Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.26541

210 (2021) 152–163
January

Evaluation of solar chimney performance enhancement using energy produced by Albian geothermal water in southeastern Algeria

A. Azizi[a,*], T. Tahri[b], R. Belakroum[c], M.H. Sellami[d], L. Segni[d], K. Loudiyie[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: a.azizi@univ-chlef.dz*
[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: +21327721794; email: t.tahri@univ-chlef.dz*
[c]*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*
[d]*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)*
[e]*Laboratory of Renewables Energies, Al Akhawayne University, Ifrane, Morocco, Tel. +212 535862108; Fax: +212 535862108; email: k.loudiyi@aui.ma*

Received 5 February 2020; Accepted 6 September 2020

ABSTRACT

The purpose of this work is to evaluate the performance enhancement of a solar chimney by coupling it to Albian geothermal water, a natural source of hot water, to ensure energy production in the absence of solar radiation. As the temperature of this groundwater can reach up to 70°C in the southeastern Sahara (Algeria), the energy produced is not negligible and could be valorised. The continental intercalary groundwater is mainly used for irrigation and requires a a prior cooling. Given the absence of Albian drilling near the solar chimney prototype, we used a water heater to produce water at a temperature close to that of natural Albian water. The explored prototype was built in the city of Ouargla, located in the southeast of Algeria. It was observed that this hybrid energy generation system operates day and night and ensures an uninterruptible power supply. The proposed system also lowers the temperature of the hot water, thereby making it suitable for irrigation.

Keywords: Solar Chimney; Albian Geothermal Water; Hybrid System; Sustainable Energy Systems; Experimental; Electrical Power

1. Introduction

Societies are increasingly implementing cleaner and more environmental friendly methods of energy generation to mitigate the damage caused by the use of fossil fuels [1]. Because most power worldwide is still generated using fossil fuels, humanity must find new methods and techniques using clean and renewable solar, wind and geothermal energy to generate environmental friendly, low-cost power. One technique that converts solar energy to electrical power is the solar chimney power plant (SCPP). A classic SCPP has three main components: (1) collector (greenhouse), (2) chimney and (3) turbine. This device can be used in sunny areas, especially in arid and semi-arid regions such as southeastern Algeria, where solar radiation rate is high [2].

The prototype of SCPP was proposed and developed by Professor Schlaich and was built and tested in Manzanares, Spain, in 1980 [3,4]. The plant was continuously operated for

* Corresponding author.

seven years from 1982 to 1989, and the system proved reliable with low operation and maintenance costs [5]. Multiple studies were conducted to analyse the airflow characteristics in the SCPP system and assess the effects of different parameters on system performance. Furthermore, numerical and analytical studies, together with experimental studies, were conducted to enhance and improve SCPP power generation and efficiency. Ming et al. [6] analysed the thermodynamics of the SCPP system (SCPPS), the pressure profile of the air and the performance of different SCPPS sizes. The results showed that the solar radiation and pressure differential of the turbine influenced the energy utilisation markedly, which would increase with the increasing SCPPS size.

Hamdan [7] studied the feasibility of the solar chimney specifically for the United Arab Emirates and Persian Gulf climatic conditions. He implemented and solved a simplified Bernoulli equation combined with fluid statics and the ideal gas equation to predict SCPP performance.

Bernardes et al. [8] developed a model for solar chimneys to estimate power output and examine the effect of various ambient conditions and structural dimensions on the power output. The results confirmed that the height of the chimney, the amount of pressure drop at the turbine, and the diameter and the optical properties of the collector are important parameters for the solar chimney design.

Ming et al. [9] used simple analysis and mathematical models on the airflow through a solar chimney power generation system. The results showed that the ideal cycle efficiency and actual efficiency of the standard Brayton cycle corresponding to a medium-scale SCPPS were 1.33% and 0.3%, respectively, while the same parameters for a large-scale SCPPS were 3.33% and 0.9%, respectively. The results provided theoretical guidance for the commercial application of solar chimney power generation systems in China.

Choi et al. [10] used an analytical model for a solar chimney to estimate the power output and temperature configuration of the collector. The analytical model results were validated by experimental data from a prototype plant in Manzanares, Spain. They also studied the water storage system beneath the collector, used to conserve heat energy during the night. Depending on the depth of the water storage system, the power variation throughout a 24-h period was analysed.

Dai et al. [11] developed a theoretical model for an SCPP to be installed in northwestern China. Three regions, with relatively higher solar radiation than other parts of the country, were selected as pilot locations to construct solar power plants. The SCPP with a chimney height and diameter of 200 and 10 m, respectively, and a solar collector with a diameter of 500 m were capable of producing an average of 110–190 kW of electric power per month.

Several numerical studies have attempted to improve and evaluate the performance of the SCPP. Chergui et al. [12] studied the influence of geometric parameters on thermo-hydrodynamic behaviour of the airflow in solar chimney systems. The flow transport equations were modelled and solved numerically using the finite volume method with generalised coordinates to study the effects of the form of some SCPP components such as the cover-tower junction and the convergent-divergent tronconique tower. The authors found that geometrical modifications of the chimney could successfully eliminate airflow perturbations, which were observed with the previous geometry.

Kasaeian et al. [13] performed an analytical and numerical study for geometrical optimisation of a solar chimney prototype in Iran. They used a fundamental mathematical model to evaluate and simulate solar chimney performance. The results confirmed that the results of numerical predictions were validated by the experimental results of the pilot solar chimney 2-m height with a 3-m collector radius. In addition, the results showed that the diameter and the height of the chimney are the crucial parameters determining the performance of the solar chimney, and the ideal configuration of the pilot solar chimney included a collector inlet of 6 cm and chimney height and diameter of 3 m and 10 cm, respectively. The authors also found that the velocity could be raised to 4%–25% in different circumstances, and confirmed that the height and diameter of the chimney are the most critical geometrical variables for solar chimney design.

In the warm and semi-arid climate of Kota, India, Shiv et al. [14] studied the thermal performance of a laboratory-scale prototype SCPP. Mathematical and computational fluid dynamic (CFD) models were used to calculate the specific parameters, energetic and exergetic efficiencies, and the predicted results were validated through experimental studies. The SCPP energetic and exergetic efficiencies were estimated to be 3.5% and 8%, respectively, at 12:00 h. The location of maximum velocity, estimated with the help of CFD simulation, was 0.25–1 m inside the chimney, indicating the ideal location of turbine installation.

Fei et al. [15] evaluated the SCPP performance using a program based on TRNSYS. The parameters that influence the SCPP performance, the configuration size design and techno-economic aspects were analysed, and the results found that the TRNSYS program can be used as a convenient tool for SCPP investigation.

