Experimental study of performance dependence on absorber and number of air inlets of solar updraft tower

Rabie Naceur[1,*], Amaria Ould Abbas[1],
Mohamed Amine Bezzerrouk[2], Mohamed Bousmaha[2],
Ahmed Akriche[2], Khaled Djakhdane[3], Ismail Hattabi[3]

1. Laboratoire de matériaux et énergies Renouvelables, département de Physique, Faculté des Sciences, Université Abu Bakr Belkaid, B.P 119, Tlemcen-13000, Algérie

2. Conception of Materials and Electronic Devices in Diagnostic in Veterinary Medicine, Reproduction of Farm Animals LABORATORY, Veterinary Sciences Institute, Ibn Khaldoun University, Tiaret-14000, Algeria

3. Physics Department, Faculty of Materials Sciences, Ibn Khaldoun University, Tiaret-14000, Algeria

rabie_nacer@yahoo.fr

ABSTRACT. *The objective of this study is to investigate the effect of absorber material under collector and number of air inlet in the collector of small pilot solar chimney power plant. Experimental prototype setup in Tiaret, Algeria, was constructed which consisted of a chimney with 6 m height and 3 m diameter of collector. The study focused to carry out several measurements such as air velocity, air temperature and humidity inside the station. From results, it was found that the black plastic as absorber and two air inlets are the appropriate parameters for this study. The air temperature increased to reach a maximum value of 78 °C, which generates an updraft air velocity in the chimney with a maximum value of 2.8 m/s. These results can be used as reliable study of the performance and the efficiency of solar chimney power plant.*

RÉSUMÉ. *L'objectif de cette étude est d'étudier l'effet du matériau absorbant sous le collecteur et le nombre d'entrées d'air dans le collecteur d'une petite centrale solaire à cheminée. Un prototype de montage expérimental a été construit à Tiaret, en Algérie, avec une cheminée contenant un collecteur de 6 m de hauteur et de 3 m de diamètre. L'étude s'est concentrée sur plusieurs mesures telles que la vitesse de l'air, la température de l'air et l'humidité dans la station. Les résultats ont montré que le plastique noir utilisé comme absorbeur et deux entrées d'air sont les paramètres appropriés pour cette étude. La température de l'air a augmenté pour atteindre une valeur maximale de 78 ° C, ce qui génère une vitesse de l'air dans la cheminée avec une valeur maximale de 2,8 m/s dans la cheminée. Ces résultats peuvent être utilisés comme une étude fiable des performances et de l'efficacité d'une centrale solaire à cheminée.*

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KEYWORDS: solar chimney, collector, temperature, air velocity, humidity.

MOTS-CLÉS: cheminée solaire, collecteur, température, vitesse de l'air, humidité.

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1. Introduction

The rapid increase in population and new technologies, execute the continuous production of energy, fossil fuels account for about 85% (27% coal, 35% oil, and 23% natural gas) of the total energy consumption and 68% of total electricity generation worldwide (Kanoglu, 2015).

Fossil fuels are non-renewable sources of pollution, this is why the researchers help with the development of the clean and renewable power station of energy production, which do not pollute. The challenge, at the present time, is to find systems of production of energy, which do not generate the preceding problems. Of this concept, it is thus necessary to develop means of exploiting renewable energies.

The solar chimney power plant (SCPP) is a technology allowing the conversion of solar energy into electricity. The power station with solar chimney consists of three essential components, the solar heat collector, the chimney (the tower) and the turbine. The solar chimney used the force of an ascending draft. The solar rays heat the greenhouse, the hot air becomes lighter than the surrounding air circulates until worms the tower while passing by turbines, and those transform the energy of the flow of air into mechanical energy and actuate generators to produce electricity.

