tall pilot plant, with a 10 m collector diameter, was rebuilt multiple times for various uses. On the University of Zanjan campus in Iran, Kasaeian et al. [2] constructed another solar chimney prototype with a chimney 12 m of high and a collector 10 m in diameter. In Subrata (Libya), Shuia et al. [3] built a solar chimney prototype with a collector surface area of 126 m^2, and its PVC chimney measures 0.2 m in diameter and 9.8 m in height. The prototype's performance at noon was greater than in the morning and evening, according to the experimental results. This performance is barely affected by wind speed. The temperature differential between the interior collector temperature and the outside air temperature directly affects the maximum air speed.

In Aswan (Egypt), Hanna et al. [4] have constructed a solar chimney setup with 6 m in collector diameter, 6m in chimney height, and 0.15 m in chimney diameter. The collector was inclined, with a collector outer height of 0.25m and a collector inner height of 0.5m. They have presented the effect of environmental factors such as ambient temperature, the clarity of the sky, and solar radiation on the performance of the solar collector. The results indicated that the collector, air, and absorber temperatures increased from the outer to the inner collector diameter. The main factors that impact the collector's efficiency are sky clarity, ambient temperature, and solar radiation.

A mathematical model has been created by Choi et al., [5] to assess the impact of ground-based heat storage medium and geometric parameters on solar chimney power produced. The findings show that increasing chimney height and diameter increases power output. However, it is discovered that taking into account a ground-based heat storage medium lowers power output during the day and significantly increases energy generation before sunset.

Aurybi et al., [6] proposed a mathematical modeling of a new technique of integrating the solar chimney power plant with an external heat source. The findings indicated that adding thermally boosting channels to the solar chimney's collector could raise the air temperature within. When solar intensity is 1000 W/m^2 and the wall temperature of thermal boosting channels is 100°C, the percentage of temperature increase for the collector's air achieved 5.88% and 23.1%, respectively, for power generation. A positive effect of solar radiation and a negative effect of ambient temperature on the chimney solar power output were noted in the literature [7, 8]. Additionally, wind speed has a positive effect on solo chimney solar performance [9].

Numerous 3D simulation studies have been documented in the literature for the study of the solar chimney. Using genetic algorithms, Amir and Toghraie [10] carried out a geometric optimization and computational fluid dynamics study of a solar chimney. The findings indicate that while raising the chimney's height can significantly boost its power, doing so may also somewhat lower its power when the collector's radius is raised. A simulation analysis of the geometric parameters on the chimney power output performance was conducted by Toghraie et al., [7]. The findings showed that the effectiveness of solar chimneys is increased with increases in collector diameter and chimney height. Similar effects of the chimney's height have been noted by Cuce et al., [8], and Ayadi et al., [11]. The seam effect of collector diameter have been noted by Karimipour-Fard et al., [12], Yapici et al., [13] and Ihaddadene et al., [14].

Recently, Şen et al., [15] studied the combined effect of chimney height and collector radius on solar chimney performance to find the optimal value. As it is well known, increasing the chimney height or the collector surface increases the chimney performance, but in terms of construction, it is costly. They conclude that, the chimney height of 388.2 m and the collector radius of 146.4m are the optimum values.

Another parameter that affects a solar chimney's performance is the shape of the collector and the chimney. A simulation research was done in 2014 by Patel et al. [16] to investigate the impact of chimney divergence. In terms of mass flow rate and kinetic energy, the results showed that the diverging chimney outperforms the conventional or converging chimney [17]. The collector's inclination (negative slope) causes an increase in air velocity at the chimney's input section, which then increases power output [18]. Higher collector slopes, however, can also affect continuous air flow by creating vortices and air recirculation, which can hinder airflow and lower the performance [19]. Additionally, using the collector's divergence and the chimney's convergence improves the solar chimney's performance [18, 19]. Recently, Cuce et al., [20] studied a new design with a divergent chimney and convergent collector using numerical simulation. The results show an increase of three times in power, 36.8% in the maximum velocity and 40% in mass flow. The influences of the inclination angle (θ) from 50° to 80° at chimney inlet on chimney performance were investigated numerically [21]. The results indicate that the increase in the inclination angle increase the chimney performance (an increase of 24.5% in the power output).

