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Experimental and CFD investigation of small-scale solar chimney for power generation. Case study: southeast of Algeria

A. Azizi[a], T. Tahri[b,*], M.H. Sellami[c], L. Segni[c], R. Belakroum[d], K. Loudiyi[e]

[a]*Mechanical and Energetic laboratory, Mechanical Engineering Department, Faculty of Technology, Hassiba Benbouali University, Chlef 02000, Algeria, Tel. +213 660434233, Fax +213 27721794, email: azizi2020yha@gmail.com (A. Azizi)*
[b]*Laboratory of Electrical Engineering and Renewable Energy LGEER, Electrical Engineering Department, Faculty of Technology, Hassiba Benbouali University, Chlef 02000, Algeria, Tel. +213 551591304, Fax +213 27721794, email: t.tahri@univ-chlef.dz (T. Tahri)*
[c]*Process Engineering Laboratory, Process Engineering Department, Faculty of Applied Sciences, Kasdi Merbah University, Ouargla 30000, Algeria, Tel. +213 771168857, Fax +213 29 711975, email : sellami2000dz@gmail.com (M.H. Sellami), Tel. +213 668411139, Fax:+213 29 711975, email : Ladjelsegni@yahoo.fr (L. Segni)*
[d]*Laboratory of Dynamics, Interactions and Reactivity of Systems, Faculty of Applied Sciences Kasdi Merbah University, Ouargla 30000, Algeria, Tel. +213 558934865, Fax +213 29 711975, email : rassim.belakroum@gmail.com (R. Belakroum)*
[e]*Laboratory of Renewables Energies, Al akhawayne University, Ifrane, Morocco, Tel. +212 535862108, Fax +212 535862108, email: k.loudiyi@aui.ma (K. Loudiyi)*

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ABSTRACT

Solar chimney power plant (SCPP) is an alternative technology for electricity generation from solar energy. The aim of this study is to investigate the performances of solar chimney. A small-scale prototype of solar chimney power plant was built in Ouargla University, Algeria. A theoretical model is developed in this study to evaluate the performances of a solar chimney and the effects of the chimney height on the chimney efficiency and the power output. The standard turbulence numerical model of CFD is adopted to simulate air flow in the solar chimney prototype. The study found that the air velocities measured at the chimney inlet are in a good agreement with the predicted ones by the use of CFD model. The simulation results show a recirculation zone at the inlet of the collector with negative velocities which cause a reduction of the solar chimney performances. Furthermore, a maximum air velocity of 1.6 m/s in the entry of the chimney was observed. In addition, a disturbance zone is observed at the inlet of the chimney and the air particles are randomly oriented. This disorganization of the velocity field causes a loss of kinetic energy by a pressure drop. The variation trend of theoretical generated power output in the SCPP prototype follows the same trend of the solar irradiance and reached around 1.10 W between 10:00 to 17:00. Using the Manzanares SCPP prototype dimensions and the meteorological parameters conditions of Ouargla, we found that the predicted power output produced reached 104 kW which is greater than the power produced in Manzanares City (75 kW). These results show that solar chimney technology is very suitable for the hot and arid zones like the southeast of Algeria.

Keywords: Solar chimney; Experimental; Mathematical model; CFD; Electrical power; Ouargla

1. Introduction

Increase in CO_2 released mainly by the use of fossil fuels may cause several negative impacts to our ecosystem namely extinction of animals, receding of glaciers, loss of productive forests and biodiversity, acidification of oceans, etc [1].

With the problem of worldwide pollution and the depletion of fossil energy reserves, renewable and clean energies seem to be the best way and the most reliable source for the energy use of humanity in the near future.

*Corresponding author.

Due to the urgent need to accelerate the evolution of advanced energy technologies to refer the universal challenges of clean energy and sustainable development, the solar thermal electricity (STE) has significant capability to satisfy apart of electricity energy demands [2].

The conversion of solar energy into heat and electric energy has become the world's leading research center. The production of electric power by thermal power plants and solar chimneys is now a reality, especially in regions that contain a high solar radiation, It is a promising technology to exploit and convert solar energy into electrical energy using three components; namely: solar collector, tower or chimney and wind turbine unit. Low efficiency, mass size and high dependence of the solar radiation are the main problems encountered in solar chimney power plants. However, the performances of the system can be optimized and enhanced by the integration of another source of thermal energy and the use of an efficient storage of solar energy [3].