The concept of the solar chimney has been proposed for more than 100 years. In 1903, Isidoro Cabanyes, a colonel of the Spanish army, was originally proposed a solar stack power station, in the store "La energia elèctrica" (Lorenzo, 2002). In 1931, a German researcher, Hanns Günther advanced a solar chimney energy generation technology, this technology simply used the chimney effect and the greenhouse effect to drive a turbine. The first experimental work in the SCPP was built in Manzanares, Spain in 1982, by a German structural engineering company, Schlaich Bergermann. The plant had a collector diameter of 244 m and 194.6 m height, 10 m diameter of the chimney, to produce 50kW peak (Haaf *et al.*, 1983), this prototype was in operation from 1982 to 1989 (Trieb *et al.*, 1997).

Pasurmarthi and sheriff (1998), built and designed a demonstration model for solar chimney in Gainesville, Florida, with a collector radius of 9.15 m and a chimney height of 7.92 m, and examined its theoretical and experimental performance, tow experimental were tried the collector and the absorber. The modification helped increasing the air temperature as well as the mass flow rate inside the chimney. Mathematical model results were validated by comparing them to published data on the solar chimney system built in Manzanares, Spain. Zhou *et al. (*2007, 2008) build small pilot solar chimney power plant consisted of collector 10 m in diameter and an 8 m height chimney. The air temperature in SCPP was measured. It is found that air temperature inversion shows after sunrise both, on a cool day and on a warm day, temperature difference between the collector outlet and the ambient usually can reach

24.1°C. Kasaeian *et al.* (2011) have designing and making a pilot SCPP with 10 m collector diameter and 12 m chimney height. The study was measured the air temperature and air velocity for some specified places of collector and chimney with varying some parameters on different days. The air inversion at the bottom of the chimney was observed after sunrise, on both cold and hot days. The temperature difference between collector and the ambient achieve to 25°C. Al-Dabbas (2012) built a prototype SCPP consisted of 4 m tall chimney, radius 0.29 m, collector area 36 m^2 with 1 m height, wind turbine installed in chimney with a diameter 0.5 m and a small generator 6 V. The pilot given measurement of air velocity, air temperature, solar radiation and voltage difference. The result in this study experimental show that the maximum tall chimney and pressure difference gradually increase with the solar radiation. A small pilot of SCPP with a chimney height of 3 m, a diameter of 10 cm and a collector of 2 m, was constructed at University of Tehran (Kasaeian *et al*., 2014). The numerical model was validated through comparison with the experimental data of the SCPP. The result indicated that the height and diameter of the chimney are the most important physical variables for solar chimney design. Ghalamchi *et al.* (2015) presented an experimental study of geometrical and climate effects on the performance of a small solar chimney.

The maximum air velocity of 1.3 m/s was recorded inside the chimney, while the collector entrance velocity was around zero. The temperature difference between the chimney inlet and ambient reached to 26.3°C. A year later, an experimental study on the thermal performance of a solar chimney with the same prototype, was studied in different dimensional parameters (Ghalamchi *et al.*, 2016). Many researchers have theoretically scrutinized the solar updraft tower performance.

An enhanced numerical model of heat transfer in a pipe with the twisted tape in the turbulent regime was carried out for various twist ratio. The velocity field in terms of axial, tangential and radial velocity and temperature field were studied with the twist severity and Reynolds number as governing parameters. The tangential velocity increases with the distance from the center of the pipe and affects the thermal and velocity boundary layer. The numerical results are correlated for the friction factor and Nusselt number and show good agreement with the experimental data (Chaware *et al.*, 2017)