The research work cited in the literature focuses more on the air temperature between the absorber and the collector, either by simulation or experimentally. This study is an experimental one; it focuses on the analysis of the temperature distribution in a solar chimney (air between the absorber and the collector, collector, absorber, and chimney) in order to determine the impact of the absorber temperature and the collector temperature on the air temperature and the chimney temperature. Following this introduction, which outlines the background and goals of this work, the second part describes the experimental section which describes the solar chimney prototype, the measurement devices that have been realized, and the experimental procedure. The third part presents a discussion of the obtained results, while the fourth part compiles the work's conclusions.

MATHERIALS AND METHODS

As depicted in Figure 1, a solar chimney prototype consisted by a collector, absorber, and chimney was constructed and used in this study. The plastic chimney measures 10 cm in diameter and 1 m in height. The absorber has a 100 cm diameter and is made of iron. The collector is made of plexiglass, presents a diameter of 100 cm and 10 cm of high.

Four temperature probes of type DS18B20, measuring the temperature in the range of -55° to 125°C with an accuracy of 0.1°C, are positioned on the collector. The first is one centimeter from the chimney, and each of the other three sensors is positioned successively at a distance of 13 cm. Four other sensors are positioned on the absorber according to the same distribution diagram as noted on the collector. Four additional sensors are placed to measure the air temperature between the collector and the absorber, following the same placement on the collector and the absorber.

The first temperature sensor on the chimney is positioned 2 cm above the collector's canopy level. The second sensor is positioned 32.5 cm above the first, the third at the same distance from the second, and the fourth sensor at the same distance from the third sensor (Figure 1). Furthermore, an additional temperature sensor is intended to measure ambient temperature. All of these temperature sensors are connected to Arduino systems that record these values every minute. The experience was conducted at the University of Biskra(34° 51' 00" N, 5° 44' 00" E) on February 23, 2023, from 9:25 a.m until 15:05 p.m.

Figure 1. Experimental device.

RESULTS AND DISCUSSION

Collector, Absorber and Air Temperature Evolution

Figure 2 shows the temperature evolution on the collector according to points 1, 2, 3, and 4. Over time, all of these temperatures have the same pace. The maximum temperature values for all the points are recorded at 12:32 p.m. Additionally, as shown in Figure 3, Temp1 (the farthest from the chimney) has the lowest values when compared to the others, while Temp4, the closest to the chimney, has the highest values, and the other temperatures are distributed in increasing order between these two temperatures (Temp4 and Temp1). The same tendency toward change in temperature that is observed on the collector (Temp1, Temp2, Temp3, and Temp4) is also shown on the absorber (Figure 3). In this instance, the absorber temperature values are higher than the collector temperature values. Likewise, the temperature differences between Temp1 and Temp4 in the absorber are larger than those noted on the collector. The temperature differences between the last two temperatures (Temp3 and Temp4) are not significant.

The air temperature at each of the four measurement points follows the same pattern as the collector and absorber,

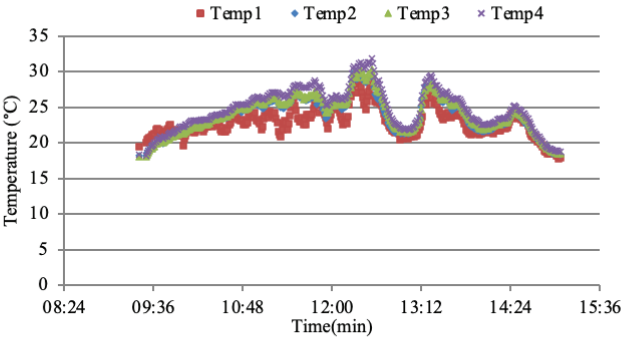


Figure 2. Collector temperature evolution.

