

Improving Electricity Production in Solar Chimney Power Plants with Sloping Ground Design: An Extensive CFD Research

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Abstract: Unlike other solar energy systems, solar chimney power plants (SCPPs) allow power output even when there is no sun. SCPPs are promising with their simple structure and 24-hour electricity production potential. Massive pressure tower in the system maintains continuous energy generation irrespective of climatic conditions. Solar energy harnessed by the huge collector area is transmitted to the ground material for sensible or latent heat storage purpose, and this stored energy during daytime yields to enhanced thermal and buoyant effects even after sunset. SCPPs are also in the centre of interest owing to their eco-friendly operation not causing any CO₂ emission. Design aspects in SCPPs are widely studied numerically by researchers. However, geometric design factors are merely analysed for collector and chimney, and very few attempts are done for the ground design. In the present work, a new design for ground is proposed in order to improve the energy stored in the ground material, and the upward movement of the air flow in the system from collector to chimney by changing the ground geometry. The upward movement of the air under the collector is enhanced with the new design created by inclining the ground at a distance of 21 m from the chimney inlet to a certain distance from the collector inlet. ANSYS WORKBENCH based CFD analysis is carried out based on the geometric dimensions of the Manzanares pilot plant. Analyses are based on a 90° 3D CFD model for the purpose of time saving in iterations. The CFD model is supported by RNG k-ε turbulence and DO (discrete ordinates) solar ray tracing models. After CFD results are verified with the experimental data, simulations are repeated for different designs and the ideal design is achieved. It is observed that the maximum air flow velocity, which is 14.202 m/s on the horizontal ground for the reference case, is improved by 34.1% in the new design to 19.046 m/s. In addition, it is seen that the power output of the reference case (54.333 kW) is enhanced by 23.04% to 66.855 kW.

Keyword: Solar chimney, Electricity production, Power output, Ground slope, Pressure distribution.

1. INTRODUCTION

In recent years, when energy sources have diversified and increased, scientists have turned to more studies on how energy is obtained rather than the amount. The fact that fossil fuels are predominant has alerted the developed and developing countries to environmental pollution and CO₂ emission issues. Technological developments have brought great innovations to the use of clean and renewable energy sources and made great contributions to increasing their efficiency. Solar energy is a great resource that can be an alternative to fossil fuels, both with its use in wide geographies and with its high potential. However, the biggest limitation of systems connected to solar energy is that they do not allow energy generation during hours when there is no sun. SCPPs differ from other solar energy systems by enabling electricity production during both onshine and offshine hours [1]. SCPPs are ideal systems for obtaining clean energy with zero CO₂ emission and simple structure consisting of collector, chimney and turbine [2].

Although theoretically dating back to the past, its first application was carried out in Spain in the 1980s [3]. The Manzanares prototype, with 122 m collector radius and 194.6 m chimney height, has been brought to the literature as the first facility to put solar chimney power plants from theory into practice [4]. When the experimental results obtained from the first facility are gone through, it is seen that they are consistent with the results achieved from previous theoretical studies. It is measured that the system gives a maximum power output of 50 kW at a solar intensity of 1000 W/m² [5]. Although the Manzanares prototype did not continue its operation in the following years, it has pioneered many studies to increase the performance of SCPP systems with mathematical, theoretical and CFD models developed in the light of experimental measurements [6]. Mullet [7] claimed that the efficiency of the system at 1000 m chimney height for large-scale systems will exceed 1%. The performances of small-scale systems and SCPP systems established in the following years have been experimentally investigated by researchers many times. Zhou *et al.* [8] designed a pilot SCPP with a collector in diameter of 10 m and a chimney height of 8 m by considering the cost and strength calculations of SCPP systems. They claimed that the temperature