Ming *et al.* (2008) introduced a numerical analysis on the performance of the solar chimney they found that the heat storage ratio, the relative static pressure decreases while the velocity increases significantly inside the system and the average temperature of the chimney outlet increases with the solar radiation increasing from 200 W/m^2 to 800 W/m^2. Patel *et al.* (2015) studied the geometry of the SCPP using a computational fluid dynamics (CFD) software, the study improves the flow inside the SPP consisted 10 m height to the chimney and 8 m diameter to the collector, the collector inlet opening was varied from 0.05 m to 0.2 m. The collector outlet diameter was also varied from 0.6 m to 1 m. The different divergence angles varied with 0° and 3°, the diameter of the chimney was also varied from 0.25 m to 0.3 m. The results indicated that the best configuration was achieved using the chimney with a divergence angle of 2°, and chimney diameter of 0.25 m together with the collector opening of 0.05 m and collector outlet diameter of 1 m. Kasaeian *et al.* (2017)

compared a CFD simulation with the experimental data of the Manzanares solar chimney to show the effects of the turbine rotational speed, the quantity of turbine blades, the collector diameter and the chimney height. These runs were based on 3, 4 and 5 blades, rotational speeds of 40, 80 and 100 rpm, chimney heights of 100, 200 and 300 m and collector diameters of 122, 244 and 366 m. The results show that, with a fixed number of blades, increasing the rotational speed would decrease the mass flow rate of air and the chimney height and collector diameter increasing intensifies the mass flow rate and power output.

The objective of this work is to optimize several parameters such as absorber material under collector, number of air inlet in the collector of small pilot solar chimney power plant installed in Tiaret, Algeria. Air temperature, humidity and air velocity were measured at an interval of ten minutes for a whole day during period from April to June. We note that we took the results of a few sunny days to obtain maximum yield of our prototype.

The remainder of this research is organized as follow: experimental setup section describes the construction of our experimental solar chimney using different materials and electronic devices for measurement; the next section presents the results and discussion; the last section summarizes our work by a conclusion.

2. Experimental set-up

2.1. Solar chimney setup

An experimental solar chimney setup consists of:

- Air sloped collector with angle equal to 30° and 3 m in diameter which covered by low density polyethylene (LDPE) in order to achieve Greenhouse effect. The melting point of commercial LDPE for average is typical 105 to 115 °C.

- Black plastic and aluminum materials were used as absorbers under the collector because of their efficient thermal and high reflection properties respectively.

- Chimney with 6 m height, 110 cm in diameter and 3.2 mm of thickness was fabricated by polyvinyl chloride (PVC) because of its high resistance to heat transfer. Details of sizes in the solar chimney are regrouped in Table 1. Some characteristics of PVC are regrouped in Table 2 (Jemli *et al.*, 2017).

- Internal structure was built by iron because of its economic price and robustness property.

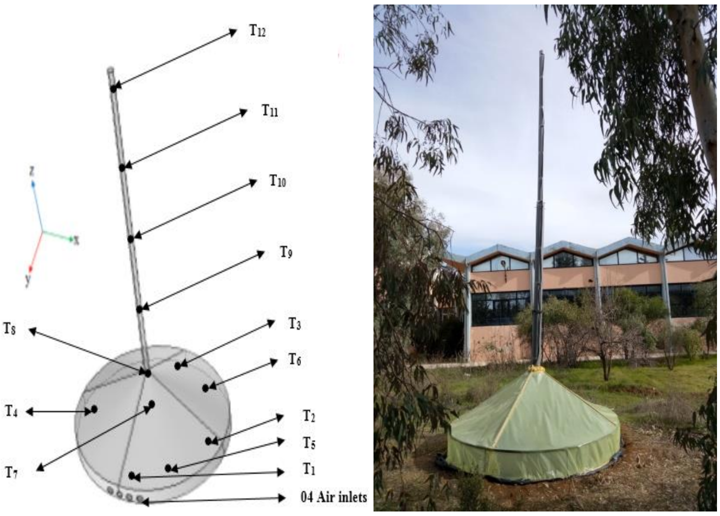
Table 1. Geometrical parameters of solar chimney setup

Parameters	**Size (cm)**
Collector height	115
Collector diameter	300
Chimney height	600

Chimney thickness	0.32
Chimney diameter	11
Air inlet diameter	11
Air outlet diameter	11