The SCPP solar chimney power plant devise could also be integrated with other solar devices such as seawater desalination, and also solar heaters or solar dryers in order to improve their performances [4,5].

Many SCPPs prototype of different geometries have been constructed since 1978. The first one has been constructed by Schlaich in 1978, and has been proved with the successful operation of a 50 kW pilot plant in Manzanares in the early 1980s with the support of both German government and Spanish electric company. Since, many pilot SCPPs have been constructed throughout the world, the American scientist Krisst constructed a solar chimney power plant in 1983 with power output of 10 W, in Turkey by Kulunk in 1985, in Florida by Pasurmarthi and Sherif in 1997 and in many other parts in the world [6].

Several studies of solar chimneys have been carried out by researchers. These studies can be divided into two categories:

The first category is an experimental study using real prototypes with different geometries. The studies consist in seeing the effect of either local climatic parameters such as solar irradiance, ambient temperature and wind speed [7–10], or geometric parameters of the chimney itself such as its height, its diameter, its collection surface and its slope on the speed of the air flow inside the chimney or otherwise on the electric power output [11–13].

The second category is a theoretical and numerical analysis of the SCPP. In their studies, researchers developed a program using the commercial 2D or 3D CFD software FLUENT or TRNSYS to simulate the performances of the SCPP [14–19]. Other theoretical studies have used mathematical calculation methods of many physical and/or thermodynamic parameters concerning the air flow and the heat transfer coefficients inside the chimney [20–22]. To improve the performance analysis of a solar chimney power plant in Adrar city where solar radiation is better than other areas of Algeria, a mathematical was developed. The results show that the SCPP can produce from 140 to 200 kW of electricity during the year, according to an estimate made on the monthly average of sunning [23]. Other researchers added a heat storage medium by the use of heat storing materials to ensure the continuous of SCPP operation overnight or when the solar irradiance is low [24]. Several works have been carried out in region of Iran to study the performance analysis of sloped solar chimney power plant (SSCPP). The obtained results show that the sloped solar chimney power plants can produce from 2.98 to 5.91 MW of electricity power in the selected regions during different months of year [25]. The performance of floating solar chimney (FSCPP) has been also studied in Isfahan city. The results show that these power plants are able to be built in large scales of 100 and 200 MW of electricity with an annual capacity of 381 and 712 GW with 44 and 60% respectively [26]. In the aim to find the best area for the FSCPP, 14 different areas were studied. The results found also that these power plants are able to be built in large scales of 100 and 200 MW of electricity with the annual capacity of 311 and 641 GW, respectively [27].

Algeria has substantial solar energy throughout its territories which constitutes a considerable asset for arid and semi-arid zones. The mean solar irradiance period in the town of Ouargla in the southern region of Algeria is around 3,500 h/y, delivering 2,650 kWh/m^2/y of solar irradiation on the horizontal surface [28]. Therefore, the total solar potential of Algeria is estimated to 169,440 TWh/y, which represents 5000 times of the national annual electricity power consumption [29]. So, the SCPP can make significant contributions to the power generation supply of Algeria where there is plenty of sunny desert lands.

2. Modeling the performance of SCPP

Based on the work of Lal et al. [30], the total efficiency of the solar chimney is defined as the product between turbine the collector efficiency, chimney efficiency and turbine/generator efficiency according to Eq. (1):

$$\eta_{SCPP} = \eta_{Coll} \cdot \eta_{Ch} \cdot \eta_{tg} \tag{1}$$

The total electric power produced by the solar chimney is given by Eq. (2):

$$P_{SCPP} = Q_s \times \eta_{SCPP} \tag{2}$$

where P_{SCPP} is the total electrical power produced and Q_s is the total solar energy received by the collector, which is calculated by Eq. (3):

$$\mathrm{Q_s} = I_s \cdot A_{Coll} \tag{3}$$

where I_s is the solar radiation measured and A_{coll} is the surface of the collector.

To obtain the individual efficiency of each component of the system, the equations are developed in the next section.