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difference between collector outlet and ambient temperature could reach about 24.1 °C. Bugutekin [9] designed an experimental SCPP system with a collector diameter of 27 m and a chimney height of 17.15 m. A special layer was integrated to the ground to study the impact of energy storage on the system performance. Experimental results revealed that the temperature rise in the range of 21-26 °C at the collector outlet. Eryener *et al.* [10] emphasised that smaller collector areas can be used for the same power output by increasing the collector efficiency. For this purpose, some part of the collector surface was covered with polycarbonate. In line with the experimental results, they reported that the collector efficiency is increased 2 times compared to normal collectors and ranges between 60 and 80%. Ayadi *et al.* [11] developed a CFD model with a small-scale prototype of SCPP system. They evaluated the effect of changing the collector height on temperature, velocity, and pressure distribution in the system with reference to the 2.75 m diameter collector and 3 m prototype height. They found that increasing the collector height would reduce the power output. In SCPP systems, the collector is responsible for absorbing solar radiation as well as maintaining the system air underneath [12]. Kalash *et al.* [13] analysed the velocity and temperature distribution in the SCPP system which they built on a sloping ground. They stated that with the current system, the temperature rise in the system reaches 19 °C even in winter months, and the upward air velocity is 2.9 m/s. Koonsrisuk and Chitsomboon [14] carried out CFD simulations by creating a theoretical approach to analyse the effects of collector and chimney geometry on the performance of SCPP systems. They claimed that the divergent chimney structure compared to the standard cylindrical chimney design positively affects the system and increases the power output.

Researchers conducted a significant number of measurements on SCPPs with different geometric aspects, and they analysed the main performance parameters for different solar intensity and ambient temperature [15-17]. Since the experimental studies on SCPP systems do not provide much opportunity to change the geometric parameters, researchers focused on studying these effects by developing theoretical, numerical and CFD models through the results obtained from the experimental data. Since increasing the collector radius will increase the solar radiation reaching the system, it is a parameter that directly improves the system performance [18]. Ghalamchi *et al.* [19] reported that increasing the collector diameter

of the system increases the power output through the model they developed based on experimental results. They stated that a SCPP system with 500 m chimney height would give 468 kW power output with a collector of 420 m diameter, and when the collector diameter was 820 m, the power output would be quadrupled to approximately 1872 kW. In SCPP systems, the chimney is the driving element of the system that allows continuous power output with the pressure difference it creates owing to its height [1]. Since increasing the chimney height will increase the pressure difference in the system, it directly affects the power output. In the studies based on the geometric properties of the Manzanares pilot plant, the researchers claimed that the height of the chimney would notably increase the performance of the system [1,20-21]. On the other hand, Karimipor *et al.* [22] developed a CFD model based on the dimensional characteristics of the Manzanares pilot plant, and they claimed that making the chimney height of the existing system more than 400 m will not increase the power output of the system too much, and will even have a negative effect on the system after a certain point. Some researchers also analysed the influence of chimney height on power output in the systems designed in various geometries [23-28]. According to their findings, it has been widely accepted that increasing the chimney height in different geometries increases the performance of the system [18]. Although collector and chimney are the main structural elements of the system in SCPPs, there are different design aspects affecting the system performance. Collector height and structure are among the design factors that noticeably affect the performance of the system. Ayadi *et al.* [11] designed a small-scale system for experimental performance assessment. They also developed a CFD model with the results obtained from on-site tests. By repeating the CFD simulations, they analysed the temperature, pressure and velocity distributions in the system by varying the collector height 0.05, 0.10, 0.15 and 0.20 m. They claimed that increasing the collector height at 800 W/m² constant solar intensity and 306 K ambient temperature would reduce the chimney inlet velocity from 2.4 to 1.85 m/s and similarly reduce the power output by 33%. Toghraie *et al.* [26] designed a SCPP system with a chimney height of 100 m and a collector radius of 100 m, and analysed the performance through a CFD model. For this system with 2 m collector height and 8 m chimney diameter, they analysed the impacts of the change in geometric parameters on the system performance at 800 and 600 W/m² of solar intensity values, and ambient tempera-