Table 2. Characteristics of PVC

Property	Value	
Glass-transition temperature	81 °C	(Ribelles *et al*., 1987)
Melting temperature	115-245 °C	(Summers, 2008)
Density	1380 Kg/m3	(Jemli, 2016)
Heat capacity	500 J/ kg.K	
Heat conduction	0.14 W/ m.K	
Emissivity	0.91	



(a) (b)

Figure 1. (a) Prototype of solar chimney; (b) Temperature sensors in prototype

Our experimental solar chimney was constructed on the park of Ibn Khaldoun University in Tiaret, Algeria (35°21’00.0”N 1°18’47.2” E) (Figure 1a). Twelve (12) temperature sensors were installed in the station according to the locations mentioned in Figure 1b.

2.2. Measuring devices and data processing

- The thermo-Hygro-Anemometer PCE-THA 10 (2016) was used to measure temperature, humidity and air velocity with the included software and USB cable to computer Figure 2a. Technical data for this device is summarized in Table 3.

- The LM35 (2016) is an integrated –circuit temperature sensor, with an output voltage which is linearly proportional to the Centigrade temperature. The LM35 is rated to operate over a -55°C to +150°C temperature, it has very low self-heating, less than 0.1°C in still air. (Figure 2b).

- An Arduino Mega microcontroller (2016) (Figure 2c) was used in this work as a development platform which is based on the AT mega 1280. It has 54 digital input/output pins, 16 analog input, 4 UARTs (hardware serial ports), a 16 MHz crystal oscillator, a USB connection.

(a) (b) (c)

Figure 2. (a) The thermo-Hygro-Anemometer PCE-THA 10; (b) The temperature sensor LM35; (c) Arduino Mega microcontroller

Table 3. Technical data for the thermo-hygro-anemometer PCE-THA 10

Temperature	
Measuring range	-15 ... +50 °C
Accuracy	± 0.6 °C
Resolution	0.1 °C
Wind Speed	
Measuring range	0.4 ... 35 m/s
Accuracy	± 3 %
Units	m/s
Humidity	
Measuring range	5 ... 95 % r.H.

Accuracy	± 3 % r.H. (25 °C, 30 ... 95 % r.H.) ± 5 % r.H. (25 °C, 10 ... 30 % r.H.)
Resolution	0.1 %
Operating Conditions	Temperature: 0 ... +50 °C Humidity: <80 % r.H.
Dimensions	244 x 77 x 43 mm

3. Results and discussion

This study was devoted to optimize the solar chimney power by investigating some different condition to obtain a maximum energy. The experience is started from April to June to enjoy the best climate conditions. Two parameters were chosen to be optimized:

- The number of air inlets.
- The absorber material (ground).

About the air inlet, we used a circle form, which had the same section of air outlet of the chimney, the number of air inlets was between 01 and 05, which were localized in the opposite direction of the prevailing wind. Aluminum and black plastic were used as absorber material, the first one due to the rate of reflection of sunrays (>90%). The second one is good heat’s absorber, which helps to warmed up the air.

3.1. Absorber’s material efficiency

From our experimental results, Figure 3 represents the variation of air temperature from sensor T3 as function as time for the two absorbers, black plastic and aluminum. We can see with the black plastic that the air temperature can exceed 78 °C at the time period between 10:00h to 18:00h and it is clearly seen that there is more stability in the air temperature evolution. With aluminum ground, the air temperature increased quickly inside the collector where it reached up 70°C due to its high reflection property but there is a disruption in the air temperature evolution. For this study, we have used the black plastic as absorber material because of its excellent characteristics in this field.

