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Experimental and CFD analysis of performance of solar chimney power plant prototype

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Abstract: The solar chimney is a low-temperature power station generating electricity. The most important parameterizes the value of the air velocity along the chimney. A 3D numerical model is developed to estimate and analyze various parameters of the solar chimney power plant prototype set up in Ibn Khaldoun University, Tiaret. Computational simulations have been conducted using the commercial computational fluid dynamics (CFD) code COMSOL 5.2. The turbulence model k-ε was tested to present the distribution of the air flow characteristics such as the velocity, the temperature, the pressure, and the turbulence characteristics. The results were validated by comparing them with the experimental data of the prototype. The results revealed the same value of the velocity in the experimental prototype and numerical model equal 2.5 m/s, the temperature recorded (72-76) °C in the prototype and 72°C in a numerical model. The comparison between the numerical and the experimental results showed a good agreement.

Keywords: Solar chimney; Temperature; Experimental prototype; Greenhouse effects.

1. INTRODUCTION

Nowadays, a permanent evolution of the gas rate with greenhouse effects in the atmosphere is observed. The systems of energies, which pollute are numerous, impose on our environment. Wasting of imposed fossil energies of the constraints of our beautiful planet, 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. From 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.

An extensive literature investigation has been shows based on late developments on the solar chimney power plant. Several SCPP prototypes have been built to analyze various parameters, the ambient condition, the geometrical configuration of the chimney and collector. The first prototype 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 50 kW peak [1]. Pasurmarthi and sheriff [2] in 1997, built for solar chimney power plant in Florida to assess a demonstration model its theoretical and experimental Two experimental modifications were tried on the collector. (1) Extending the collector base and (2) Introducing an intermediate absorber.

Yang et al. [3] has been built a prototype solar chimney power plant consisted 10 m diameter of collector and 8 m height of the chimney. The temperature in the station was measured. Temperature difference between the collector and the ambient temperature usually equal 24.1 °C. Cristiana et al. [4] introduced an experimental study of the airflow inside a solar chimney. The tests were performed in a prototype built on the campus of Universidade Federal de Minas Gerais, consisted 22 m diameter of the collector and 11 m tall of the chimney. The results of temperature, velocity, solar radiation, and humidity in the experimental prototype were controlled over a nine-month period, permitted the characterization of the airflow.

Kasaeian et al. [5] has been making has been making a small pilot solar chimney pilot power plant with 10 m collector diameter and 12 m chimney height. The temperatures and air velocity were measured. The temperature difference between inside the collector and the temperature ambient reached to 25 °C. The maximum air velocity of 3 m/s was recorded in the chimney inlet. Al-Dabbas [6] built the first pilot solar updraft power plant in Jordan, 4m height of the chimney and 3.4 m diameter of the collector. Various parameters were measured the air velocity, temperature, solar radiation, and voltage difference.

Kasaeian et al. [7-9] constructed small solar chimney power plant with 3 m collector diameter and 3 m chimney height in University of Tehran, Iran. The temperature difference between inside the station and ambient temperature equal 26.3 °C to 27 °C. The maximum air velocity was recorded in the chimney inlet reached 1.3 m/s to 1.7 m/s. our study on the effect of latent heat storage (LHS) on the same experimental prototype. Two kinds of experiments including with and without phase change material (PCM) were made, and the various parameters were measured the temperature and the velocity to investigate the solar chimney performance. Paraffin wax was used as a PCM in the solar chimney pilot. The results show that the maximum absorber surface temperature for the solar chimney with PCM are 72°C and the maximum air velocity equal to 2 m/s.

Jemli et al. [10] built solar tower prototype with 8 m of diameter and 2 m of height chimney in Centre of Energy (CRTEn), Borj Cédria, northern Tunisia. The results indicated that when the temperatures equal 45°C, the electric power reaches an average value of about 0.3 W/m^2. Bouabidi et al. [11] investigated the effect of the chimney configuration on the solar chimney power plant. An experimental setup was developed in Tunisia consisted the collector is given by the diameter equal D =2.75 m and 3 m tall of the chimney. The study focused on studying the solar chimney power plants with: standard, divergent, convergent and opposing Chimney. The parameters were introduced the velocity, the static pressure and the temperature. The results show the maximum velocity emerges with divergent configuration.