ture of 308 K. They found that when the collector height was in the reference geometry at solar radiation of 800 W/m², the power output would be 78.61 kW and the power output would be 60 kW, decreasing 23.6% when the collector height was 4 m. They stated that a similar effect would be seen in the efficiency of the system. Esfidani *et al.* [29] proposed a mathematical model referencing the Manzanares pilot plant, and they analysed the effect of increasing the collector height on the power output and efficiency of the system for 300 K ambient temperature. They reported that the system efficiency and the power output are 0.79% and 298.387 kW, respectively at the reference case. However, when the reference collector height is changed to 4 m, the efficiency of the system would decrease by 26.6% to 0.55% and the power output would be 211.29 kW, decreasing by 29.1%. Gitan *et al.* [30] also conducted a mathematical study based on the geometric dimensions of the Manzanares pilot plant. They evaluated the impact of collector slope on the performance of the SCPP system likely to be installed in Malaysian climatic conditions. They claimed that the maximum power output could be obtained at 10° collector slope. 3.5 kW more power is achieved than the horizontal collector, with a maximum collector efficiency of 51% and a maximum system efficiency at 0.165%. The effect of collector slope on the performance of SCPPs is evaluated by researchers also for different geometries [19,31-35]. When evaluating the effect of the collector slope on the system for different geometries, it is seen that a separate evaluation should be made for each system. Ikhlef and Larbi [36] investigated the effect of chimney diameter on the performance of the system with a mathematical model based on the Manzanares pilot plant. They claim that changing 10 m chimney diameter to 30 m will increase the power output from 51.86 kW to 82.8 kW. Karimipour Fard and Beheshti [22] analysed the SCPP performance in Isfahan for Iranian climatic conditions via a CFD model based on the design characteristics of the Manzanares pilot plant. They found that the maximum power output would be 45.48 kW at 6.17 m chimney radius, 3.7% more than the reference case radius of 5 m. Similarly, they concluded that this change would increase the efficiency of the system by 4.5% to 0.69%. Since the chimney design will directly affect the air flow in the system, it notably affects the system performance. In this respect, researchers analysed the effect of divergent and convergent chimney design on system performance. Hassan *et al.* [37] investigated the divergent chimney design in the core CFD studies of the Manzanares pilot plant. They claimed that when the

divergent chimney angle of the system is changed to 1°, system power output almost doubles compared to the reference case. They also reported that the power output is 65 kW when the chimney angle is 2°, and 59 kW when it is 3°, and the 1° chimney angle is the peak point for the power output.

Some researchers have also examined the impact of divergent and convergent chimney design on the system performance with experimental, theoretical and CFD studies [17,37-43]. Through the findings, it is seen that the effect of geometric aspects and design parameters on the performance of SCPP systems is repeatedly analysed. However, it is observed that the ground slope impact has not been adequately examined in the literature. In the meantime, it is obvious that the ground slope will directly affect the thermal and momentum effects in the system. This phenomenon constitutes the motivation source behind the study. In this research, a different approach is proposed for the ground design and an extensive CFD analysis is conducted to increase the performance of SCPP systems. The ground surface area is attempted to be increased by sloping the ground 21 m inside the collector entrance. In addition, the slope created on the ground is intended to support the upward movement of the system air stored under the collector.

2. METHODOLOGY AND CFD MODEL

The performance of SCPP systems has been analysed over and over by researchers in literature with different methods. In the present work carried out, the performance of the system is tried to be increased with a unique ground design. Simulations are repeated at constant ambient temperature and solar intensity. During simulations, momentum, continuity and turbulence equations are solved simultaneously. In order to facilitate the simulations, the following assumptions are adopted:

- Air within the SCPP system is considered incompressible.
- Flow regime is considered as constant, 3-dimensional, and turbulent.
- Climatic parameters are considered constant.
- Boussinesq model is accepted for density analysis.

a. Momentum equation

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u u)}{\partial x} + \frac{\partial(\rho u v)}{\partial y} + \frac{\partial(\rho u w)}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (1)$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (2)$$

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (3)$$

b. Continuity equation

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0 \quad (4)$$

c. Energy equation

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial p}{\partial x} + \mu \left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2} \right) \quad (5)$$

In SCPP systems, there is natural convection between the collector and the system air [1]. The Rayleigh number for natural convection is obtained from the following equation:

$$Ra = \frac{g\beta\Delta TH_c^3}{\alpha\nu} \quad (6)$$

Here H_c is collector height, α is thermal diffusion coefficient and ν is kinematic viscosity. In the study carried out, the system is accepted as turbulent since the Ra number is higher than 10^9 , which is the critical value [44]. There are 3 different turbulence models in the CFD software used in the analysis of SCPP systems. In the study carried out, RNG k- ϵ turbulence model is used, which gives better results than other turbulence models in rotating flows [45]. Equations of the turbulence model are as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j} \left[\alpha_k \mu_{eff} \frac{\partial k}{\partial x_j} \right] + G_k + G_b + \rho \epsilon - Y_M + S_k \quad (7)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_i}(\rho \epsilon u_i) = \frac{\partial}{\partial x_j} \left[\alpha_\epsilon \mu_{eff} \frac{\partial \epsilon}{\partial x_j} \right] + C_{1\epsilon} \frac{\epsilon}{k} (G_k + C_{3\epsilon} G_b) - C_{2\epsilon} \rho \frac{\epsilon^2}{k} - R_\epsilon + S_\epsilon \quad (8)$$

When the Manzanares pilot plant and other installed power plants are examined, it is seen that the air

temperature in the system does not change much [5,8-11]. Researchers claim that the Boussinesq model can be used for density analysis in systems where the temperature change is not very large [1,6,12,41,44,45]. Its equation is as follows:

$$(\rho - \rho_a)g \approx -\rho_a \beta (T - T_a)g \quad (9)$$

In Equation 9, ρ_a and T_a are the density and temperature of the inlet air of the system, β is the thermal expansion coefficient.