Ming et al. [16,17], Xu et al. [18] and Ming et al. [19,20] conducted several studies to analyse the characteristics of heat transfer and airflow in the SCPPS and developed a numerical investigation of SCPP. The investigation included determining the effects of various parameters on the relative static pressure, driving force, power output and efficiency using the solar chimney prototype in Manzanares, Spain, as a practical example.

To investigate experimentally and numerically the airflow, heat transfer and flow characteristics in an SCPP, Shahreza and Imani [21] installed a novel small-scale solar chimney. They used the RNG k–ξ model to simulate the turbulence and the well-known SIMPLE algorithm to solve the coupled velocity and pressure equations. The results showed that the maximum velocity reached is 5.12 m/s.

In another study by Das and Chandramohan [22], a 3D computational model was used to investigate the influence of the chimney divergence angle on the flow and performance characteristics of a solar updraft tower (SUT) plant. The effect of ambient temperature on the performance of SUT was also studied. The results showed that the velocity of air at the chimney base was enhanced by 59.4% relative to a CC-SUT plant. From the parametric study, it was observed that a 2° chimney angle provided superior system performance.

Zuo et al. [23] experimentally investigated a SCPP combined with a seawater desalination system in Hohai, China. The results confirmed that the integrated system could produce energy and fresh water simultaneously.

To study the feasibility of installation of an SCPP in northern Tunisia, Jemli et al. [24] tested a small scale of a solar tower power plant (STPP) with chimney height and collector diameter of 2 and 8 m, respectively, in Borj Cédria. The results indicated that when the temperatures reached 45°C, the electric power was, on average, approximately 0.3 W/m^2 for this prototype.

Ming et al. [25] carried out experimental research on a mini-scale SC prototype of a solar chimney, where the air temperature distribution of the system in time and space, and velocity variations within the chimney over time were all measured. The results demonstrated that the toggle speed of the SC system is very rapid. Furthermore, the effect of the season on the heat transfer and flow characteristics of the system and the temperature distributions inside the collector show excellent agreement with the analysis.

In Iran, Ghalamchi et al. [26] designed and constructed a solar chimney pilot power plant with a 3 m collector diameter and 2 m chimney height. The results revealed that the temperature difference between the chimney inlet and ambient air reached 26.3°C. The output data for different collector inlet heights were measured, and reducing the inlet size was found to have a positive effect on the SCPP performance. In addition, a maximum air velocity of 1.3 m/s was recorded inside the chimney.

Zuo et al. [27] evaluated the output characteristics under different conditions using a physical and mathematical model for a wind supercharging SCPP combined with seawater desalination and waste heat (WSCPPDW) and an SCPP combined with seawater desalination and waste heat (SCPPDW). The results showed that the increase in chimney height and flue gas temperature was both beneficial to the overall performance of both power plants, the performance of WSCPPDW was always better than that of SCPPDW, and the overall energy utilisation efficiency of WSCPPDW was increased by 15.4% throughout the utilisation of high-altitude wind. Practically, the hourly freshwater yield, power generation and overall efficiency of WSCPPDW reached 193.7 kW, 17.2 ton/h and 13.5%, respectively.

Several researchers have investigated improving the power output of SCPP. For example, Pretorius [28] studied the use of an intermediate secondary roof to enhance heat storage in the ground under the collector. The heat storage medium was used as an energy supply to enhance power production during the lack of solar irradiance or overnight. Aja et al. [29,30] studied a hybrid SCPP process using the residual heat of combustion gases. Aurybia et al. [31] proposed a new technique of integrating the SCPP with an external heat source by installing thermal enhancing channels inside the collector between the canopy and the ground to enhance the kinetic energy of the air inside the collector. The results found that the temperature of the air inside the collector could be increased by the addition of thermal enhancing channels within the collector of the solar chimney. The air temperature inside the collector increased up to 5.88% and for power generation, 23.1%. Cao et al. [32] developed a theoretical analysis to investigate the performance of a geothermal–solar chimney power plant (GSCPP), through the introduction of low-temperature geothermal water into the SCPP to overcome the problem of discontinuous SCPP operation.

Zhou and Xu [33] conducted a numerical simulation of a large-scale hybrid SCPP, using an additional waste heat source connected to the collector-to-chimney transition section. The results showed that the incorporation of waste heat with enough high heat flux into SCPP caused apparent enhancement of the power output. The daily total electricity output increased by 119.99% with the increase in the effect of effective waste heat flux (EWHF) from 0 to 2 GW, indicating that sufficient high waste heat flux helps to flatten the daily profile of the plant power output, especially for weak solar radiation, while low waste heat flux has little influence on the power output.

We present an experimental study on a conventional solar chimney coupled to a source of hot water. All the experiments were conducted at the University of Ouargla where the solar irradiance is very high and the mean solar irradiance period is approximately 3,500 h/y, delivering 2,650 kWh/m^2/y of solar irradiance on a horizontal surface. The region of Ouargla is also known for the availability of a large geothermal water reserve [34,35].

Due to the unavailability of the Albian water source at the University of Ouargla, where the SCPP prototype is implemented, and to heat the water to temperatures close to that of natural Albian water (approximately 70°C), we used an electric water heater. The hot water circulates in a serpentine tube installed inside the collector by means an electrical pump. Therefore, the hot water will help to heat the air inside the collector and promote the thermosiphon phenomenon. We contend that this will improve system performance and extend the operation of the hybrid solar chimney system even overnight, in the absence of solar light.

2. Perspectives on geothermal sources (Albian water) in the region of Ouargla

The Albian aquifer is the largest reserve of fresh water in the world. It straddles three countries, Algeria, Libya and Tunisia. Approximately 70% of the Albian aquifer water is in southeastern Algeria (Fig. 1) [36]. It contains more than 50,000 billion m^3 of fresh water, the equivalent of 50,000 times the Beni Haroun dam in eastern Algeria, which supplies six bordering provinces. This water is the result of the accumulation that occurred during successive wet periods millions of years ago in the region [37]. The Albian water temperature is approximately 70°C, making it a potentially significant source of energy.