As to the study of numerical analysis of the solar chimney power plant, many researchers have attained detailed studies on diver's subjects. Ming et al. [12] 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. Kasaeian et al. [13] validated a numerical study by

comparison with the experimental data of a solar chimney prototype was carried out at the University of Tehran.

Patel et al. [14] studied the geometry of the SCPP using a computational fluid dynamics (CFD) software, the study improve 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. [15] 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.

Pritam et al. [16] developed a 3D numerical model to estimate the flow and performance parameters of the solar chimney power plant. Various geometrical parameters are studied, such as chimney height and collector roof angle. The results show concluded that with an increase in collector roof angle, air velocity increases but air temperature decreases. Ayadi et al. [17] studied the effect of the numerical model on the air flow characteristics inside a solar chimney power plant. Five turbulence models were tested by the code Ansys-Fluent 17.0; the simulations have been carried out using the commercial computational fluid dynamics (CFD). The study put the distribution of the air flow characteristics such as the velocity, the temperature, the pressure, and the turbulence characteristics.

Afrand et al. [18] investigated the influences of geometrical properties on a solar chimney power plant by applying the numerical model. The results showed that output power and solar chimney efficiency have positive relationships with chimney height and collector radius but a negative one with collector height.

2. MATHEMATICAL MODEL

Three modes of transferring thermal energy, conduction, convection and radiation transfer in solar chimney power plant, analysis of energy transfer necessitate the application of

conservation of energy principals. More energy conservation laws are expressed in terms of temperature.

Energy conservation equation

$$\frac{\partial(\rho C_p T)}{\partial t}+\frac{\partial(\rho C_p u T)}{\partial x}+\frac{\partial(\rho C_p v T)}{\partial y}+\frac{\partial(\rho C_p w T)}{\partial z}=\lambda(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}) \quad (1)$$

Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \quad (2)$$

To model heat conduction and convection

$$\rho C_p \frac{\partial T}{\partial t}+\rho C_p u \nabla . T=\nabla .(k.\nabla T)+Q \quad (3)$$

For transport conduction and convection, the heat flux vector approximated by

$$q=-k.\nabla T+\rho C_p T u \quad (4)$$

Heat flux

$$n.(k.\nabla T)=q_0+h\left(T_{inf}-T\right)+C_{const}(T_{amb}^4-T^4) \quad (5)$$

Model radiation heat transfer with the surrounding environment

$$C_{const}(T_{amb}^4-T^4) \quad (6)$$

Where;

$$C_{const}=\varepsilon\sigma \quad (7)$$

3. VALIDATION OF THE MATHEMATICAL MODEL

The mathematical model was simulated by the model of surface-to-surface radiation heat transfer which exists in COMSOL 5.2 software. The results obtained from this model were compared with experimental results of the realized prototype consisting of the parameters in Table 1.

Table 1. Geometrical parameters of the solar chimney pilot.

Parameter	Figure index	Size (m)
Chimney radius	$r_{chimney}$	0.110
Collector radius	r_{radius}	0.300
Collector height	$H_{collector}$	0.100
Chimney height	H_{chimny}	0.600

In this study, the phenomenon to be evaluated is natural convection, and the Boussinesq hypothesis was used. Reynolds number (*Re*) is low inside the solar chimney is defined the nature of airflow (laminar flow). More experimental and numerical boundary conditions were also summarized in Table 2.

Table 2. Boundary conditions of the prototype.