3.2. Optimization of air inlets numbers in the collector with black plastic absorber

The most interesting objective in the solar chimney power plant (SCPP) is to have the optimum energy efficiency to produce electricity, using turbine in the entrance of the chimney. Air velocity is a product of airflow under the collector coming from outside environment by the greenhouse effect. The Figures (4-6) show the variation of air temperature, air velocity and humidity versus numbers of air inlets (from 01 to 05), in a time period of 24 hours (full day). The operational time (t), time period (Δt), maximum of air temperature (Tmax) and maximum of air velocity (Vmax) are regrouped in Table.4. From our results, we can see clearly that airflow started from 06:45h– 07:00h to 19:00h-21:00h with an operational period of 12 to 13 hours. We observed that there is airflow in the night from 00:00h to 06:00h (Especially for 02 and 05 air inlets); this is due of the external wind that there was no relationship with the airflow produced by greenhouse effect. About the air temperature versus number of air inlets, we can remark that it varied from 74 °C to 78 °C, and about the maximum air velocity versus number of air inlets, we have values from 2.5 m/s to 2.8 m/s. By analyzing these results carefully, we have seen that the choice of 02 air inlets is good for this study.

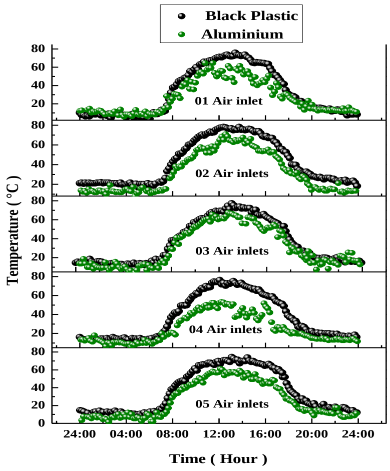


Figure 3. Variation of air temperature versus time for two absorbers, black plastic and aluminum

Table 4. Operational time period, Δt, Tmax, Vmax for four air inlets

Nbr of Air inlets	Operational time Period	Δt	T_{max} (°C)	V_{max} (m/s)
01	07^h:00 to 19^h:00	12Hours	76	2.5
02	07^h:00 to 19^h:30	12Hours + 30 min	78	2.8
03	07^h:00 to 20^h:00	13 Hours	77	2.6
04	07^h:20 to 21^h:00	13 Hours + 20 min	76	2.6
05	06^h:45 to 20^h:00	13 Hours + 15 min	74	2.5

Nbr of Air inlets	Operational time Period	Δt	T_{max} (°C)	V_{max} (m/s)
01	07^h:00 to 19^h:00	12Hours	76	2.5
02	07^h:00 to 19^h:30	12Hours + 30 min	78	2.8
03	07^h:00 to 20^h:00	13 Hours	77	2.6
04	07^h:20 to 21^h:00	13 Hours + 20 min	76	2.6
05	06^h:45 to 20^h:00	13 Hours + 15 min	74	2.5

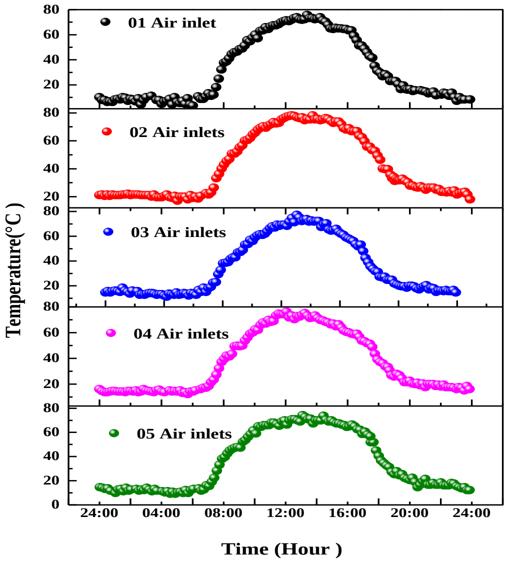


Figure 4. Variation of air temperature versus time with various numbers of air inlet