3. Experimental setup and methods

An SCPP operates during the day where there is enough solar radiation, and it is almost stopped overnight. The goal of the present experimental study is to maintain the production of energy continuously and therefore enhance the performance of the solar chimney. We propose coupling a conventional solar chimney to a geothermal source of Albian water, which is available in Ouargla, to ensure continuous operation. An experimental solar chimney prototype (Fig. 2)

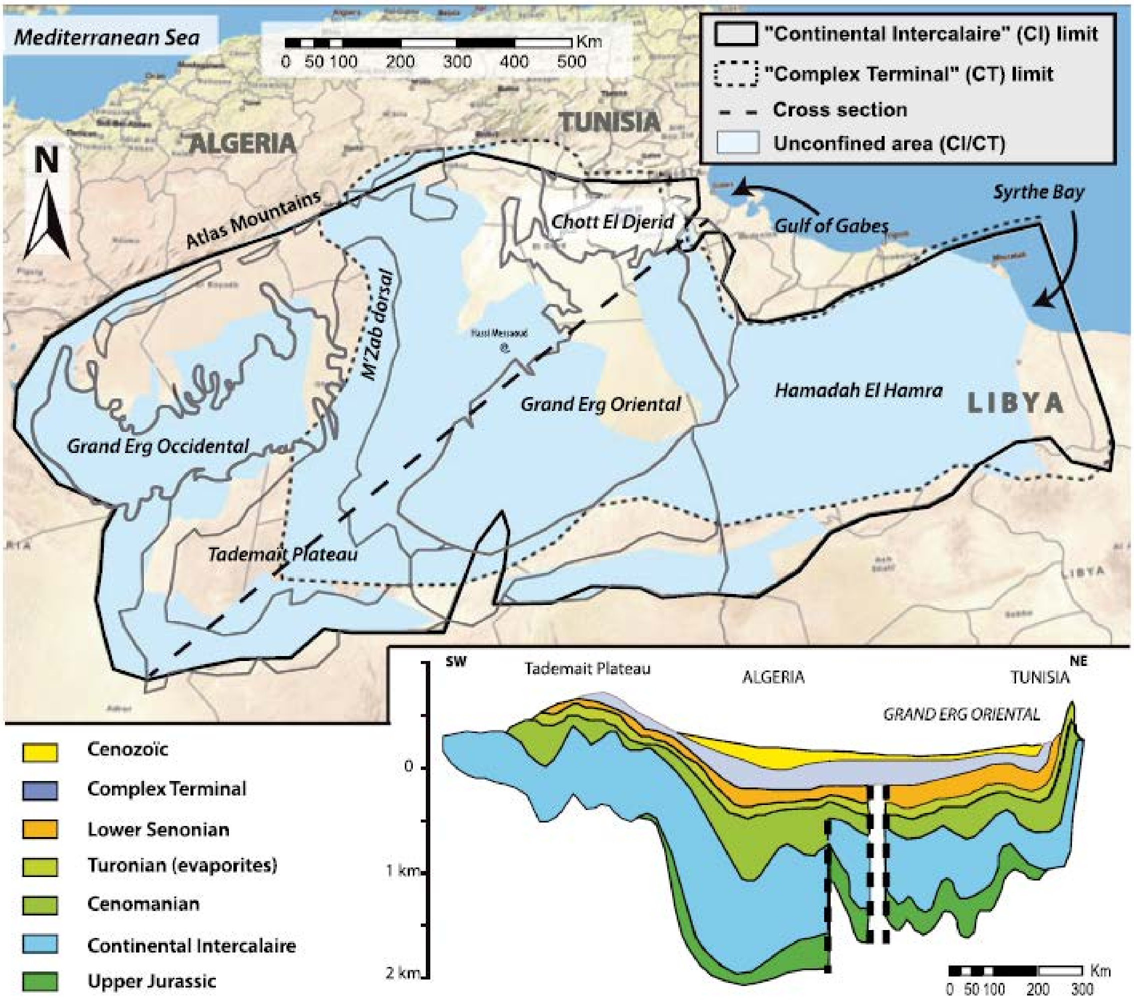

Fig. 1. Situation map of the North-Western Sahara Aquifer System (NWSAS), the inset shows a schematic cross-section and represents the main Albian aquifers' geometry, South Algeria [36].

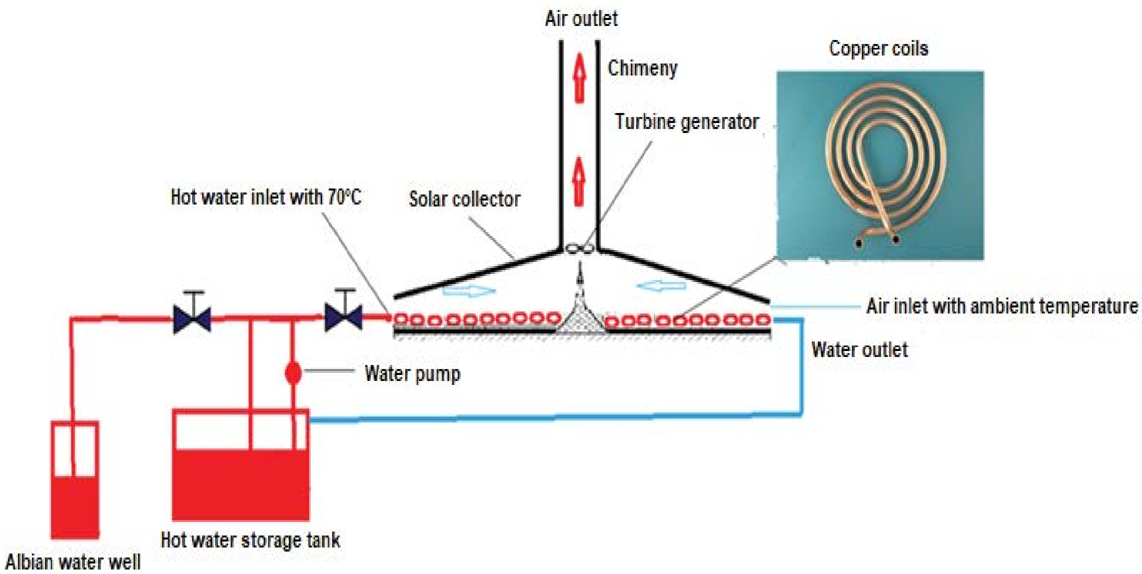

Fig. 2. Schematic layout of the proposed solar chimney power plant integrated with geothermal source (Albian water).

was implemented in the University of Kasdi Merbah-Ouargla. The small-scale prototype (Figs. 3 and 4) consisted of a 12 m diameter collector and a chimney with a 20 cm diameter and 8 m height. The chimney was a pipe isolated by glass wool and supported by steel beams.

The collector was constructed using steel beams in addition to a steel wired network used to support a clear plastic cover. The collector was designed with a tilt angle of approximately 8° to allow water drainage in the event of rain. The ground was covered with black plastic to enhance the absorption of solar irradiance and to increase the greenhouse effect. The main geometric parameters of the SCPP are summarised in Table 1.

3.1. Collector structure

The collector is an essential element for producing hot air by the greenhouse effect. Adequate thermal insulation must be provided at the ground to improve the performance of this device. To prepare the collector location, we excavated the ground to a 0.3-m depth to deposit the six layers of the insulation system (Figs. 5 and 6).