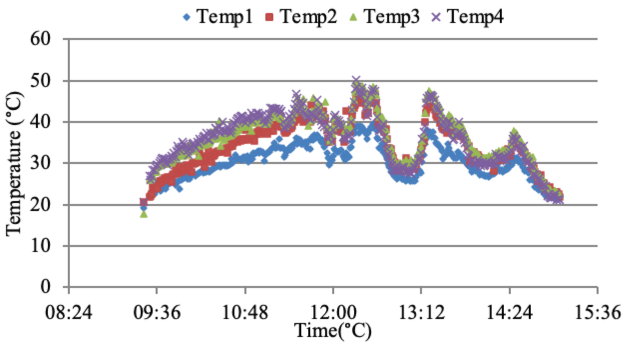


Figure 3. Absorber temperature evolution.

as shown in Figure 4. When the diameter decreases, the air temperature increases. These findings are in agreement with experimental and numerical findings reported in the literature [3, 22]. Noting that the temperature difference between T4 and T1 is not as significant as that noted in the absorber. The amount of heat collected by the absorber is related to solar radiation and has a significant impact on the air temperature at the collector's output [4]. The rise in air temperature in the collector causes air velocity to increase, increasing the air's kinetic energy [23].

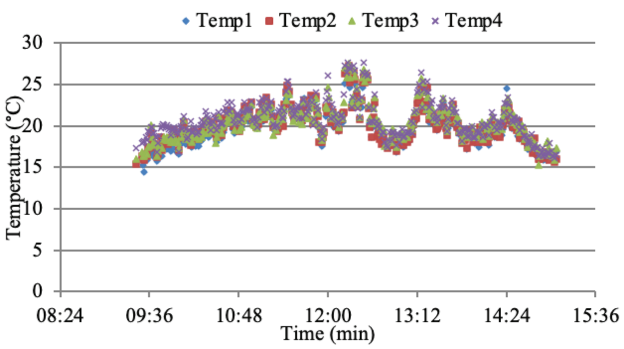


Figure 4. Air temperature evolution.

Air Temperature Evolution in the Chimney

Figure 5 illustrates the evolution of the chimney air temperature in the four locations noted. These temperatures have the same appeal as those observed in the air, the absorber, and the glass; they present a maximum value at 12h 30 min. Throughout the experiment, the temperature at the bottom of the chimney (Temp1) takes the highest value, followed by Temp2, Temp3, and finally Temp4. According to its axis, the temperature inside the chimney depends on its position; it decreases until it reaches the outside temperature. The same results were noted in the literature [24, 25].

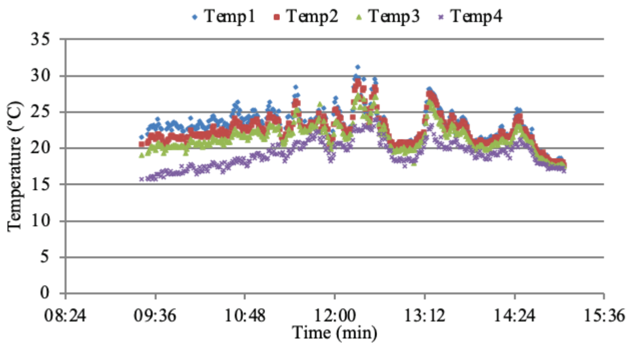


Figure 5. Air temperature evolution in the chimney.

To see the effect of the point position on the temperature variation, the temperature evolution in the chimney was presented at two times: 12 p.m. and 1:30 p.m., as noted in Figure 6. The temperature in the chimney degrades following a linear law according to the position, which varies according to the conditions (solar radiation, ambient temperature). At 12 p.m., the temperature evolution in the chimney is given by the following equation:

$$Tch(x) = -2.07 \times x + 29 \quad (R^2 = 0.94) \tag{1}$$

Where Tch(x) is the chimney temperature at the location x. This equation presents degradation in the chimney temperature following a linear evolution with a coefficient of correlation (R^2) of 0.94. At 1:30 p.m., the change in temperature is also expressed by a linear relationship R^2 of 0.91. It is of the form:

$$Tch(x) = -0.91 \times x + 24.05 \quad (R^2 = 0.91) \tag{2}$$

Absorber, Collector, and Air Temperature Evolution Based on Position

Figure 7 shows the temperature evolution of the collector, the air, and the absorber in relation to the four temperature sound positions. For all four positions, these three