Different calculation methods are available in literature for determining power output of SCPP systems. The generally accepted calculation method is to calculate the power from the pressure drop (ΔP_t) in the turbine [1,6,12]. The power output of the system is calculated from the following equation: [12, 13].

$$P_0 = \eta_t \Delta P_t Q_v \quad (10)$$

In the equation, η_t is the turbine-generator efficiency and taken as 0.8 [1,6,12]. It is seen that the power output of the system is proportional to the pressure drop (ΔP_t) in the turbine and the volumetric flow rate (Q_v). The turbine pressure drop is taken from the CFD results in the work carried out. Based on the Manzanares pilot plant, it is obtained from the average pressure (P_t) at the location where the turbine is located 9 m above the ground and is calculated as follows:

$$\Delta P_t = r_t P_t \quad (11)$$

Here r_t represents the turbine pressure drop rate and 2/3 is taken [1]. In the analyses, a 3D CFD model is developed based on the dimensions of the Manzanares pilot plant. The geometric dimensions of the reference facility are given in Table 1. Since there is no temperature change in experimental measurements below 0.5 of the ground, the ground thickness is taken as 0.5 [5]. In traditional SCPP systems, the ground is designed horizontally. In this study, a slope is given to the ground starting at 21 m of the collector entrance and ending 21 m behind the chimney. With this slope, it is aimed to improve the upward movement of the heated air in the system. Design details and boundary conditions of the system are given in Figure 1. For the purpose of time-saving in calculations, a 90° model with 2 planar symmetries (YZ and XZ) is created in the study. Simulations are completed in approximately 10 hours with the CORE i7 8th generation processor and 16 GB RAM workstation. In simulations using ANSYS FLUENT commercial software, the RNG k- ϵ turbulence

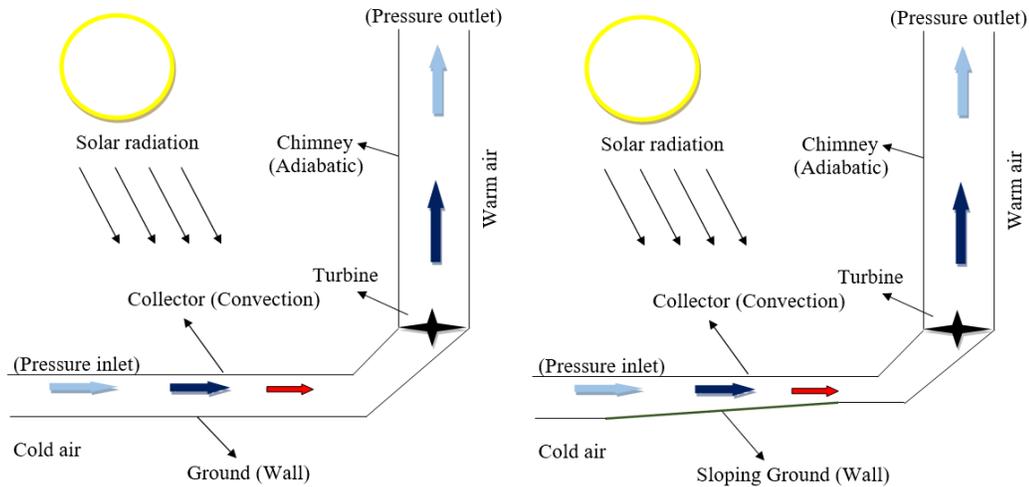


Figure 1: Standard SCPP system and the new design with the sloping ground, and boundary conditions.

model DO (discrete ordinates) is used together with the solar ray tracing algorithm. The solar beam direction is entered into the program using the location of the Manzanares, Spain pilot plant. In SCPP systems, the collector is semi-transparent and transmits the sunlight falling on it to the ground. Transparent glass is generally used as collecting material. The materials and physical properties used in the system are given in Table 2 based on the pilot facility. The SIMPLE algorithm is found appropriate for the pressure and velocity interaction of the air in the system. PRESTO technique is used for pressure interpolation. The Boussinesq approach is adopted to determine the density of air by temperature change. The convergence criterion is taken as 10^{-6} for energy and radiation and 10^{-3} for other parameters. All simulations are performed at a solar radiation intensity of 1000 W/m^2 and a constant ambient temperature of 293.15 K . CFD details, operational and climatic parameters of the study are given in Table 3.