3.2. Measurement instrumentation

For the temperature measurements inside the collector at predefined positions, we used a *K*-type thermocouple with a maximum continuous temperature of approximately

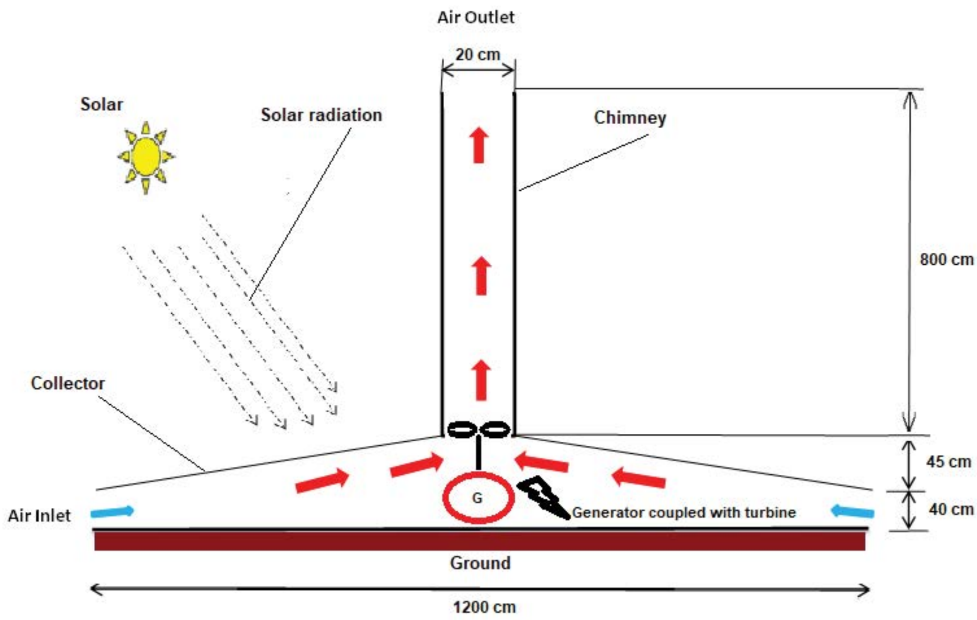

Fig. 3. Prototype solar chimney power plant schematic layout.

Fig. 4. Solar chimney prototype installed at the University of Kasdi Merbah Ouargla.

Table 1
Main geometric parameters of the solar chimney prototype

Parameters	Value
Collector area, m^2	113.04
Chimney height, m	8
Height from collector inlet to ground level, m	0.4
Chimney diameter, m	0.2
Height from collector outlet to ground level, m	0.85
Collector mean tilt angle, degree	≈8°

1,100°C and ±2.2°C accuracy. The ambient temperature was recorded by a Mac Solar digital thermometer fixed outside the chimney during the experiment. The solar irradiance was measured by a Mac Solar global irradiance measuring device with a measuring range from 0 to 1,250 W/m². The air velocity was measured using a portable hot wire probe with velocity ranging from 0.6 to 40 m/s with ±0.2 m/s accuracy.

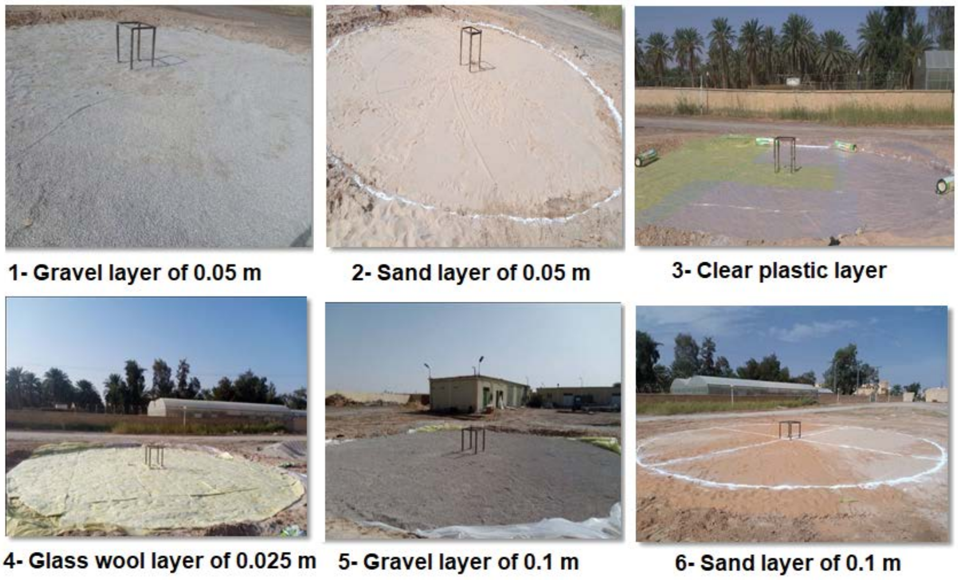

Fig. 5. Different steps for preparing the collector ground.

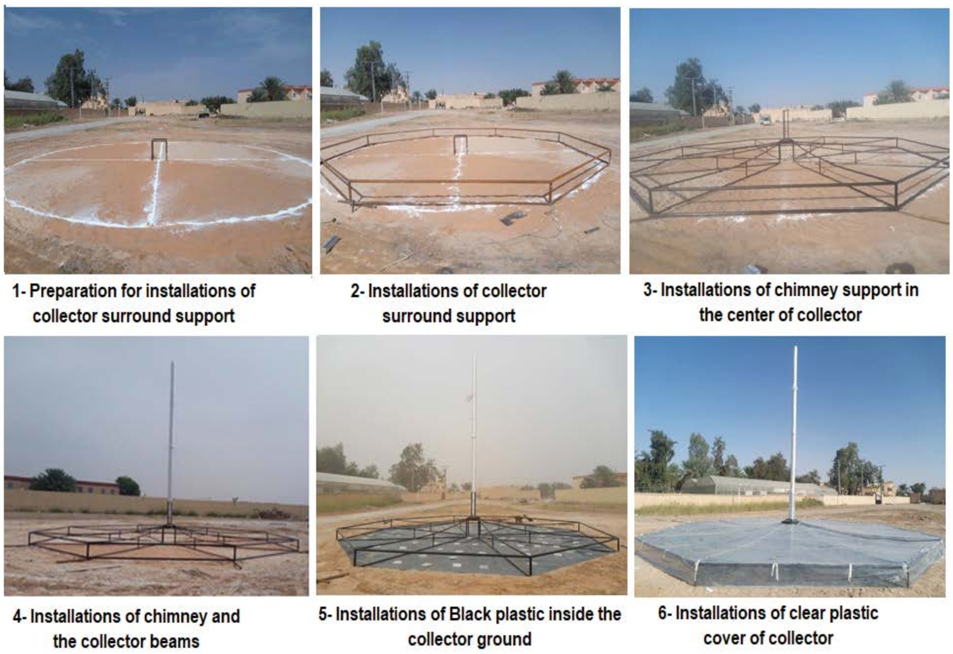

Fig. 6. Different steps for the construction of the collector roof.

