

A NUMERICAL study of solar chimney power plants in Tunisia

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Abstract. A 3D CFD (Computational fluid dynamics) model of a Solar Chimney Power Plant (SCPP) was developed and validated through comparison with the experimental data of the Manzanares plant. Then, it was employed to study the SCPP performance for locations throughout Tunisia.

Key words: solar power, solar chimney, Numerical study.

1. Introduction

The solar chimney power facility has the potential to become a valuable technology for renewable electrical energy production. However, its financial viability depends on a thorough understanding of the processes affecting its performance, particularly because of the large startup costs associated with facility design and construction. The first solar chimney prototype was built in Manzanares Spain with a chimney that has a height of 195 m and a diameter of 10 m, surrounded by a collector 240 m in diameter [1,2]. The power output produced by this plant was about 50 kW. Other prototypes were built in Algeria [3] and Iran [4]. Larger projects are planned in Australia and Spain.

High levels of direct solar radiations and large available lands in Tunisia's desert are major factors to encourage the development of solar power plants for both thermal and electrical energy production for various uses. Among these, Solar Chimney Power Plants (SCPP) are quite attractive, for their technological simplicity but mainly because they do not require cooling nor the use of water, a scarce resource in the desert. The present work is the first step of a research program aimed at studying the performance of the solar chimney plants in the Tunisian context.

2. Methodology

The numerical simulations were performed for steady flow using the commercial CFD package ANSYS Fluent [5]. They involved the simultaneous solutions of the continuity, momentum and energy equations. Given that the turbulent flow inside the chimney power plant system is induced because of the density variation with temperature, the RNG k- ϵ turbulence model including buoyancy



effects (Boussinesq approximation) was considered. The Simple algorithm was selected as the pressure-velocity coupling scheme and the convective terms were discretized with a first order upwind scheme. The Presto! algorithm was selected for the treatment of the pressure in the momentum equation. Structured grid was adopted and it was adaptively refined in the vicinity of the walls.

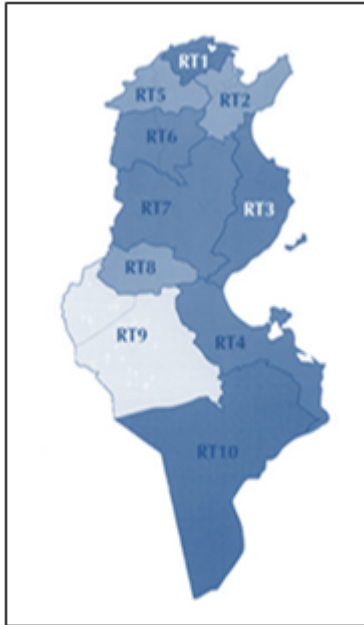


Figure 1. Locations of 10 selected regions for solar chimney power plant (SCPP) performance evaluation in Tunisia [6].

The SCPP is presented schematically in Figure 2. The main aerodynamic boundary conditions are listed in Table 1. The thermal boundary conditions are considered adiabatic except for the surface of the collector, where an incoming radiation is imposed, and the ground, where the constant soil temperature at a depth of 5 m is used as boundary condition. This temperature is obtained by solving the space-time heat equation in the soil during a year.

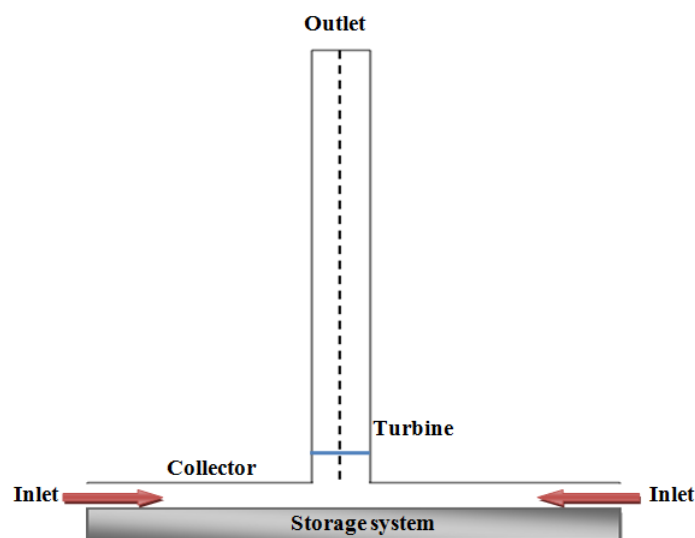


Figure 2. The Solar chimney plant schematic layout.