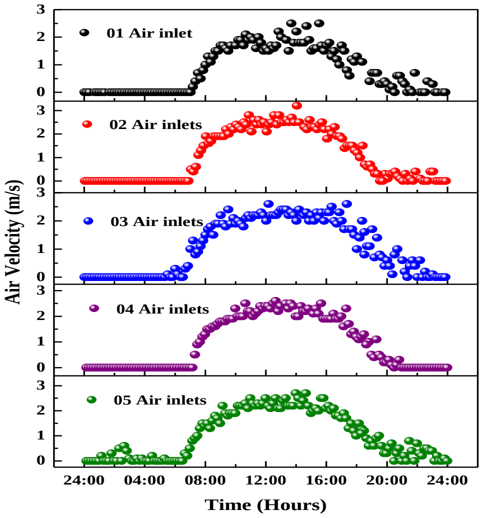


Figure 5. Variation of air velocity versus time with various numbers of air inlet

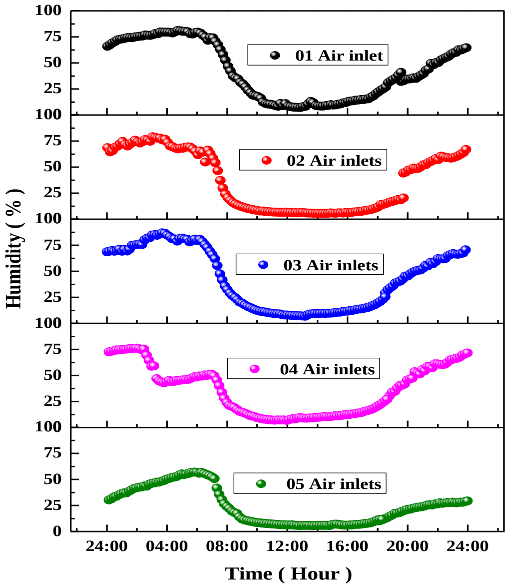


Figure 6. Variation of humidity versus time with various numbers of air inlet

3.3. Variation of air temperature, air velocity and humidity using black plastic and (02) air inlets throughout full day

3.3.1. Air temperature changes

In this experimental work, we chose twelve typical points where our sensors (T1 to T12) were used to measure the air temperatures in the solar chimney. Two other air temperature sensors (T13, T14) were placed in outside of station to measure the ambient temperature under sun and shade respectively (Figure 7). The air temperature changes were obtained during a full day. According to Figure 8 which illustrates the variation of air temperature in the collector and along the chimney, we note that the topology of the graphs is the same for the all sensors, we can see clear that there is an increasing of air temperature from sensors T1 to T6 corresponding to the incoming cold air from outside, at the same time there is a decreasing of air temperature along the chimney (sensors T8 to T12) because of the cooling by the internal walls of chimney. As a result, three zones are distinguished from the variation of the air temperature for each sensor during 24 hours. The first interval between (00:00h to 08:00h) and (20:00h to 00:00h) or a stable air temperature is noted and it is of the order of 15°C for all sensors. The second area from 08:00h in the morning until 14:00h in the evening, where we have a remarkable increase in air temperature going from 15 °C up to 78 °C for the sensors which is at the level of collector and this due to the increase of solar radiation. Finally, we have a loss of air temperature in the period from 14:00h to 20:00h this is due to the drop in solar radiation.

We can also notice that we have an air temperature gradient between the sensors located at collector (T1 to T7) and chimney (T8 to T12) and those are outside of the collector (T13, T14). This gradient will generate airflow (heated air inside solar chimney to cold air outside) this phenomenon creates an air velocity, which can be used to turn a turbine for electricity production. The variation of air temperature is in good agreement with those.