3.3. Heat exchange system integrated with the solar chimney

Due to the unavailability of the Albian water at the University of Ouargla, where the prototype was implemented and to heat the water to temperatures close to that of natural Albian water, which is approximately 70°C, we used an electrical heater. The hot water circulated in a coaxial coil installed inside the collector utilising an electrical pump. Therefore, the hot water contributed to the heating of the air inside the collector and promoted the thermosiphon phenomenon, improving the system performance and extending operation of the hybrid chimney overnight (Figs. 7 and 8).

4. Evaluation of solar chimney power output

Based on the work of Aurybi et al. [29], we calculated the parameters affecting the overall efficiency, power output, and air velocity at the chimney inlet. This latter parameter is calculated using Eq. (1).

$$V_{\mathrm{Ch,In}} = \sqrt{2gH_{\mathrm{Ch}}\frac{T_{\mathrm{air}} - T_{\mathrm{amb}}}{T_{\mathrm{amb}}}} \tag{1}$$

In which $V_{\mathrm{Ch,In}}$: air velocity at the chimney inlet, g: gravitational acceleration, m/s^2; H_{Ch}: chimney height, m; T_{amb}: ambient air temperature, K; T_{air}: temperature of the air inside the collector were calculated using Eq. (2).

$$T_{\mathrm{air}} = \frac{T_{\mathrm{air,out}} - T_{\mathrm{air,in}}}{2} \tag{2}$$

In which $T_{\mathrm{air,in}} = T_{\mathrm{amb}}$, ambient temperature (K).

The air velocity at the chimney inlet can also be written as Eq. (3).

Fig. 7. Electrical water heater integrated with solar chimney power plant.

Fig. 8. Copper coil installed inside the solar chimney collector.

$$V_{\text{Ch,In}} = C_d \sqrt{2gH_{\text{Ch}} \frac{T_{\text{air}} - T_{\text{amb}}}{T_{\text{amb}}}} \quad (3)$$

In which C_d is the coefficient of discharge according to previous experimental work. This factor depends on the geometry and can be calculated using Eq. (4).

$$C_d = \frac{V_{\text{exp}}}{V_{\text{Ch,In}}} \quad (4)$$

The air mass flow rate inside the chimney can be calculated using Eq. (5).

$$\dot{m}_a = \rho_{\text{air}} A_{\text{Coll}} V_{\text{Ch,In}} \quad (5)$$

Also, according to Aja et al. [30], the geothermal energy Q_{geo} can be calculated using Eq. (6).

$$Q_{\text{geo}} = \eta_w \frac{\dot{m}_w c_{\text{Pw}} \left(T_{\text{wi}} - T_{\text{wo}}\right)}{A_{\text{Coll}}} \quad (6)$$

According to Bernardes et al. [38], the maximum power from the air gained by the turbine is given by Eq. (7).

$$P_{\text{Turb,Max}} = C \cdot V_{\text{Ch,In}} \cdot A_{\text{Ch}} \cdot \rho_{\text{air}} \cdot g \cdot H_{\text{Ch}} \cdot \left(\frac{T_{\text{air}} - T_{\text{amb}}}{T_{\text{amb}}}\right) \quad (7)$$

In which the constant C represents the ratio of the turbine pressure drop to the total pressure potential, and this coefficient has different values between 0 and 1 [38], and the ideal value is 2/3.

The electrical power can also be evaluated by Eq. (8).

$$P_{\text{ele}} = \eta_{\text{Turbine}} \cdot \eta_{\text{generator}} \cdot P_{\text{Turb,max}} \quad (8)$$

In which the efficiency values η_{Turbine}, $\eta_{\text{generator}}$ for turbine and generator are, respectively, 0.8 and 0.95.

5. Results and discussion

In this section, we present the main results obtained during the experimental investigation. Our goal is to highlight the effect of using Albian water on the aerothermal behaviour of a solar chimney. We are interested in the behaviour of a conventional chimney under the influence of the meteorological conditions of southeastern Algeria, and then we will analyse the effect of integrating a system producing hot water to a solar chimney.

5.1. Effect of environmental parameters on the conventional solar chimney

The considered environmental parameters are solar radiation and ambient temperature. The performance of the solar chimney is estimated through the air velocity measured at the inlet of the chimney. On 8th of February 2017, as shown in Fig. 9, the air velocity varied proportionally to the solar radiation. After sunrise, the solar irradiance and air velocity were 539 W/m² and 1.24 m/s, respectively. The maximum values occurred at approximately 14:00 h and then decreased to minimum values after sunset.

For the same day, 8th of February 2017, Fig. 10 presents the temporal evolution of the ambient temperature and the measured air velocity. As observed in Fig. 9, the air velocity varied proportionally to the ambient temperature. It is impossible to conclude whether the ambient temperature improved the performance of the solar chimney because, in this case, there are simultaneous effects of solar radiation and ambient temperature.

5.2. Behaviour of the hybrid solar chimney

By using an additional source of energy, which is in our case was hot water, and a suitable heat exchanger that promotes heating of the air in the collector, we improved the natural convection. We conducted overnight analyses of hybrid solar chimney energy production also, and as depicted in Fig. 11, after 19:00 h, the airflow produced by the conventional solar chimney was practically zero. However, after integrating the water heater, we recorded an average air velocity of 2.8 m/s overnight. Between 10:00 h and 16:00 h, the measured air velocities were relatively the same

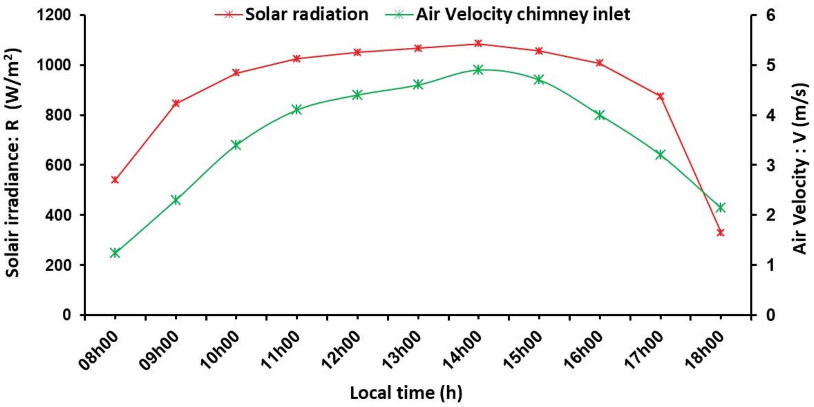

Fig. 9. Measured solar irradiance and air velocity vs. local time on 8th of February 2017, without water heater integration.