The solar Load model provided by Fluent was adopted to estimate this solar radiative heat. The latter was modeled using the sun position vector and the illumination parameters. Such a model is an efficient and practical approach to applying solar loads as heat sources in the energy equations.

Table.1. The thermal and aerodynamic boundary conditions for the SCPP simulations.

Boundary conditions	Type
Surface of the chimney	Wall, adiabatic
Surface of the collector	Mixed semi-transparent wall, (radiation, convection)
Inlet of the collector	Pressure inlet, (P gage=0Pa, T _{inlet})
Outlet of the chimney	Pressure outlet (P _{gage} = 0Pa)
Bottom of the ground	Wall (T= T _{ground})
Pressure drop across the turbine	Reversed Fan

The numerical method was validated using the experimental data of the Manzanares prototype [1], [2]. In fact, as shown in Figure 3, a good agreement is obtained between the numerical results and the experimental data.

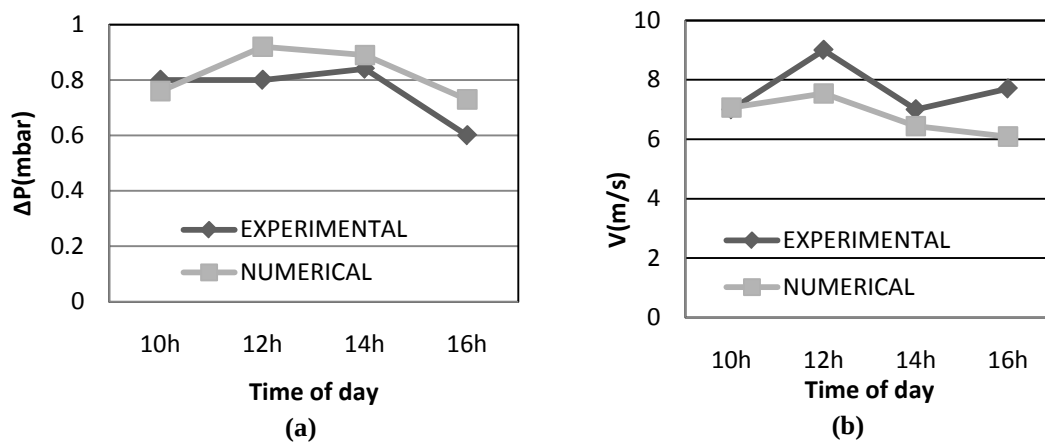


Figure 3. Comparison of the calculated and experimental (a) pressure drop across the turbine and (b) outlet velocities, for September 2, 1989.

3. Numerical and Theoretical Results

As a first step in the study of the SCPP performance in the Tunisian context, we've considered geometrically similar plants to that of Manzanares implemented in 10 different regions of the country. Information about these regions are presented in the Table 2. Annual solar radiation of the major selected regions is more than 5700 MJ/m². The average annual ambient temperature lies between 19°C and 23.5°C.

Table.2. Annual global solar radiation and atmospheric conditions of 10 selected regions in Tunisia [6].

Region	Longitude	Latitude	Average annual ambient temperature (°C)	Average annual wind speed (m/s)	Annual solar radiation [MJ/m ²]
Rt1 Bizerte	9°48'E	37°15'N	19.9	3.7	6168
Rt2 Tunis	10°14'E	36°50'N	20.6	4.3	6168
Rt3 Sfax	10°41'E	34°43'N	21.2	3.7	6782
Rt4 Djerba	10°46'E	33°52'N	21.8	3.3	6651
Rt5 Jendouba	8°48'E	36°29'N	20.5	2.5	5701
Rt6 Siliana	9°22'E	36°04'N	19.6	3.1	5701
Rt7 Kairouan	10°06'E	35°40'N	21.9	2.2	6691
Rt8 Gafsa	8°49'E	34°25'N	21.7	3.9	6732
Rt9 Tozeur	8°06'E	33°55'N	23.4	4.9	6733
Rt10 Rameda	10°24'E	32°19'N	23.1	2.9	6732

Figure 4 and figure 5 shows, respectively, the monthly and the annual power output from the reference SCPP at various locations, calculated with the average conditions presented in Table 2. For these preliminary calculations, the incoming solar radiation was simply estimated from the total annual value divided by the total sun hours. As expected the power output profile is proportional to the solar radiation profiles among the considered regions. Summing the results shows that the SCPP can produce from 109 to 140 MWh/year in the selected regions. It can be observed that Tozeur and Remeda have the highest power generation per year of all the studied regions.