Place	Type	Description
Absorber	Wall	q =8 (W/m^2·K)
Collector Roof	Wall	q=8 (W/m^2·K)
Chimney	Wall	$n.k.\nabla T = 0$
Collector inlet	Pressure inlet	T = 313 K
Chimney outlet	Pressure outlet	P = 0 atm

4. EXPERIMENTAL SET-UP

The prototype solar chimney power plant was constructed in University Ibn Khaldoun-Tiaret, Algeria (35.35N; 1.3131 E). The pilot scale solar chimney power plant (SCPP) consists by three components: (03) metre radius of collector, (06) metre height of chimney and ground black (Absorber). The Temperature measuring of the air under collector and in the chimney, we used (12) thermal sensors planted in the collector and chimney, the locations mentioned in Fig. 1a. For performing this study of comparison between the values of the experimental air (temperatures, velocity) and the values of the simulation, we selected a day of 28 May 2017. The climatic conditions are: the ambient temperature T = 39 °C, the wind speed V = 1.11 m/s, H = 30% of humidity level and pressure P = 1018 Pa at 12 pm.

4.1 Solar chimney setup

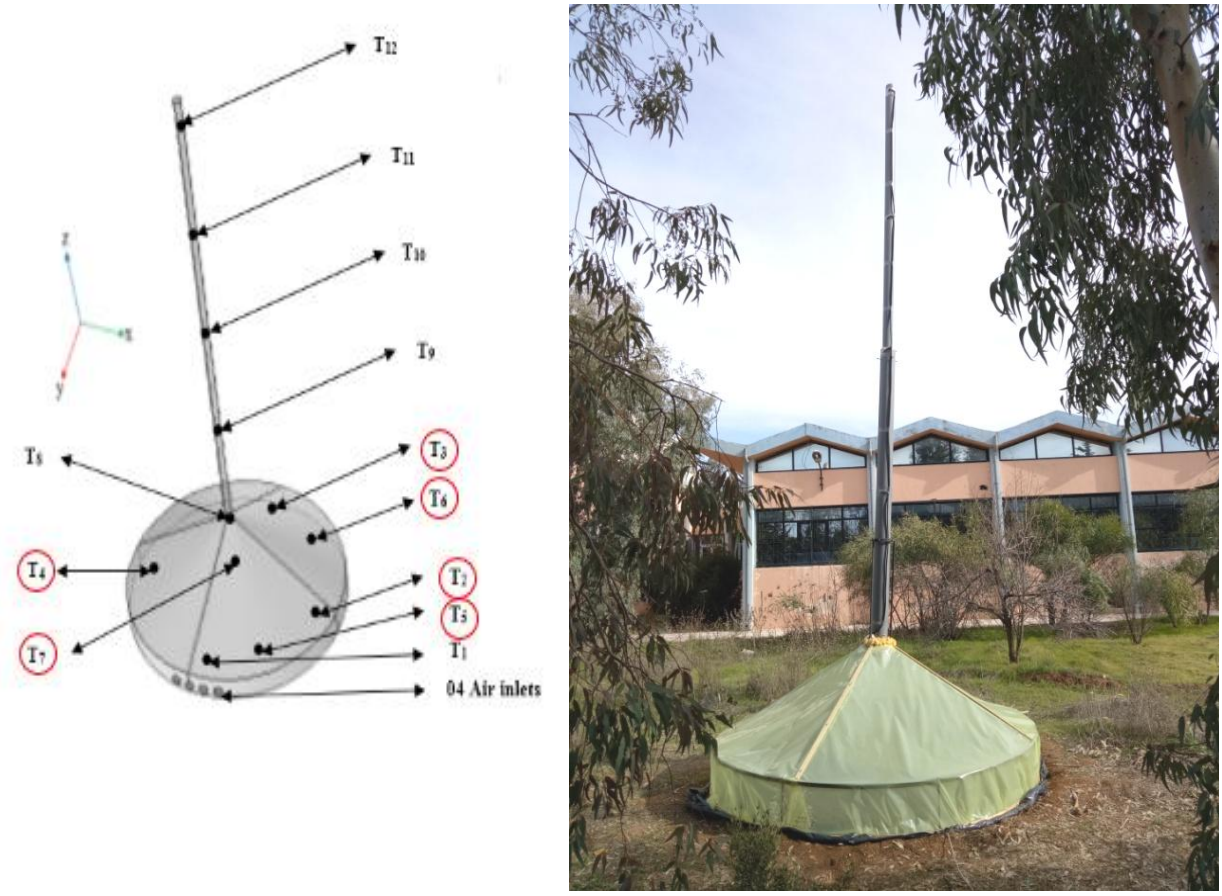
An experimental solar chimney setup consists of:

- 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 m in diameter and 3.2 mm of thickness was fabricated by polyvinyl chloride (PVC) because of its high resistance to heat transfer.