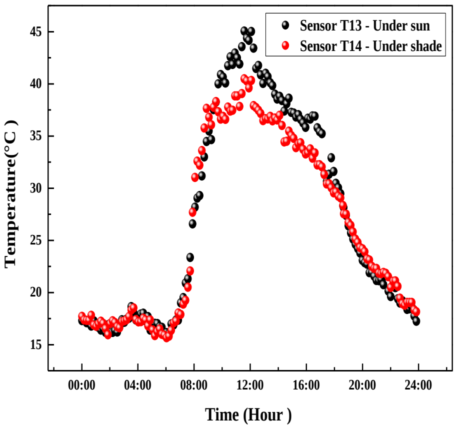


Figure 7. Variation of air temperature versus time under sun and shade

3.3.2. Air velocity changes

Figure 9 shows the variation of the air velocity along full day for two air inlets. It is clearly seen that the air velocity evolution has the same topology with air temperature evolution. The airflow started from 07:20h to 21:00h with time period of thirteen hours and twenty minutes, this result is in better agreement with those found by Ghalamchi *et al.* (2016) and Nasirivatan *et al.* (2015). We can note that air velocity reached up a maximum in the time between 12:00h and 15:00h, this period corresponds to the high sunshine and high air temperature.

3.3.3. Humidity changes

Moreover, we studied the impact of humidity on the operating potential and efficiency of the solar chimney power plant. The presence of Humidity in the air under the collector slowing down the adiabatic thermodynamic phenomenon that decreases the temperature and accelerates the decrease in the density of updraft air (Ninic, 2006). The humidity plays a very important role especially for the areas located near the sea. Figure 10 shows the evolution of this parameter for 24 hours under the collector of the solar chimney. From this figure, we distinguish three zones, the first zone from 00:00h to 05:00h, where humidity rate is greater than 80 % and that is due to air saturation with water vapor, while in the second zone, humidity decreases to reach its minimum of 6 % at 12:00h. This value indicates that the air become very dry. Finally, the third zone from 16:00h until the night where one can notice an increase of the humidity.

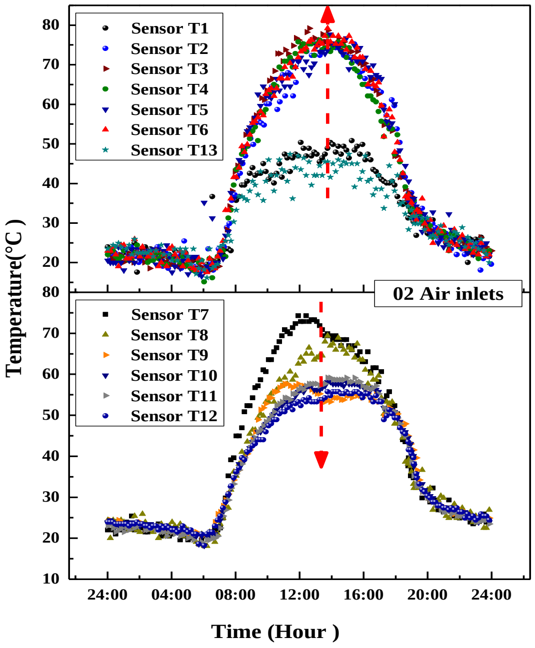


Figure 8. Variation of air temperature in collector and along chimney throughout full day for two air inlets