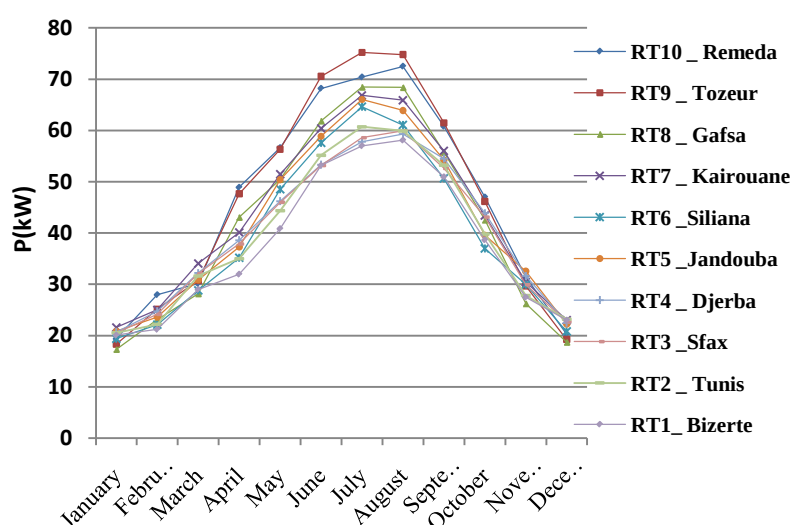


Figure 4. Monthly electrical power generation of the SCPP in selected regions of Tunisia.

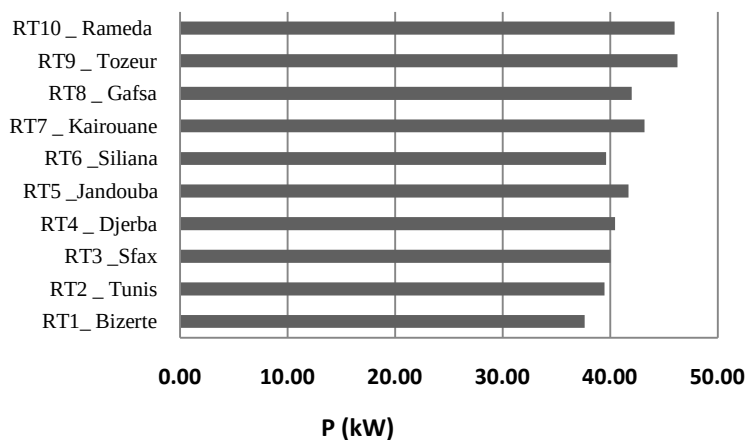


Figure 5. Annual electrical power generation of the SCPP in selected regions of Tunisia.

Figure 6 and Figure 7 show respectively the mass flow rate in the chimney and the power output of the system at the locations of Remada and Tozeur. The maximum mass flow rate and power output are observed in June, July and August when sunshine intensity and ambient temperature are at their maxima.

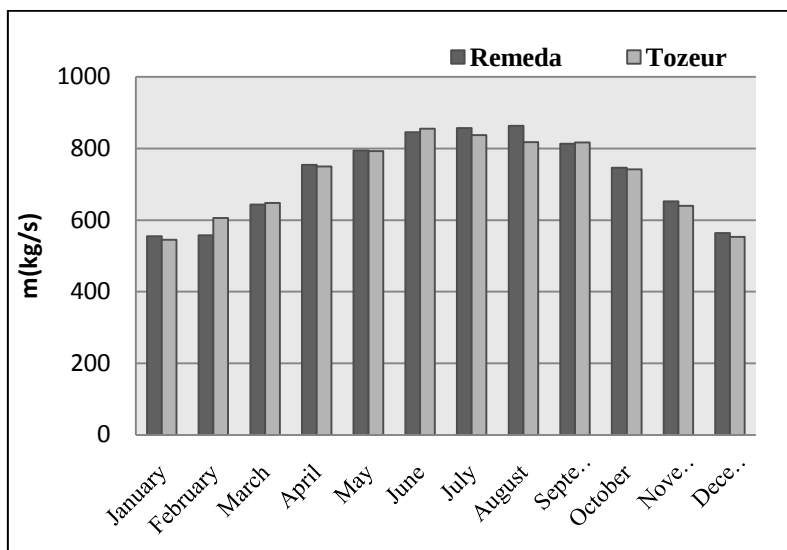


Figure 6. Mass flow rate at the chimney exit at two locations in Tunisia.