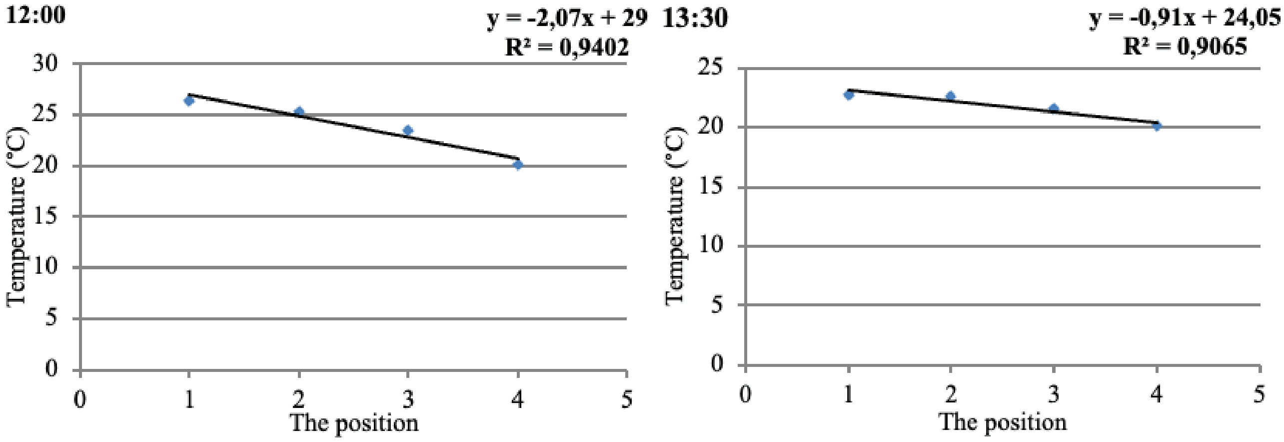


Figure 6. Temperature evolution in the chimney as a function of the position for two different times.

temperatures follow the same trend. Additionally, throughout time and in all locations, the absorber's temperature is higher than the air and collector temperatures [3, 4, 26].

The evolution of ambient temperature and the average temperatures of the collector, air, absorber and chimney over the time is shown in Figure 8. It was seen that all average temperatures follow the same trend, which is also noted in all positions as mentioned above (3.3) and were higher than the ambient temperature. The absorber displays the highest average temperature values than mean air and collector temperatures. The mean air temperature displays the lowest values, as shown by each position. The same collector, air, and absorber temperature behavior has been seen in the Aurybi et al., [6] model on the Manzanares prototype. It was also reported by Roozbeh et al., 2011[26] and Ayed et al., [22]. The air inside the solar chimney expands and