2.1. Solar collector

The efficiency of the collector is calculated by dividing the amount of heat transmitted to the air by the collector (Q_u) by the amount of solar radiation introduced by the surface of the collector

(Q_s) according to Eq. (4):

$$\eta_{Coll} = \frac{Q_u}{Q_s} \tag{4}$$

The energy balance of the solar collector can be calculated by Eq. (5):

$$Q_u = \dot{m} \cdot C_P \cdot \Delta T = \alpha \cdot A_{Coll} \cdot I_S - \beta \cdot \Delta T_0 \cdot A_{Coll} \quad (5)$$

where ΔT_0 is the temperature difference between the collector surface and the ambient air, and ΔT is the temperature difference between the average warm air in the collector and the ambient air. α is the effective absorption coefficient of the collector with a typical value of 0.75 to 0.8 and β is an adjusted heat transfer coefficient which makes it possible to calculate the losses by radiation and by convection. $\dot{m}$ is the mass flow of air inside the collector.

By replacing Eqs. (5) and (3) in Eq. (4), the efficiency of the collector is given by Eq. (6):

$$\eta_{coll} = \alpha - \frac{\beta \cdot \Delta T_0}{I_S} \quad (6)$$

The calculation of the average temperature of the hot air and the surface of the absorber is delicate. The assumption for the above Eq. (7) is that the surface temperature of the absorber is equal to the average temperature of the airflow.

$$\Delta T = \Delta T_0 \quad (7)$$

where $\Delta T = Tf - Ta$ and $\Delta T_0 = Tf - Ta$ with Tf, Ta and T_0 are respectively the average temperature of the hot air in the collector, the ambient air temperature and the outlet temperature of the collector.

2.2. Solar chimney

The performance of the chimney is given by Eq. (8):

$$\eta_{Ch} = \frac{P_{Ch}}{Q_u} \quad (8)$$

where P_{ch} is the power contained in the airflow at the bottom of the chimney and is given by Schlaich [31] according to Eq. (9):

$$P_{Ch} = \Delta p_{Ch} \cdot V_{Ch} \cdot A_{Ch} \quad (9)$$

where Δp_{ch} is the pressure difference produced between the base of the chimney and the ambient air.

According to Schlaich [31], the pressure difference and the maximum velocity in the chimney are given by Eqs. (10) and (11):

$$\Delta p_{Ch} = g \cdot \rho_{ch} \cdot k \cdot H_{ch} \cdot (T_0 - T_a)/T_a \quad (10)$$

$$V_{Ch} = \sqrt{2gH_{Ch}(T_0 - T_a)/T_a} \quad (11)$$

By substituting Eqs. (10) and (11) into Eq. (9) we obtain Eq. (12):

$$P_{Ch} = 1.414 \cdot \rho_{ch} \cdot A_{Ch} \cdot g^{3/2} \cdot H_{Ch}^{3/2} \cdot \left(\frac{T_0 - T_a}{T_a}\right)^{3/2} \quad (12)$$

By substituting the value of P_{ch} from Eq. (12) and Q_u from Eq. (5) in Eq. (8), we obtain the value of chimney efficiency. The theoretical efficiency of chimney is given by Eq. (13):

$$\eta_{Ch} = \frac{1.414 \cdot \rho_{ch} \cdot A_{Ch} \cdot g^{3/2} \cdot H_{Ch}^{3/2} \cdot \left(\frac{T_0 - T_a}{T_a}\right)^{3/2}}{A_{Coll} \cdot (\alpha \cdot I_S - \beta \cdot \Delta T_0)} \quad (13)$$

According to Schlaich [31], another equation that can help to calculate the efficiency of the chimney in an easier way is given by Eq. (14):

$$\eta_{Ch} = \frac{g \cdot H_{Ch}}{C_p \cdot T_a} \quad (14)$$

Thus, the chimney efficiency is directly proportional to the ratio between chimney height and the ambient temperature.