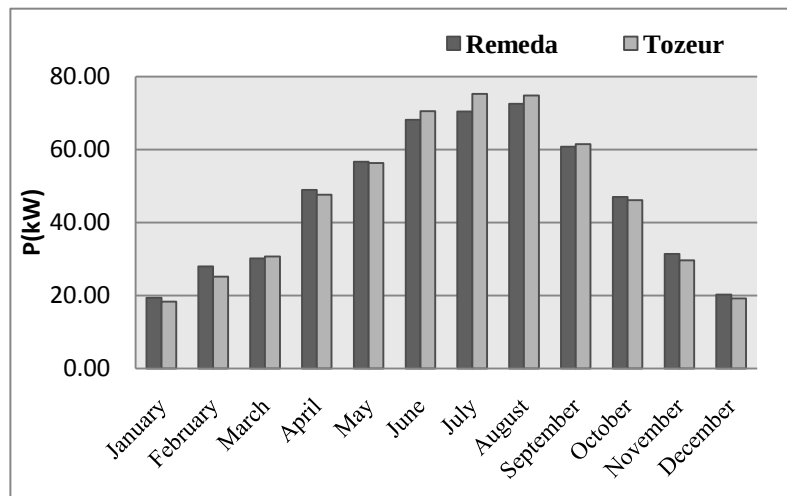


Figure 7. Monthly average SCPP power generation at two locations in Tunisia.

These results show that the solar chimney power plant can produce monthly from 4 MWh (for the month of January) to 25 MWh (for the month of July) of electrical energy. Examples of daily variations of the updraft velocity, the pressure drop across the turbine, the SCPP electrical power generation and the collector efficiency in Tozeur and Remeda were calculated for the 15th July and the 1st January. The atmospheric conditions, needed for these calculations, are given in Table3.

Table 3. Atmospheric conditions in Tozeur and Rameda for July 15th and the 1st of January.

1 st January			15 th July		1 st January		15 th July	
Tozeur					Remeda			
	Ta	V(m/s)	Ta	V(m/s)	Ta (°C)	V(m/s)	Ta(°C)	V(m/s)
10h00	8.68	1.86	31	8.35	11,02	2,17	27,89	3,17
12h00	11.19	1.3	32.85	8.94	12,79	2,24	32,33	0,89
14h00	12.8	3.57	36.17	2.24	15,02	2,24	33,99	4,92
16h00	13.89	2.74	37.12	4.27	14,96	1,77	33,98	4,82

The updraft velocity and the pressure drop across the turbine are presented in Figure 8 and Figure 9, for plants located in Remeda and Tozeur. Typical days are shown, corresponding to the hot (July 15) and cold (January 1) seasons. The power output of the turbine, shown in Figure 10 is directly proportional to the pressure drop and the volume flow rate across it. For the hot season, higher values of updraft velocities and pressure drop are obtained for both locations.

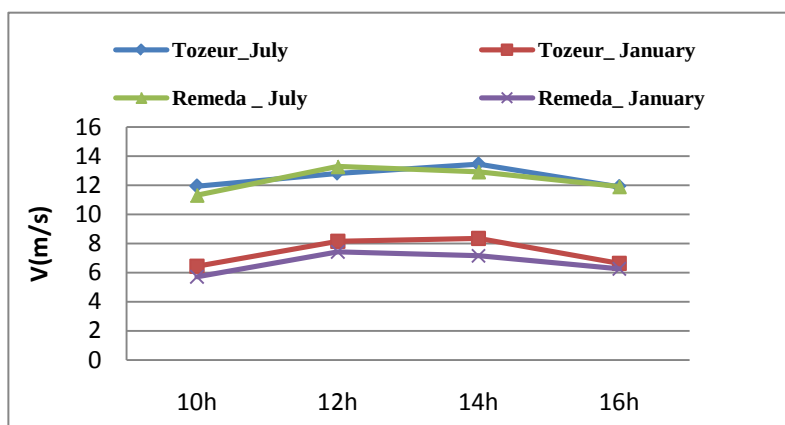


Figure 8 . The SCPP updraft velocity in m/s, for plants located in Tozeur and Remeda for the hot (July15th) and cold (1st of January) seasons.