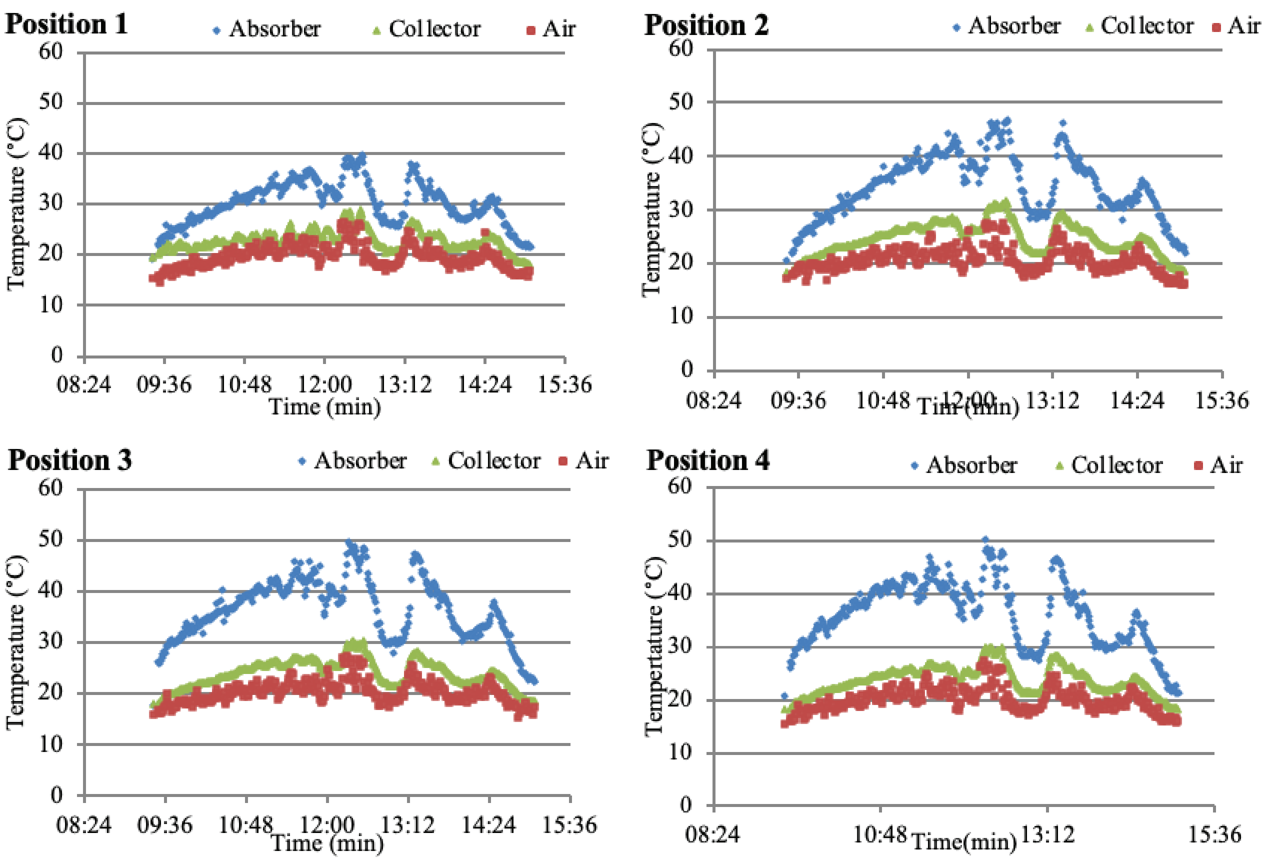


Figure 7. Temperature evolution (collector, absorber and air) in the four positions.

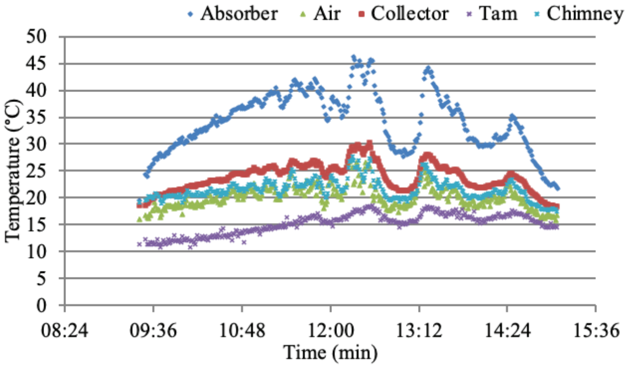


Figure 8. Mean temperature evolution (collector, absorber and air).

speeds up as a result of the rise in air temperature caused by the increase in absorber and collector temperatures based on the increase in solar radiation. The average chimney temperature was somewhat higher than the air mean temperature. The temperature difference between these two temperatures ranges from 0 to 4.68 °C.