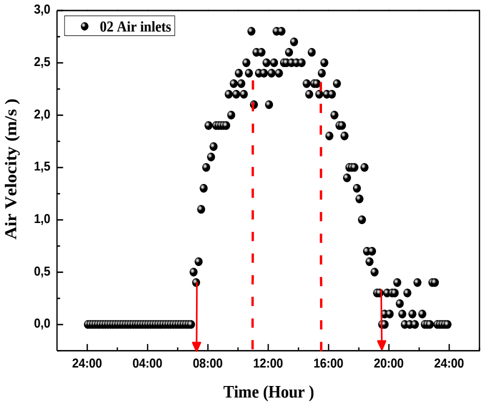


Figure 9. Variation of air velocity throughout full day for two (02) air inlets

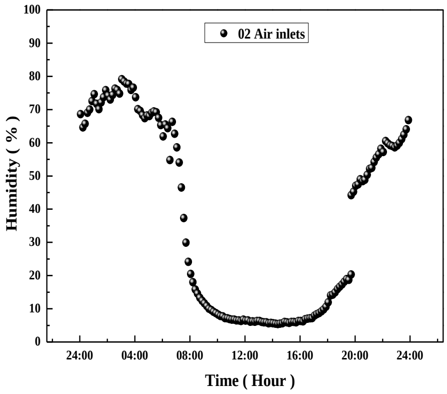


Figure 10. Variation of humidity throughout full day for two (02) air inlets

3.4. Effect of air temperature on air velocity and humidity

3.4.1. Air velocity versus air temperature

In this section, we study the dependence of air velocity on air temperature. The variation of air velocity is plotted as function of air temperature in Figure 11. One can distinguish two regions (a) and (b). At air temperatures below 45°C, air velocity indicates a sharp increase, otherwise, for values higher than 45 °C, it increases slowly and tends toward a limit, which means that there is a threshold of air velocity, which cannot be exceeded, this threshold depends on geometry, configuration and dimensions of solar chimney power plant. We note that we have taken the more repeated values for the maximum of air temperatures and air velocity because if we return to graphs we can see that the air velocity reached up the value of 3.2 m/s (02 air inlets).

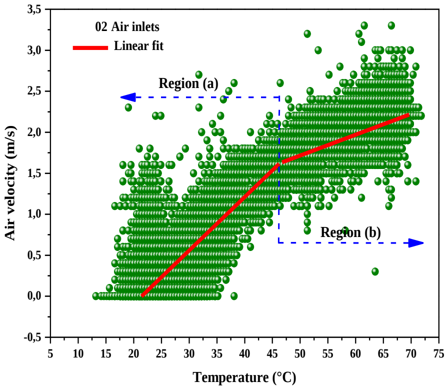


Figure 11. Variation of air velocity as function as temperature

3.4.2. Humidity versus air temperature

Figure 12 gives the variation of the humidity as function of the air temperature. From the graph, it is clear that the humidity is proportionally reversed with the air temperature. In the daytime, we notice a decreasing of humidity due to the increasing of air temperature, at the same time there is an increasing of air velocity, but at night, the opposite phenomenon happens; low air temperature accompanied with high humidity, which causes a decreasing of air velocity. As a result, we can say that humidity plays a negative role in the yield or productivity of the solar chimney power plant.

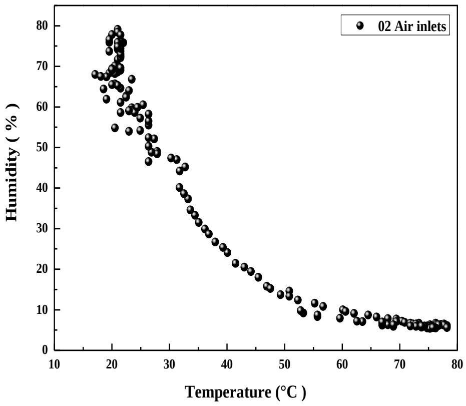


Figure 12. Variation of humidity as function as temperature

4. Conclusion

Solar chimney power plant is considered as renewable power source, which is used as clean source of electricity production. A small experimental solar chimney was built with three meters of collector diameter covering by Low-density polyethylene (LDPE), six meters for chimney height using the Polyvinylchloride (PVC) and two types of absorbers, Aluminum and black plastic. Thermo-Hygro-Anemometer, LM 35 and Arduino maga were used as measuring devices and data processing. We resorted to many factors to achieve this work; climatic conditions such as temperature, time of sunshine, solar radiation. These factors will help to increase air temperature under collector by greenhouse effect, which creates an airflow that can generate electricity. In our optimization, we have found that the black plastic is better than the aluminum to be used as absorber material. The choice of two air inlets is the optimal choice to have a good performance. As results with optimized factors such as air temperature, which reached the value of 78°C and 2.8 m/s of air velocity. These results have opened a large window of research in the field of renewable energy, many works are underway to improve the performance of this kind of energy source.

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