2.4. Wind turbine

Low velocity vertical air turbines have always been located at the base of solar chimney where air force converts maximum 2/3 times of air flow into mechanical power and finally produces electrical power [31], the maximum mechanical power produced by the turbine is given by Eq. (15).

$$P_t = \frac{2}{3} P_{Ch} \quad (15)$$

By substituting the value of P_{ch} from Eq. (8), Q_u from Eq. (4), η_{ch} from Eq. (14) and Q_s from Eq. (3) in Eq. (15), we obtain the value of the maximum mechanical power produced by turbine according to Eq. (16):

$$P_t = \frac{2}{3} \cdot \eta_{Coll} \cdot \frac{g}{C_P \cdot T_a} \cdot H_{Ch} \cdot A_{Coll} \cdot I_S \quad (16)$$

Again efficiency of the electrical generator is given by Eq. (17) and the efficiency of the turbine/generator is given by Eq. (18):

$$\eta_g = \frac{P_{SCPP}}{P_t} \quad (17)$$

$$\eta_{tg} = \frac{P_{SCPP}}{P_{Ch}} \quad (18)$$

The efficiency of the turbine generator usually varies from 75% to 85%. A value of 80% for η_{tg} is used throughout this analysis [32], the power output of the solar chimney is calculated according to Eq. (19):

$$P_{scpp} = \frac{2}{3} \cdot \eta_{Coll} \cdot \frac{g}{C_p \cdot T_a} \cdot H_{Ch} \cdot A_{Coll} \cdot I_S \cdot \eta_{tg} \quad (19)$$

3. CFD model development

For the present study, the standard turbulence model is adopted to investigate air flow in the considered configuration. In these simulations,the Boussinesq model has been adopted. This model considers the density as a constant value in all solved equations, except for evaluating the term of the buoyancy in the momentum equation. Turbulent flows are significantly affected by the presence of walls. Modeling near walls has a significant impact on the fidelity of numerical solutions, insofar as the walls are the main source of mean vorticity and turbulence. Therefore, the exact reproduction of the flow in the near-wall area requires the use of the walls functions approach. This latter use semi-empirical formulas which provide a suitable flow field in the area affected by the viscosity or boundary layer.

The solver of dynamics fluid problems, FLUENT based on finite volume method was used in the present numerical investigations. The SIMPLE algorithm (acronym for Semi-Implicit Method for Pressure Linked Equations) is used to establish the coupling between the velocity and pressure fields. The SIMPLE algorithm connects the momentum equations to the mass conservation equation using pressure corrections. The algorithm was chosen over others because of its robustness and efficiency in the computation of fluid flows.

4. Experimental set-up

In order to perform a detailed investigation onto the measured temperature field and air velocity in solar chimney power plant, a small scale prototype (Fig. 1) was built in Ouargla University (southern Algeria). The prototype consists of a (4.60 m × 3.60 m) collector area and 6 m of chimney tall whose the schematic layout is presented in Fig. 2. A PVC pipe with 16 cm diameter and 6 m height is used to construct the solar chimney tower which is supported by steel beams. The pipe was further isolated by glass wool. The collector is made with steel beams and the steel wired network is used to support the clear plastic cover. The collector surface is designed with about 6° of tilt angle to allow water drainage in the case of rain. The collector height from the ground is 0.2 m at it send and 0.4 m at the center. For increasing the greenhouse effect, the ground was tainted with black matte paint to absorb the maximum of solar irradiance. The main geometric parameters of the solar chimney power plant are listed in Table 1.

For the temperature measurement, a K type thermocouple was used to measure inlet air temperature of chimney (outlet the collector). Furthermore, a digital thermometer was fixed outside the setup to measure the ambient temperature. An anemometer, (40 m/s max) was used to measure the airflow velocity. Finally, a Global Irradiance Measuring Device (GIMD) is used to measure the solar irradiance.