- Internal structure was built by iron because of its economic price and robustness property as shows in Fig. 1b.

4.2 Measuring devices and data processing

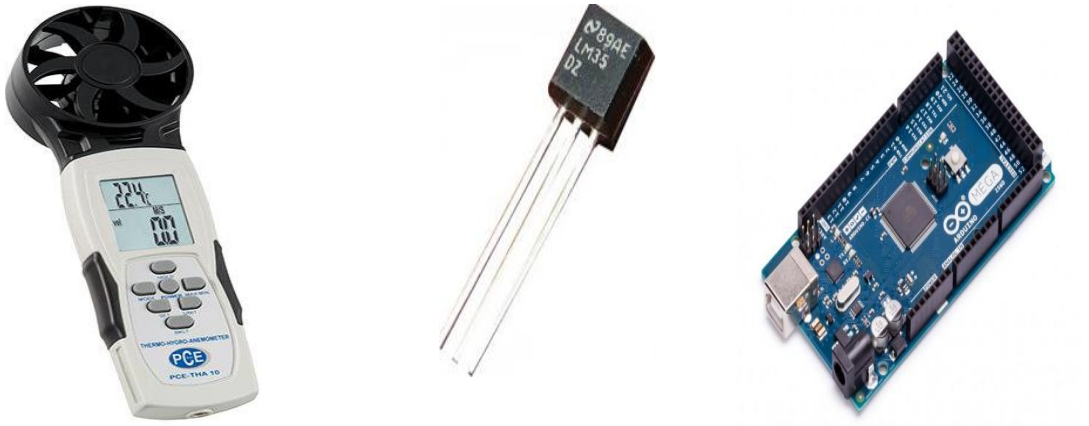
- The thermo-Hygro-Anemometer PCE-THA 10 was used to measure temperature, humidity and air velocity with the included software and USB cable to computer (Fig.3-a). Technical data for this device is summarized in Table 3.
- The LM35 is an integrated–circuit temperature sensor, with an output voltage which is linearly proportional to the Centigrade temperature. The LM35 is rated to operate over a -55 °C to +150 °C of temperature; it has very low self-heating, less than 0.1 °C in still air (Fig. 3b).



a) Location of temperature sensors *b) Experimental solar chimney*

Fig. 2: Experimental equipment.

- An Arduino Mega microcontroller (Fig. 3c) 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) Thermo-Hygro-Anemometer *b) LM 35 Sensor* *c) Arduino Mega*

Fig. 3: Equipment of measurement.

Table 3. Characteristics of PVC.

Property	Value
Glass-transition temperature	87 °C [22]
Melting temperature	212 °C [22]
Density	1380 kg/m^3 [10]
Heat capacity	500 J/ kg·K [10]
Heat conduction	0.14 W/ m·K [10]
Emissivity	0.91 [10]