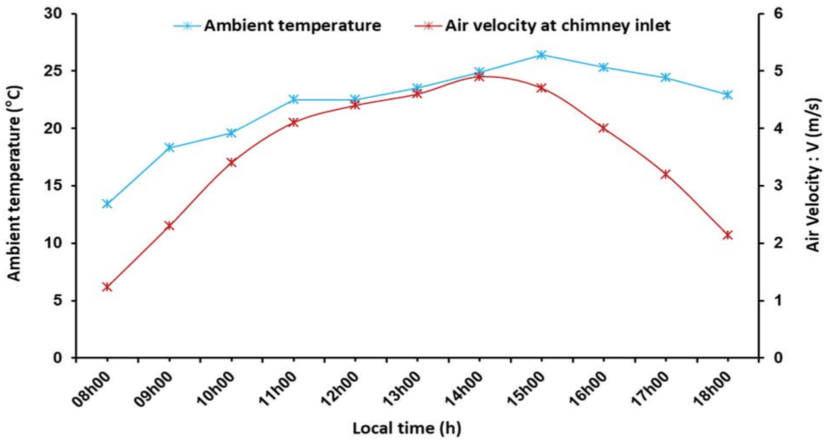

Fig. 10. Measured ambient temperature and air velocity vs. local time on 8th of February 2017, without water heater integration.

with and without a water heater. It is therefore important to highlight that the use of the water heater has a significant effect only during the night.

The results shown in Fig. 12 show the temporal evolution of different measured parameters such as water temperatures at the inlet and the outlet of the coaxial coil, ambient temperature and the air velocity at the inlet of the chimney recorded during 27th and 28th of February 2017.

The difference between the water temperature at the inlet and the outlet varied. Between 10:00 h and 16:00 h, this difference was minimal and therefore the air was heated in the collector mainly due to solar radiation. Convective heat transfer between air and hot water became dominant when the solar radiation decreased, reflected in Fig. 12 by the increase in the water temperature gradient. Noting the recorded values of air velocity, solar radiation, and water temperature gradient, it is clear that, during the day, the solar chimney was governed by the effect of solar radiation, and during the night, the solar chimney continued to produce energy due to the integrated hot water system.

Fig. 13 shows the temporal evolution of solar radiation and ambient temperature on 8th and 27th of February 2017. During these 2 d, there was no significant difference between the meteorological parameters. This allowed us to compare the power output of the conventional solar chimney recorded on 8th of February, and that produced on 27th of February by a solar chimney coupled to a source of hot water.

5.3. Solar chimney power output estimation

The variation of the power produced by a solar chimney with and without an integrated water heater is illustrated in Fig. 14. Measurements were performed during 8th, 27th and 28th of February 2017. The hybrid chimney produced overnight energy equivalent to 226.5 Wh and the average power recorded overnight was 18.9 W. The peak of production was observed between 12:00 and 15:00 h with a maximum power produced by the conventional chimney of 66.3 and 79.8 W with the integration of a water heater. During the day with the effect of solar radiation, the energy produced by the SCPP with and without the water heater was 771.5 and 376.5 Wh, respectively. Notably, the improvement in continuous energy production resulting from the use of the hot water source can be estimated at approximately 165%.

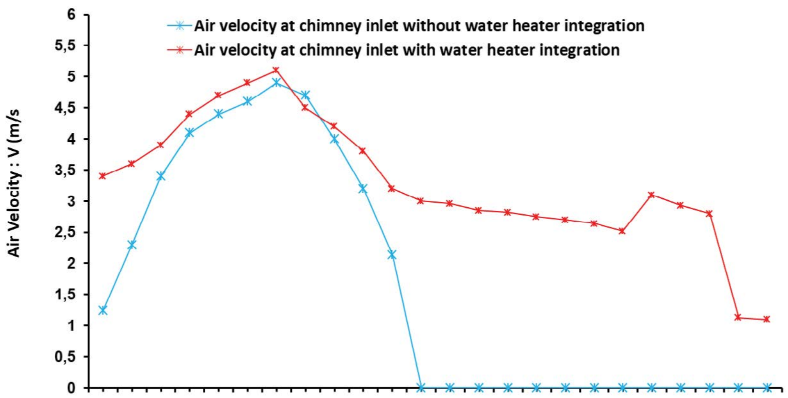

Fig. 11. Temporal variation of air velocity at the chimney inlet with and without water heater integration.

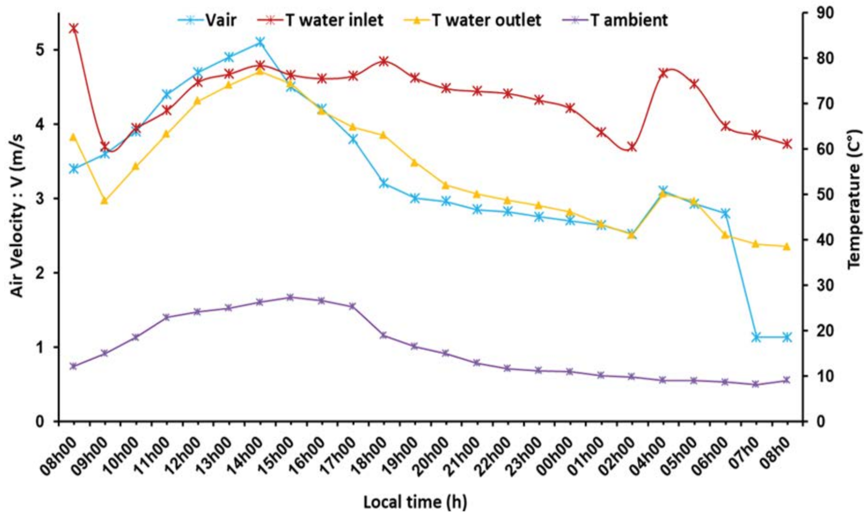

Fig. 12. Variation of air velocity, water temperature inlet and outlet in the solar chimney at night vs. local time 27th and 28th of February 2017, with water heater integration.