5. Results and discussion

In this part, we will present some environmental parameters and their effect on the air flow field inside the solar chimney and also on its thermodynamic parameters. The experimental results are compared to those obtained by simulation using the CFD model. At the end we will discuss

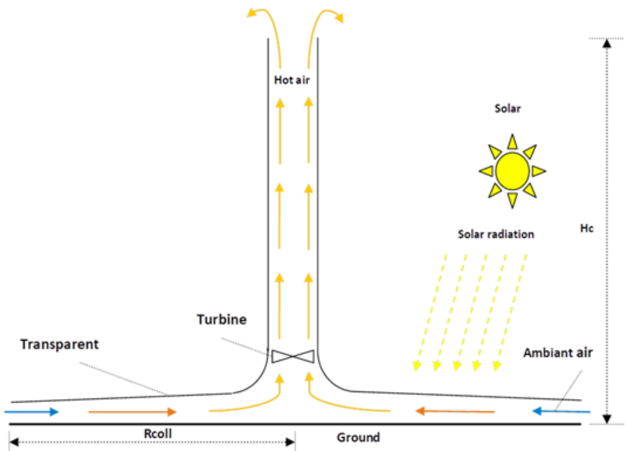

Fig. 2. Solar chimney power plant schematic layout.

Fig. 1. Photo of the small scale solar chimney in Ouargla.

Table 1
Main geometric parameters of small scale solar chimney

Parameters	Value
Collector area (m^2) Acoll	16.56
Chimney height (m) H_{Ch}	6
Height from collector inlet to ground level (m)	0.2
Chimney diameter (m) Dch	0.16
Height from collector outlet to ground level (m)	0.4
Collector mean tilt angle (°)	≈ 6°

the influence of the height of chimney on the power output and we will use the geometrical parameters of Manzanares prototype to estimate the power output resulted to the input of meteorological parameters of Ouargla city.

5.1. Measurement of environmental parameters

Fig. 3 shows the variations of the measured solar radiation (G) and the ambient temperature (T_a) according to local time. These parameters were recorded in Ouargla city during the day of July 31, 2016. It is observed that during the experiments, the ambient temperature ranged from 37°C at 8:00 to 44.3°C at 14:00 local time; it means that the average value for this day period was 40.65°C. In addition, the solar irradiance increases after sunrise and reaches the maximum value of 992 W·m^{-2} at 14: 00. After this peak, it decreases again until sunset; the average value for the day was 906 W·m^{-2}. From these results, we can easily deduce that this region is characterized by high sunlight potential and an ideal location for solar installations such as solar chimney power plants.

5.2. Validation of predictive collector outlet air velocity

Fig. 4 illustrates the comparison of the variation of the measured air velocity and the predicted air velocity by CFD model at the chimney inlet with the solar irradiance according to local time for a typical day of 31 July 2016. It is observed that the maximum air velocity is obtained at 14:00 for both experimental and CFD results which are 1.87 m/s and 2.5 m/s, respectively for ambient temperature of 44.3°C and solar irradiance of 992 W/m^2. The gap between the measured air velocity and the predicted air velocity from 08:00 to 10:00 was very close and from to 11:00 to 17:00 the gap increased with the increasing of solar irradiance. The-difference between the CFD and the experimental results depends generally on many parameters like the losses of air due to the miss of sealing inside the greenhouse and also the hypotheses used in the CFD model. Finally, we can deduce that the CFD model is validated.

5.3. Air flow field inside the chimney

Fig. 5 depicts the temperature field and streamlines as obtained by CFD. It can be observed that the generation of an up draft fluid flow which is due to heated ground. The air temperature gradually increases in the collector and the airflow is directed upwards through the chimney. The most important observation is the recirculation zone at the inlet of the collector. The negative velocities at the inlet of the collector cause a reduction in the performance of the solar chimney. A more detailed study of the air behavior at the collector inlet is required to improve flow through the chimney.

Figs. 6 and 7 show respectively the velocity field and velocity vectors in the solar chimney prototype. As depicted,

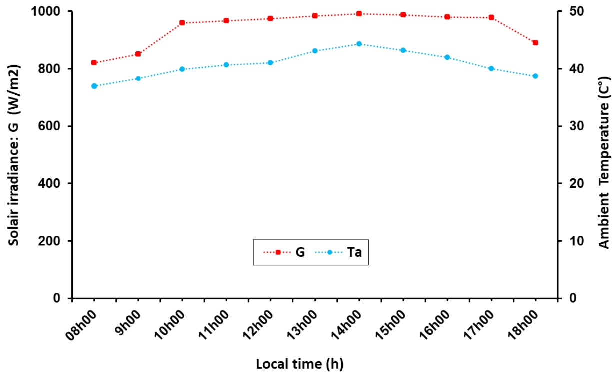

Fig. 3. Measured solar irradiance and ambient temperature according to local time (July 31, 2016).