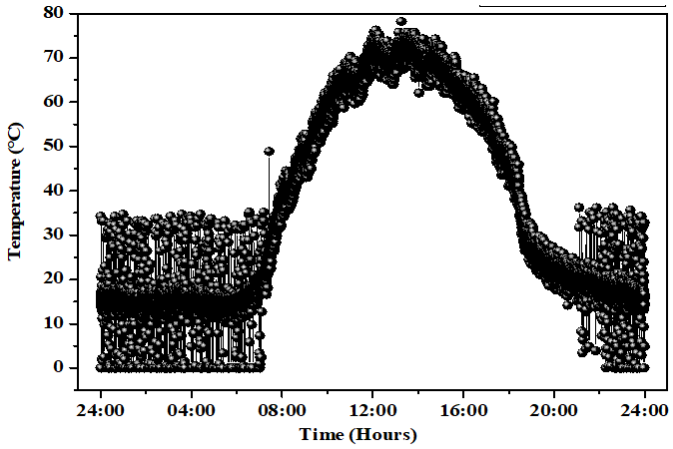
5. RESULTS AND DISCUSSION

5.1 Air temperature

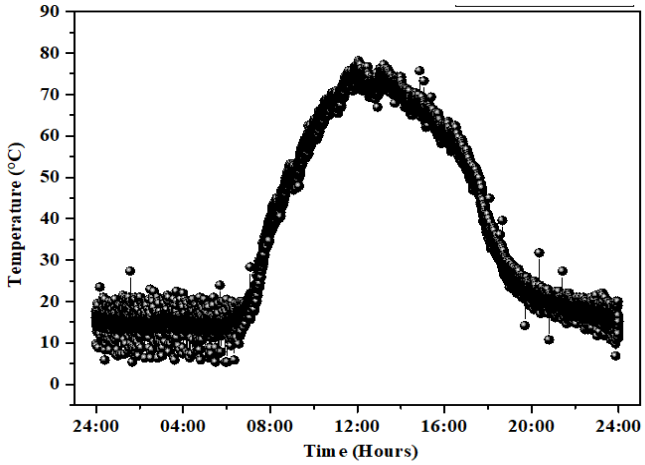
The air temperature features an important value inside the collector base in contact with the absorber; the temperature is due to the hot air flow from the collector. The highest airflow emerges in the chimney inlet and the air temperature decreases with flowing along the

chimney. However, the air temperature increases from the collector. Fig. 4 (a, b, c, d and e) shows the distribution of the air temperature in the collector during a full day, with various sensors (T2, T3, T4, T5 and T6) were used to measure the air temperatures inside the collector. From these results, it is clear that the temperature can exceed 72 °C at the time period between $10:00^{h}$ to $18:00^{h}$ and it is clearly seen that there is more stability in the air temperature evolution.

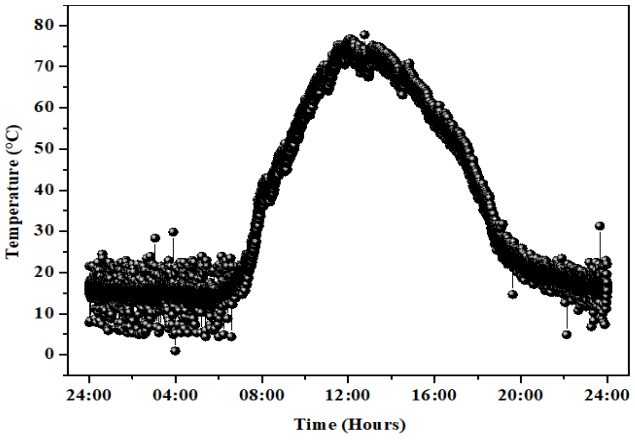
The maximum value of air temperature is equal respectively to T = 73 °C in T2 sensor, T = 78 °C in sensor T3, T = 76 °C in T4, T = 74 °C in T5, and T = 78 °C in T6. Fortunately, simulation model was reported agreeable results compared with experiment. Fig. 5 shows the heated zone of air flow inside solar chimney as temperature contours. From the figure a maximum temperature was reargued of T = 72 °C, which is present an identical value with T2 sensor measurement.