The average absorber temperature follows the same trend as the average collector temperature; the absorber average temperature rises as the average collector temperature rises, with a difference ranging from 1.03°C to 17.23°C according to climate circumstances (solar radiation, ambient temperature, and wind speed). These average absorber and collector temperatures are linked by a linear law (Figure 9) as follows:

$$Tabs = 2.07 \times Tcol - 15.052 \ (R^2 = 0.934) \tag{3}$$

The average air temperature follows the average absorber temperature as well; it rises as the average absorber temperature rises (Figure 10a), with a temperature difference ranging from 0.33 °C to 7.9 °C. The average air temperature follows an exponential evolution based on the average absorber temperature noted as:

$$Tair = 11.718 \exp(0.0157 \times Tabs) \ (R^2 = 0.6311) \tag{4}$$

Furthermore, as the collector's average temperature rises, the air's average temperature rises as well (Figure 10(b)), following an exponential form evolution noted as:

$$Tair = 8.2336 \exp(0.0371 \times Tcol) \ (R^2 = 0.7673) \tag{5}$$

According to Hanna et al., [4], the amount of heat that the absorber absorbs from the sun's radiation has an impact on the average air temperature. The average air temperature is affected by the average temperature of the absorber and collector as well, according to our results.

However, based on the energy balance of the air in the collector and the theoretical analysis of Ali et al., 2013 [27], the equation that characterizes the variation in air temperature is provided by:

$$\frac{dT_{air}(r)}{dr} = 2\pi k_2(T_{col}(r) - T_{air}(r)) - 2\pi k_3(T_{air}(r) - T_{abs}(r)) \tag{6}$$

T_{col} (r), T_{air} (r) and T_{abs} (r) are the temperatures of the collector, air and absorber at the radiant r, respectively. The variables K_2 and K_3 are defined as:

$$k_2 = \frac{h_{col-air}}{C_p\dot{m}} \tag{7}$$

$$k_3 = \frac{h_{air-abs}}{C_p\dot{m}} \tag{8}$$

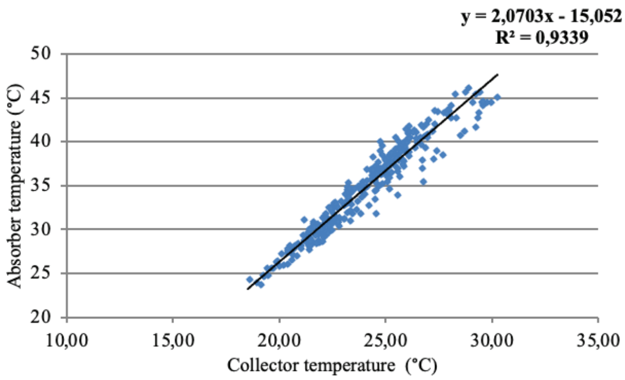
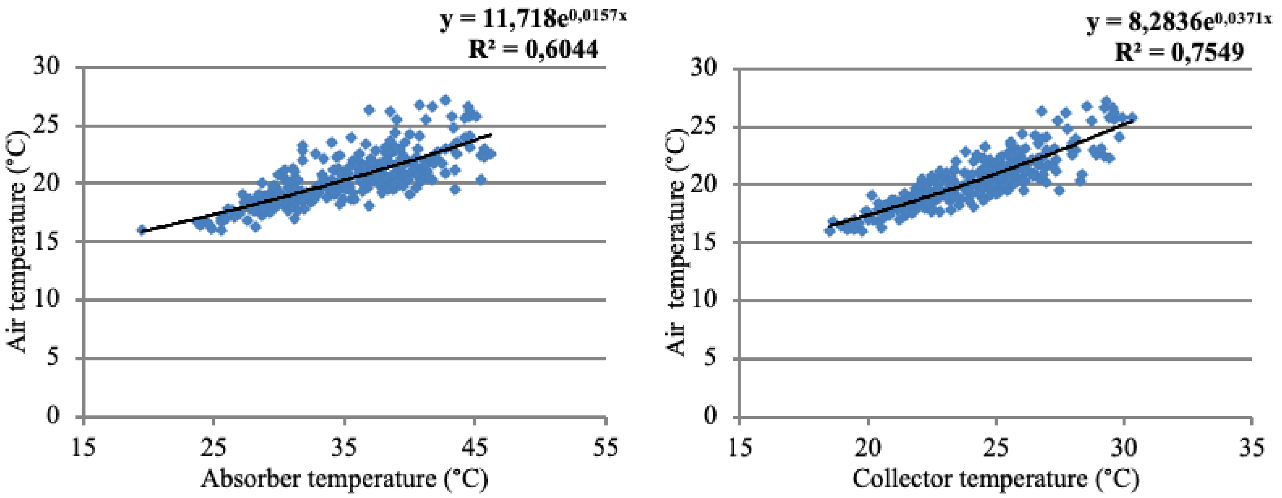


Figure 9. The mean absorber temperature variation depending on the mean collector temperature.