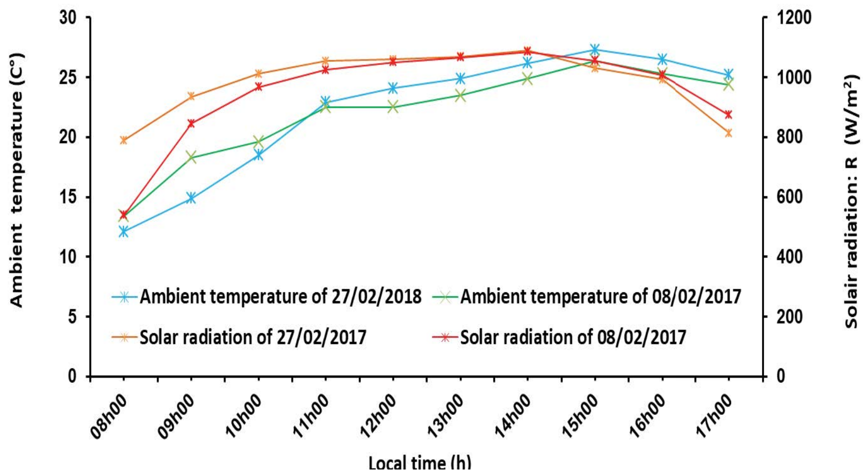

Fig. 13. Meteorological parameters of the days of 8th and 27th February 2017.

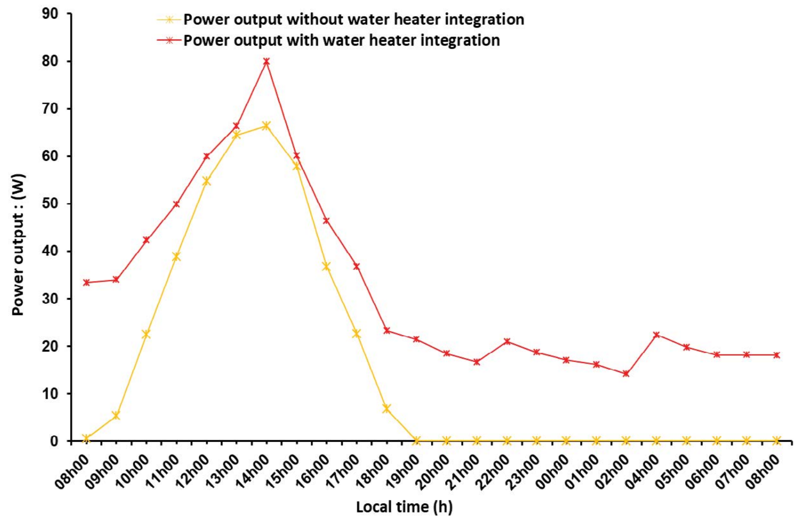

Fig. 14. Variation of power output of the solar chimney power plant with and without water heater integration.

6. Conclusions

The solar chimney is a promising technique for producing electricity in a renewable way by using solar radiation. The disadvantage of SCPP is the impossibility of ensuring the production of electricity at night. To remedy this shortcoming, we proposed the use of an external heat source to replace the solar energy during the night and in case of a cloudy sky. The proposed heat source is natural underground geothermal water (Albian water) which is present in considerable quantities in southern Algeria and especially in Ouargla province, where the small-scale prototype of the SCPP is implemented. Due to challenges of cost and lack of nearby drilling into the geothermal source, we used an electric water heater as a replacement.

The results of this study reveal that the proposed configurations improved the performance and the efficiency and allow for maintenance of continuous operation of the power plant. The maximum air velocity measured without and with water heater integration were, respectively, 4.9 and 5.1 m/s, and the maximum values of power output were, respectively, 66.3 and 79.8 W. During this study, we observed an increase of 165% in the energy produced by SCPP due to the use of a hot water source. It is also important to note that the hot natural water after passing through the solar chimney will cool and therefore become more suitable for irrigation.

Acknowledgments

The authors wish to thank the Mechanical Engineering Laboratory, Institute of Technology, Hassiba Benbouali University, Chlef, and Process Engineering Laboratory, KASDI Merbah University of Ouargla, Algeria, for sponsorship as part of the preparation of this research.

Symbols

A_{ch}	—	Chimney area, m^2
A_{Coll}	—	Collector area or absorber surface area
C_d	—	Coefficient of discharge
H_{Ch}	—	Chimney height, m
$\dot{m}_a$	—	Mass flow rate of air in collector, kg/s
Q_{geo}	—	Geothermal energy, kJ
T_{amb}	—	Ambient air temperature, K
T_w	—	Water temperature, K
$\dot{m}$	—	Mass flow rate of air in collector, kg/s
g	—	Gravitational acceleration, m/s^2
$\dot{m}_w$	—	Mass flow rate of water, kg/s
$P_{tur, max}$	—	Maximum mechanical power produced by wind turbine, W m^2
V_{Ch}	—	Maximum air velocity at chimney inlet, m/s
η_{tur}	—	Turbine efficiency
η_{gen}	—	Generator efficiency
P_{ele}	—	Electrical power produced by the SCPP
T_{air}	—	Hot air temperature, K
ρ_{Ch}	—	Air density in the chimney, kg/m^3
V_{exp}	—	Experimental air velocity at chimney inlet
$V_{Ch,in}$	—	Calculated air velocity at the chimney inlet