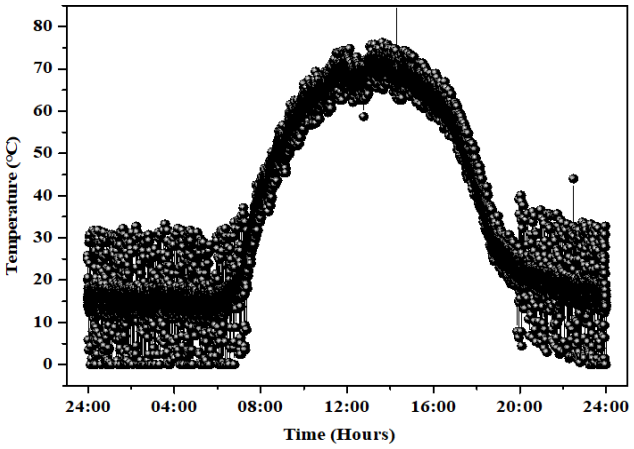
a) Sensor-T2



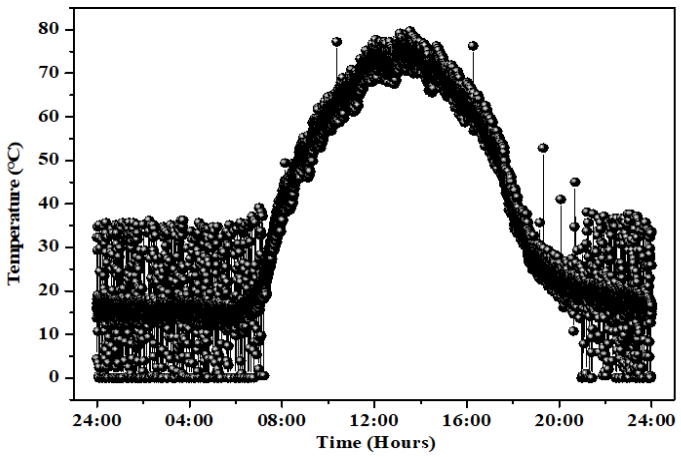
b) Sensor-T3



c) Sensor-T4



d) Sensor-T5



e) Sensor-T6

Fig. 4: Variation of air temperature throughout one full day, for four (04) air inlets for different sensors.

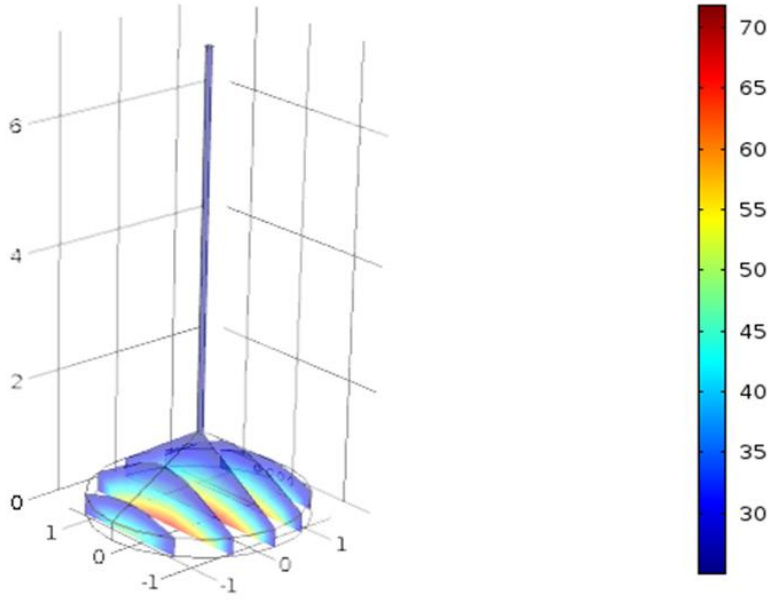


Fig. 5: Distribution air Temperature in SCPP Prototype.

Table 4 shows the percentage of error between the experimental and theoretical results. The comparison between the experimental and calculated results for same prototype solar chimney power plant gave good argument. Indeed, the present study predicted the air temperature inside the collector proximate results between experimental data and simulation model.

Table 4: The percentage of error of numerical/experimental comparison.

Sensors	Experimental prototype (°C)	Numerical model (°C)	Air temperature ΔT (°C)	Error %
T2	73	72	1	1%
T3	78	72	6	7%
T4	74	72	2	1%
T5	74	72	2	1%
T6	78	72	6	7%
T7	74	72	2	1%