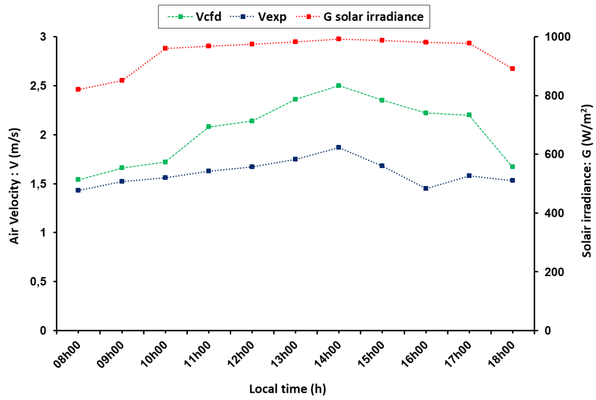

Fig. 4. Comparison of the predicted and measured air velocity at the chimney entrance with the solar irradiance according to local time of 31 July 2016.

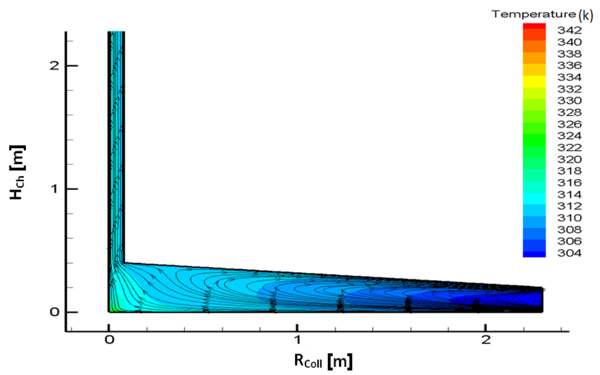

Fig. 5. Air streamlines and temperature field inside SCPP prototype using CFD.

the kinetic energy of the fluid particles increases due to thermosiphon phenomenon and therefore the velocities reach the maximum through the entrance of chimney where the wind turbine will be placed. We notice that air velocities lower than 0.6 m/s are found inside the collector but a maximum of 1.6 m/s is found in the entry of the chimney. At the inlet of the chimney, a disturbance zone is observed and the air particles are randomly oriented. This disorganization of the velocity field causes a loss of kinetic energy by a pressure drop. An optimization study of the connection shape of the collector and the chimney is very important to improve the capacities and the prototype's efficiency.

5.4. Efficiency and power output estimation

Fig. 8 shows the predicted power output of SCPP using the mathematical model and solar radiation according to

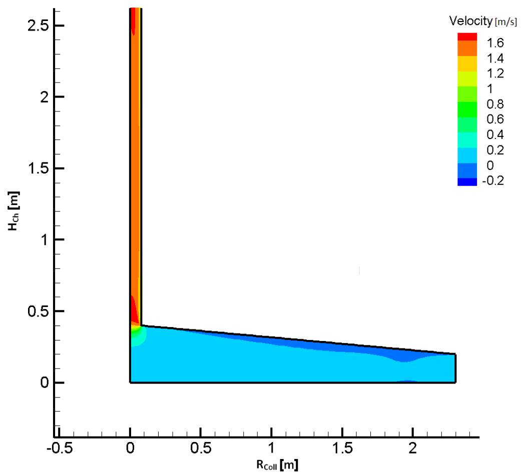

Fig. 6. Air velocity field inside SCPP prototype using CFD.