Where $\dot{m}$ and C_p are the air mass flow rate and the air specific heat respectively. $h_{col\text{-}air}$ and $h_{air\text{-}abs}$are the convective heat coefficients for collector–air and air-absorber, respectively.

It is evident that the two temperatures (that of the absorber and the collector) determine the air's temperature. Because of this, increasing the absorber's temperature is necessary to speed up airflow. Additionally, selecting a material with good thermal conductivity and capacity is necessary to ensure that the heat received during the day is recovered during the night, increasing the solar chimney's efficiency.

A mathematical model has been developed that describes the evolution of the average air temperature in relation to the average temperatures of the absorber and collector using Matlab software. Equation (9) presents the developed model; it presents a coefficient of determination (R^2) of the order of 0.84, which justifies the validity of the proposed model in describing the average temperature of the air as a function of those of the absorber and collector.



(a) **(b)**

Figure 10. The mean air temperature variation depending on the mean absorber temperature (a) and the mean collector temperature (b).

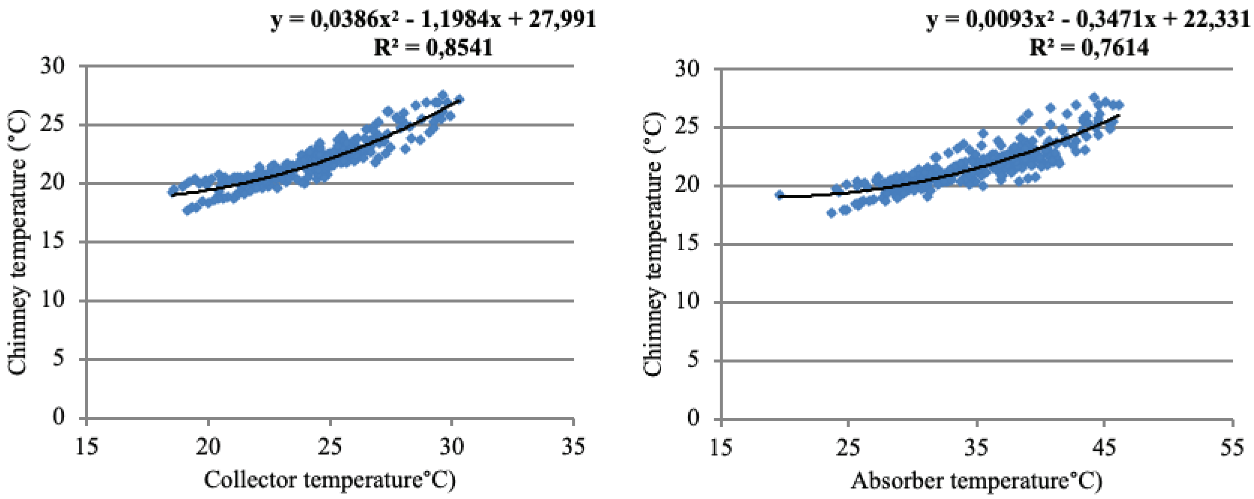
$$Tair = 8.1 + 1.522 \times \exp(0.09382 \times Tcol) - 0.02893 \times \exp(0.1244 \times Tabs)\ (R^2 = 0.8381) \quad (9)$$

The average collector temperature has an impact on the average chimney temperature (Figure 11a). It follows a polynomial law of form, increasing in step with the average collector temperature increase as noted in equation (10). Also, the average absorber temperature has an impact on the average chimney temperature (Figure 11b). It follows a polynomial law of form, increasing in step with the average absorber temperature increase as follows:

$$Tch = 0.0386 \times Tcol^2 - 1.198 \times Tcol + 27.991\ (R^2 = 0.8541) \quad (10)$$

$$Tch = 0.0093 \times Tabs^2 - 0.3471 \times Tabs + 22.331\ (R^2 = 0.7614) \quad (11)$$