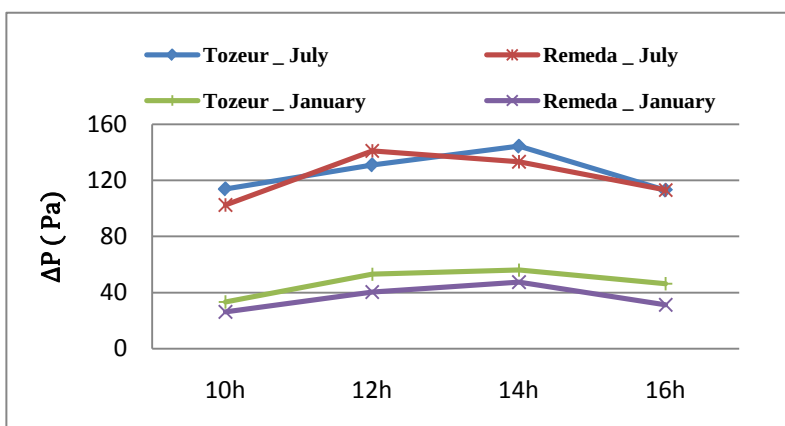


Figure 9 . The SCPP pressure drop, in Pa, for plants located in Tozeur and Remeda for the hot (July15th) and cold (1st of January) seasons.

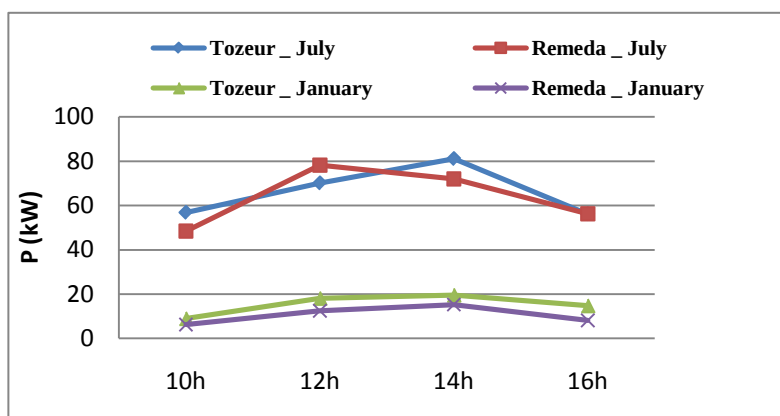


Figure 10. The SCPP electrical power generation, in kW, for plants located in Tozeur and Remeda for the hot (July15th) and cold (1st of January) seasons.

The collector efficiencies, defined as the ratio of heat carried by the air to the incoming solar radiation, for plants located in Tozeur and Remeda for the hot (15th July) and cold (1st January) seasons are shown in Figure 11. As expected, the collector efficiency is higher during hot season, and is affected by the wind speed. In fact, it decreases with increasing wind speed as the latter increases convective losses from the collector cover.

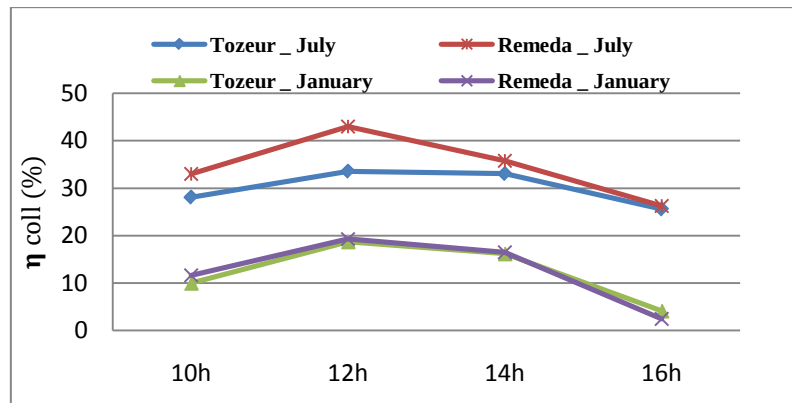


Figure 11. Collector efficiency in (%) for plants located in Tozeur and Remeda for the hot (15th July) and cold (1st January) seasons.

4. Conclusion

A 3D CFD model of a solar chimney power plant was developed and validated through comparison with the experimental data of the Manzanares SCPP. Then, it was employed to study the SCPP performance and power generation for locations throughout Tunisia. The power generation of a solar chimney in southern regions is higher than that of other regions in Tunisia due to the higher annual solar radiation and higher sunshine duration. Particularly, Remada and Tozeur present the highest power outputs with a slight advantage to the latter. There is a vast desert land and abundant solar radiation in southern Tunisia. Therefore, these regions are suitable for the construction of SCPP.

5. References

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