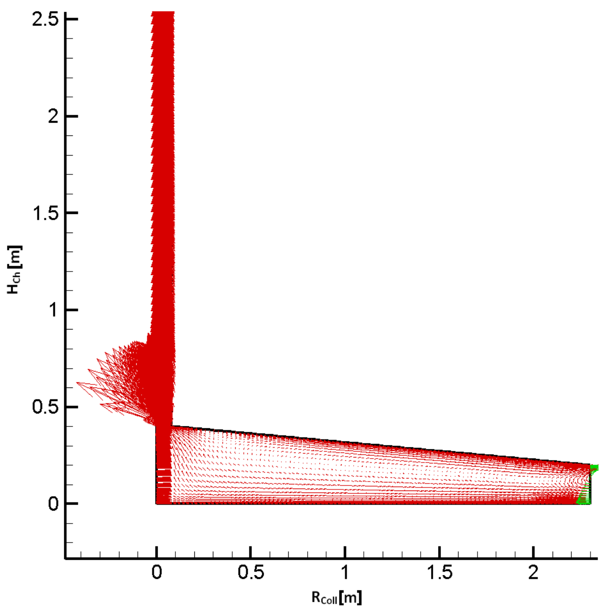

Fig. 7. Air velocity vectors inside SCPP prototype using CFD.

local time of 31 July 2016. We can observe that the power output in this prototype reaches around 1.10 W between 14:00 to 17:00. The results demonstrate that there is a good agreement between the solar irradiance and the predicted power output of the solar chimney.

Fig. 9 shows the variations of the chimney efficiency using the mathematical model according to the height of the chimney for solar irradiance and ambient temperature of 992 W·m^{-2} and 44.3°C respectively. It is clearly observed that there is a proportional relation between the chimney efficiency and the height of chimney, where the efficiency increases with the increasing of the height of the chimney.

Fig. 10 shows the variations of the predicted power output using the mathematical model according to chimney height for solar irradiance of 992 W/m^2 and ambient temperature of 44.3°C respectively. The curve traduces the existence of a proportional relation between the power output and the height of chimney.

Fig. 11 depicts the variation of predicted power output using the mathematical model for Manzanares SCCP dimensions (Table 2) and solar irradiance according to the local time using the meteorological parameters of the typical day of 31 July 2016, in Ouargla city. It is clearly observed that the power output produced with Manzanares prototype dimensions is reached around 104 kW between 10:00 to 17:00. It is important to mention that the power energy

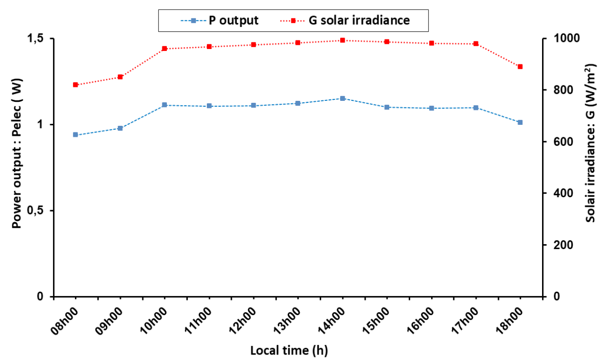

Fig. 8. Variation of predicted power output of SCPP using the mathematical model and solar radiation according to local time for 31 July 2016.

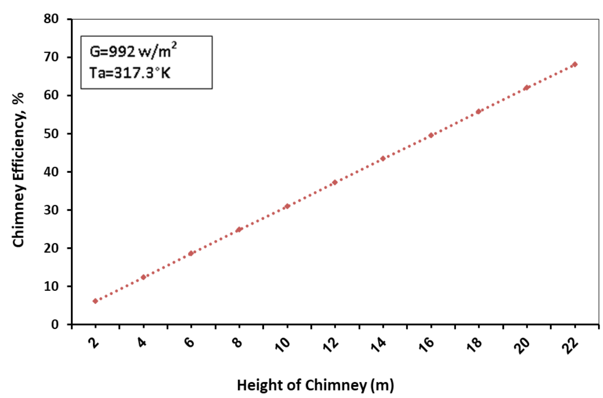

Fig. 9. Effect of chimney height on the chimney efficiency calculated using the mathematical model.

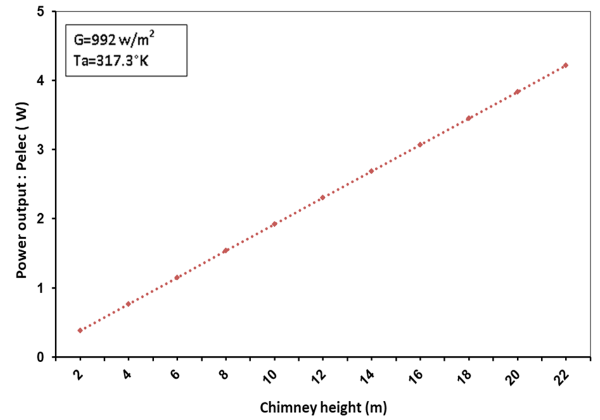

Fig. 10. Effect of chimney height on solar chimney power output calculated using the mathematical model.