References

[1] R. de Richter, T.Z. Ming, P. Davies, W. Liu, S. Caillol, Removal of non-CO_2 greenhouse gases by large-scale atmospheric solar photocatalysis, Prog. Energy Combust. Sci., 60 (2017) 68–96.
[2] M.H. Sellami, S. Guemari, R. Touahir, K. Loudiyi, Solar distillation using a blackened mixture of Portland cement and alluvial sand as a heat storage medium, Desalination, 394 (2016) 155–161.
[3] W. Haaf, K. Friedrich, G. Mayr, J. Schlaich, Solar chimneys Part I: Principle and construction of the pilot plant in Manzanares, Int. J. Sol. Energy, 2 (1983) 3–20.
[4] W. Haaf, Solar chimneys, Part II: Preliminary test results from the Manzanares pilot plant, Int. J. Sol. Energy, 2 (1984) 141–161.
[5] M. Al-Dabbas, A performance analysis of solar chimney thermal power systems, Therm. Sci., 15 (2011) 619–642.
[6] T. Ming, W. Liu, G. Xu, K. Yang, Thermodynamic analysis of solar chimney power plant system, J. Huazhong Univ. Sci. Technol., 33 (2005) 1–4.
[7] M.O. Hamdan, Analysis of a solar chimney power plant in the Arabian Gulf region, Renewable Energy, 36 (2011) 2593–2598.
[8] M.A. dos S. Bernardes, A. Voß, G. Weinrebe, Thermal and technical analyses of solar chimneys, Sol. Energy, 75 (2003) 511–524.
[9] T.Z. Ming, Y. Zheng, C. Liu, W. Liu, Y. Pan, Simple analysis on thermal performance of solar chimney power generation systems, J. Energy Inst., 83 (2010) 6–11.
[10] Y.J. Choi, D.H. Kam, Y.W. Park, Y.H. Jeong, Development of analytical model for solar chimney power plant with and without water storage system, Energy, 112 (2016) 200–207.
[11] Y.J. Dai, H.B. Huang, R.Z. Wang, Case study of solar chimney power plants in Northwestern regions of China, Renewable Energy, 28 (2003) 1295–1304.
[12] T. Chergui, A. Bouhadjar, Abd. Boualit, M. Lebbi, L. Boutina, S. Larbi, Improved Thermo-Hydrodynamic Field Quality in the Solar Chimneys, 6th International Renewable Energy Congress: IREC, Sousse, Tunisia, 2016, pp. 1–7.
[13] A. Kasaeian, M. Ghalamchi, M. Ghalamchi, Simulation and optimization of geometric parameters of a solar chimney in Tehran, Energy Convers. Manage., 83 (2014) 28–34.
[14] L. Shiv, S.C. Kaushik, R. Hans, Experimental investigation and CFD simulation studies of a laboratory scale solar chimney for power generation, Sustainable Energy Technol. Assess., 13 (2016) 13–22.
[15] F. Cao, H.S. Li, L. Zhao, T.Y. Bao, L.J. Guo, Design and simulation of the solar chimney power plants with TRNSYS, Sol. Energy, 98 (2013) 23–33.
[16] T.Z. Ming, W. Liu, Y. Pan, G.L. Xu, Numerical analysis of flow and heat transfer characteristics in solar chimney power plants with energy storage layer, Energy Convers. Manage., 49 (2008) 2872–2879.
[17] T.Z. Ming, W. Liu, G.L. Xu, Analytical and numerical investigation of the solar chimney power plant systems, Int. J. Energy Res., 30 (2006) 861–873.
[18] G.L. Xu, T.Z. Ming, Y. Pan, F.L. Meng, C. Zhou, Numerical analysis on the performance of solar chimney power plant system, Energy Convers. Manage., 52 (2011) 876–883.
[19] T.Z. Ming, R.K. de Richter, F.L. Meng, Y. Pan, W. Liu, Chimney shape numerical study for solar chimney power generating systems, Int. J. Energy Res., 37 (2013) 310–322.
[20] T.Z. Ming, Y.J. Wu, R.K. de Richter, W. Liu, S.A. Sherif, Solar updraft power plant system: a brief review and a case study on a new system with radial partition walls in its collector, Renewable Sustainable Energy Rev., 69 (2017) 472–487.
[21] A.R. Shahreza, H. Imani, Experimental and numerical investigation on an innovative solar chimney, Energy Convers. Manage., 95 (2015) 446–452.
[22] P. Das, V.P. Chandramohan, Performance characteristics of divergent chimney solar updraft tower plant, Int. J. Energy Res., (2020) 1–16, https://doi.org/10.1002/er.5304.

[23] L. Zuo, Y. Yuan, Z.J. Li, Y. Zheng, Experimental research on solar chimneys integrated with seawater desalination under practical weather condition, Desalination, 298 (2012) 22–33.
[24] M.R. Jemli, N. Naili, A. Farhat, A. Guizani, Experimental investigation of solar tower with chimney effect installed in CRTEn, Tunisia, Int. J. Hydrogen Energy, 42 (2017) 8650–8660.
[25] T.Z. Ming, Z. Zhou, W. Liu, Y. Pan, Experimental Investigation of Heat Transfer and Flow Characteristics in a Solar Chimney Prototype, Inaugural US-EU-China Thermophysics Conference-Renewable Energy 2009 (UECTC 2009 Proceedings, ASME Press, 2009.
[26] M. Ghalamchi, A. Kasaeian, M. Ghalamchi, Experimental study of geometrical and climate effects on the performance of a small solar chimney, Renewable Sustainable Energy Rev., 43 (2015) 425–443.
[27] L. Zuo, Z.H. Liu, L. Ding, N. Qu, P.Z. Dai, B.F. Xu, Y. Yuan, Performance analysis of a wind supercharging solar chimney power plant combined with thermal plant for power and freshwater generation, Energy Convers. Manage., 204 (2020) 112282.
[28] J.P. Pretorius, Optimization and Control of a Large-Scale Solar Chimney Power Plant, Thesis, University of Stellenbosch, 2007.
[29] O.C. Aja, H.H. Al-Kayiem, A.A.K. Zainal, Review on the enhancement techniques and introduction of an alternate enhancement technique of solar chimney power plant, J. Appl. Sci.,11 (2011) 1877–1884.
[30] O.C. Aja, H.H. Al-Kayiem, A.A.K. Zainal, Thermal Field Study and Analysis in Hybrid Solar Flue Gas Chimney Power Plant, National Postgraduate Conference. NPC, IEEE, Kuala Lumpur, Malaysia, 2011, pp. 1–6.
[31] M.A. Aurybi, S.I. Gilani, H.H. Al-Kayiem, A.A. Ismaeel, Mathematical evaluation of solar chimney power plant collector, integrated with external heat source for non-interrupted power generation, Sustainable Energy Technol. Assess., 30 (2018) 59–67.
[32] F. Cao, H.S. Li, Q. Ma, L. Zhao, Design and simulation of a geothermal–solar combined chimney power plant, Energy Convers. Manage., 84 (2014) 186–195.
[33] X.P. Zhou, Y.Y. Xu, Daily dynamic performance of a solar chimney power plant integrated by waste heat recovery, IET Renewable Power Gener., 14 (2020) 270–274.
[34] M.H. Sellami, K. Loudiyi, Electrolytes behavior during hydrogen production by solar energy, Renewable Sustainable Energy Rev., 70 (2017) 1331–1335.
[35] A. Azizi, T. Tahri, M.H. Sellami, L. Segni, R. Belakroum, K. Loudiyi, Experimental and CFD investigation of small-scale solar chimney for power generation. Case study: southeast of Algeria, Desal. Water Treat., 160 (2019) 1–8.
[36] J. Gonçalvès, J. Petersen, P. Deschamps, B. Hamelin, O. Baba-Sy, Quantifying the modern recharge of the “fossil” Sahara aquifers, Geophys. Res. Lett., 40 (2013) 2673–2678.
[37] UNESCO, Northern Sahara Water Resources Studies, United Nations Development Program Special Fund Component, 1972.
[38] M.A. dos Santos Bernardes, T.W. von Backström, Evaluation of operational control strategies applicable to solar chimney power plants, Sol. Energy, 84 (2010) 277–288.