So the mean chimney temperature is affected by the mean collector and absorber temperatures. Based on these two relationships (10) and (11), in the same way (as equation (9)) a mathematical model is carried out to describe how the average air temperature in the tower changes in



(a) (b)

Figure 11. The mean chimney temperature variation depending on the mean collector temperature (a) and the mean absorber temperature (b).

proportion to the average air temperature of the absorber and collector. This model is described by the following formula:

$$Tch = 22.09 - 0.8424 \times Tcol + 0.007373 \times Tcol^2 + 0.06035 \times Tabs - 0.01435 \times Tabs^2 + 0.03672 \times Tcol \times Tabs \quad (R^2 = 0.868) \tag{12}$$

This model has a coefficient of determination (R^2) of the order of 0.868, indicating that this model well reflects the evolution of the mean air temperature of the tower in relation to the collector and absorber's temperatures.

CONCLUSION

This experimental study examines the effects of mean absorber and collector temperatures on the mean air and chimney temperatures. Experiments were conducted at the University of Biskra using a solar chimney prototype with the following specifications: 0.50 m for the collector's radius, 10 cm for the collector's height, 10 cm for the chimney radius, and 1 m for the chimney's height. The temperature at the various study points has been measured using temperature measurement systems. These systems consist of temperature sensors (DS18B20 type) connected to Arduino cards, which allow measurements to be taken every minute. These are the points that this study has allowed us to remember:

The temperatures of the absorber, collector, and air follow the same pattern and vary depending on their position on the radius of the collector (or absorber). These temperatures vary with time (depending on solar radiation, ambient temperature, and wind speed), and they increase in the direction of the chimney.

The air temperature in the chimney also varies depending on the weather conditions (climatic conditions). The evolution of the temperature in the chimney follows the same pattern; it degrades following a linear law depending on the position. Each time the height increases, the temperature decreases.

The absorber, collector, and air mean temperatures follow the same trend throughout the experimental period. The absorber's mean temperature rises in accordance with the collector's mean temperature rise, according to a linear law with a coefficient of determination (R^2) of 0.934.

The mean air temperature rises in tandem with the mean absorber and collector temperatures. A mathematical model that describes the mean air temperature in relation to the mean absorber and collector temperatures has been proposed. This model follows an exponential law and has a coefficient of determination (R^2) of 0.84.

Additionally, the mean temperature of the chimney rises in tandem with the mean temperatures of the absorber and collector. A mathematical model has been proposed that describes the mean temperature of the chimney as a function of the mean temperature of the absorber and the collector. It follows a polynomial law and has a coefficient of determination (R^2) of 0.87.

The air's temperature rises as a result of the collector and absorber's increased temperatures, which also increase the air velocity. As a result, there is an increase in its mass flow rate and, consequently, in its performance (efficiency and output power). So the absorber temperature is a key parameter that affects the solar chimney performance. Also, it is possible to take advantage of the rise in the chimney's temperature by employing recovery equipment to recover this energy.

NOMENCLATURE

C_p	Air specific heat, kJm^{-3}K
$h_{air\text{-}abs}$	Air-absorber convective heat coefficient, W/m²K
$h_{col\text{-}air}$	Collector–air convective heat coefficient, W/m²K
$\dot{m}$	Air mass flow rate, kg/s
r	The radiant, cm
R^2	Coefficient of determination
T	Temperature, °C
T_{abs}	Absorber temperature, oC
T_{amb}	Ambient temperature, oC
T_{ch}	Chimney temperature, oC
T_{col}	Collector temperature, oC

Subscripts

abs	Refers to absorber
air	Refers to air
ch	Refers to chimney
col	Refers to collector
1,2,3,4	Refers to the position

AUTHORSHIP CONTRIBUTIONS

Authors equally contributed to this work.

DATA AVAILABILITY STATEMENT

The authors confirm that the data used during this study are available from the corresponding author upon reasonable request.

CONFLICT OF INTEREST

The author 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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