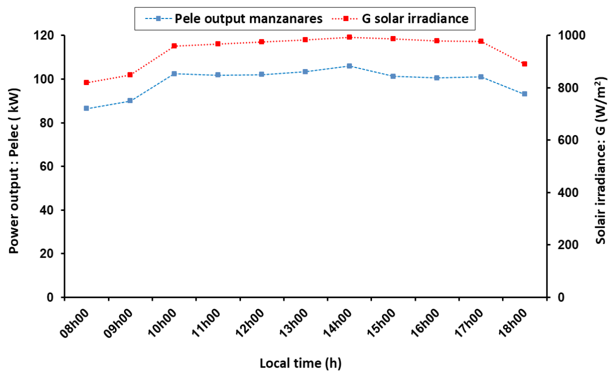

Fig. 11. Variation of predicted power output using the mathematical model for Manzanares SCCP dimensions and solar irradiance according to local time.

Table 2
Main dimensions of the Manzanares prototype in Spain

Parameters	Value (m)
Average radius of the collector	122
Average height of the collector	1.85
Chimney height	194.6
Chimney radius	5.08
Number of blades of the turbine	4

which could be produced in Ouargla city will be greater than the case of Manzanares city (75 W) when we use the same geometrical parameters. The shape of the predict power curve confirms that the mathematical model is validated.

6. Conclusion

The production of electricity using solar chimney is not a new subject of research in the world. There are many projects have been done in the aim to studying the feasibilities of the installation of the solar chimney system. This paper presents an experimental study of a small solar chimney prototype and theoretical study using CFD and mathematical model. This prototype was installed in Ouargla University, in the south east of Algeria. The measurements of the parameters which have a direct effect on the velocity of the air flow and the power output were recorded. The maximum solar radiation and maximum ambient temperature recorded are respectively, 992 W/m^{2}and 44.3°C at 14:00 on a typical day of 31 July 2016. The maximum air velocity measured in the prototype is 1.87 m/s where the predicted air velocity of 2.5 m/s was found using a CFD model with the same conditions.

A theoretical model is also used to estimate the power output produced from the small prototype and also the effect of the height of chimney on the chimney efficiency and the power output. The predicted power output reached 1.10 W between 10h00 to 17h00 using the meteorological parameters of the typical day of 31 July 2016. The chimney efficiency and the power output of SCPP using the mathematical model have proportional relation with the height of the chimney.

Finally, we used a mathematical model to predict the power output of the SCPP using the geometrical parameters of Manzanares prototype and the meteorological parameters of Ouargla city. The power output produced in the case of Manzanares prototype reached 104 W. We can conclude that Ouargla city is more advantaged than Manzanares city from climatic point of view; therefore, Ouargla city is a typical location for solar energy installations such as solar chimney power plant.

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Symbol

A — Surface area, m^2
C_p — Specific heat capacity, J/kg K
g — Gravitational acceleration, m/s^2
H — Height, m
I_s — Solar radiation intensity, W/m^2
k — Specific heat ratio
$\dot{m}$ — Mass flow rate of air, kg/s
P — Power, W
p — Pressure, pa
Q_s — Solar heat flux, W
Q_u — Useful heat flux, W

T — Temperature, K
T_f — Temperature of the air in the collector, K
V — Velocity, m/s
Δp — Pressure difference, N/m^2
ΔT — Temperature difference between the air in the collector and the ambient air, K
ΔT_0 — Temperature difference between the collector surface and the ambient air, K

Greek symbols

α — Effective absorption coefficient
β — Convective energy loss factor, W/m^2 K
η — Efficiency
ρ — Density, kg/m^3

Subscripts

a — Ambient
Ch — Chimney
Coll — Collector
SCPP — Solar chimney power plant
t — Turbine
tg — Turbine/generator
0 — Outlet

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