5.2 Air velocity

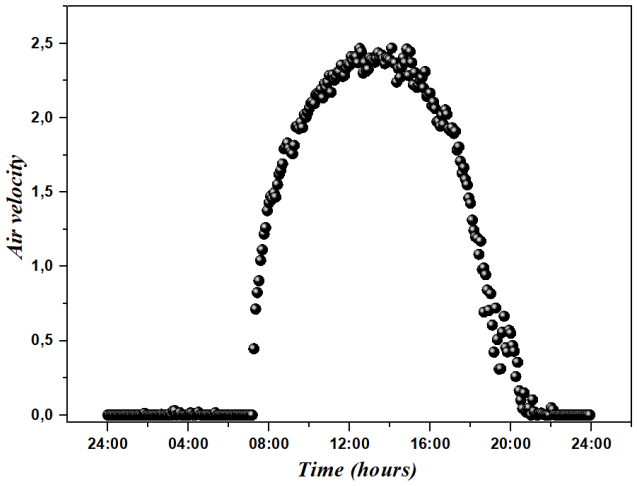


Fig. 6: Variation of air velocity throughout full day for (04) air inlets.

Fig. 6 shows the variation of the air velocity along full day for four air inlets in the whole volume of the SCPP pilot. It is clearly seen that the air velocity evolution has the same topology with air temperature evolution. The airflow started from 07:20^{h} to 21:00 ^{h} with time period of thirteen hours and twenty minutes. We can note that air velocity reached up a maximum in the time between 12:00^{h} and 15:00^{h}, this period corresponds to the high sunshine and high air temperature. The recorded air velocity is V = 2.5 m/s. Otherwise, the recorded maximum value by numerical simulations appears at the bottom of the chimney, which is equal to V = 2.5 m/s (Fig. 7). In fact, the comparison between the numerical simulation and the experimental results confirms that the numerical model is validated for the experimental prototype.

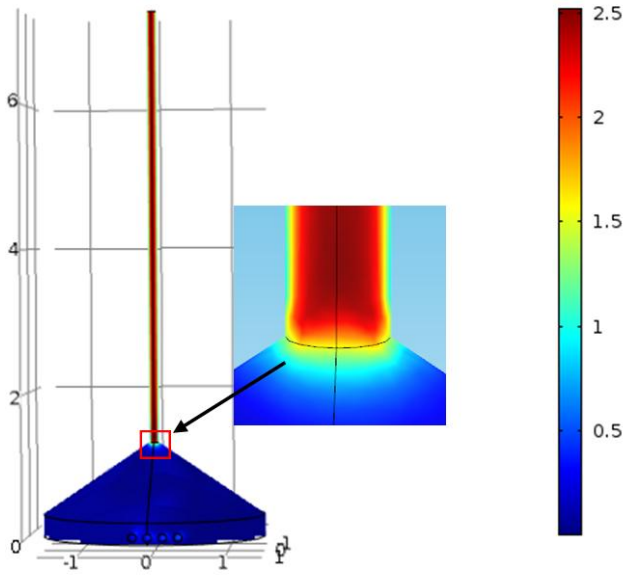


Fig. 7: Distribution of air velocity.

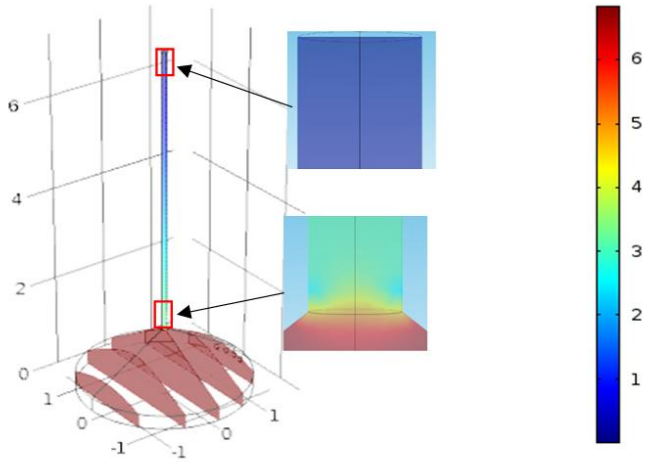


Fig. 8: Distribution of static pressure.

5.3 Distribution of static pressure

Fig. 8 presents the distribution of the static pressure for prototype solar chimney power plant. The results show that the fluid flow inside the solar chimney power plant station creates an inhomogeneous distribution of the static pressure. It has been noted the appearance of high-pressure areas and low-pressure areas.

The static pressure given maximum values under the collector and in the entrance of the chimney, it decreases again along the chimney. The pressure is important along the collector, decreases the entrance of the chimney and up to the exit. Accorded to the Bernoulli's

principle, the pressure imbalance products the airflow in every system, the pressure imbalance is responsible for the airflow and air velocity, the airflow occurs from the compression areas to the depression areas. The above results of the static pressure distribution are helpful to comprise the air velocity value variation in the prototype solar chimney power plant; in fact, the air velocity distribution in the chimney inlet is clarified by the static pressure distribution. However, the value of the maximum air velocity is related to the static pressure distribution inside the collector and in the chimney inlet to the outlet.

5.4 Turbulence characteristics

The turbulent kinetic energy distubition inside the prototype solar chimney power plant presented in Fig. 9 through such results the turbulent kinetic energy appears with important value in the chimney inlet until the chimney outlet close to the wall. The maximum value location of the turbulent kinetic energy in the whole volume of the solar chimney power plant pilot equal K = 0.049 m^2/s^2. However, these results substantiate that the collector roof angle have a direct impact on the turbulent kinetic energy in the prototype solar chimney power plant.

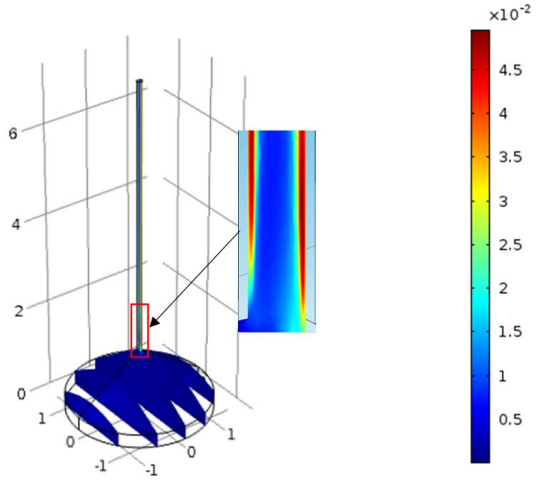


Fig. 9: Distribution of the turbulent kinetic energy.

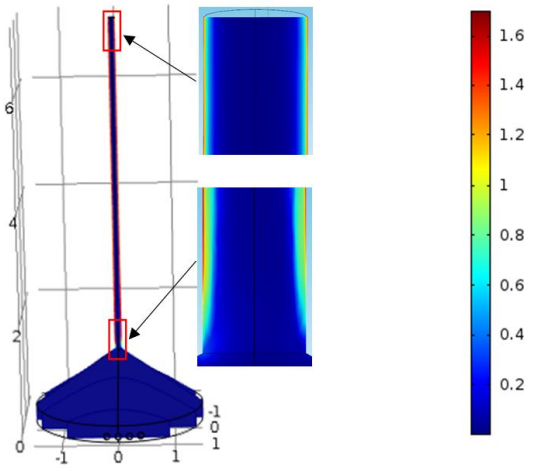


Fig. 10: Dissipation rate of the turbulent kinetic energy.

Fig. 10 shows the dissipation rate of the turbulent kinetic energy in prototype solar chimney power plant. The result shows recorded that the wake position was characteristic of the dissipation rate of turbulent kinetic energy in the inlet and at the height of the chimney near the wall. In fact, the minimum value is observed along the collector radius, the maximum

value of the dissipation rate of the turbulent kinetic energy in the chimney is equal to $\varepsilon = 1.7$ m^2/s^3.

6. CONCLUSION

In this work, a comparison between the numerical simulation and the experimental prototype is carried out using the commercial computational fluid dynamics (CFD) code COMSOL v.5.2. Where, the numerical results were validated with our experimental measurements and a satisfactory agreement is found. Similarly, two parameters such as velocity and temperature were also analyzed. The temperature in the same location as the thermal sensors (T2, T3, T4, T4, T5, and T6) under the collector in the prototype varied from 72°C to 76°C, and in numerical model equal 72° C. The velocity indicated the same value in the experimental prototype and numerical model equal 2.5 m/s. This value presents a potential result which can use as an energetic source for different mechanical systems.

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