Table 1: Dimensional Aspects of the Pilot Plant in Manzanares

Design Aspect	Value
Radius of collector	122.0 m
Height of collector	1.85 m
Height of chimney	194.6 m
Radius of chimney	5.08 m
Thickness of ground	0.5 m

3. Results and discussion

In the study, where the impact of the new design including ground slope on the performance parameters

of the SCPP system is analysed, first the system with a horizontal ground is modeled to check the accuracy of the approach through the on-site findings from the pilot plant. The 90° model and the mesh details created are given in Figure 2. The mesh is analysed and compared

Table 2: Material Properties of Ground, Glass, and Chimney

Property and Unit	Ground	Glass	Chimney
Thermal cond. (W/mK)	1.83	1.15	202.4
Density (kg/m ³)	2160	2500	2719
Specific heat (J/kgK)	710	750	871
Absorption coefficient	0.9	0.03	0
Transmissivity	Opaque	0.9	Opaque
Emissivity	0.9	0.1	1
Refractive index	1	1.526	1
Thickness (m)	0.5	0.004	0.00125

Table 3: Constants Utilised in CFD Model

Solar Intensity (W/m ²)	1000
Outdoor pressure (Pa)	101,325
Outdoor temperature (K)	293.15
Gravitational acceleration (m/s ²)	9.81
Density of outdoor air (kg/m ³)	1.2046
Ideal gas constant (J/kgK)	287
Thermal conductivity of air (W/mK)	0.0259
Kin.viscosity of air (m ² /s)	1.48×10^{-5}
Heat capacity of air (J/kgK)	1006.43
Stefan-Boltzmann constant (W/m ² K ⁴)	5.667×10^{-8}
Pressure drop ratio in turbine	2/3

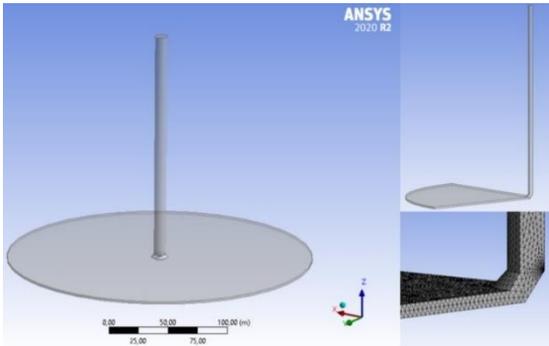


Figure 2: SCPP system model and meshing.

for 3 different cell numbers for the check of mesh-independent solution. When the maximum air velocity (V_m) in the system is compared for 250k, 300k and 380k cell numbers, it is seen that the change is almost negligible. As a consequence of the consistency of the air velocity figures with the experimental results, and since there is insignificant changes in the values for 380k and 300k cell numbers, mesh-independent solution is accepted for the case with 380k cell number. Details about the mesh-independent solution are given in Table 4.

Table 4: Details of Mesh-Independent Solution

Cell Count	V_m	% Change in V_m
250k	14,42	-
300k	13.996	2.94
380k	14.202	1.47

At 1000 W/m^2 solar intensity and 293.15 K ambient temperature, the maximum air velocity in the system is found to be 14.202 m/s through CFD results and also power output is 54.333 kW . These figures are consistent with the experimental results of Haaf [5] conducted in the Manzanares pilot plant. Details of the analysis for accuracy justification are given in Table 5.

Table 5: Comparison of Experimental and CFD Results

	Exp.	CFD	% Error
Velocity (m/s)	15	14,202	5.32
Power output (kW)	50	54,333	8.66

The CFD model, following its accuracy and reliability is confirmed with the reference geometry, is adapted to the new design and the outputs of the system are evaluated. With the new design, the system air under the collector enters the chimney with an upward velocity due to the ground slope. It is concluded that the maximum air flow velocity is 19.046 m/s in the new design and increased by 34.1% compared to the reference case. The contour of the system's air velocity is given in Figure 3. With the new design, it is seen that the system air exceeds 10 m/s without entering the chimney. It can be said that the temperature of the air in the system does not change much compared to the reference case. Temperature distribution in the system is presented in Figure 4. Two important parameters affecting the power output of SCPP systems are the

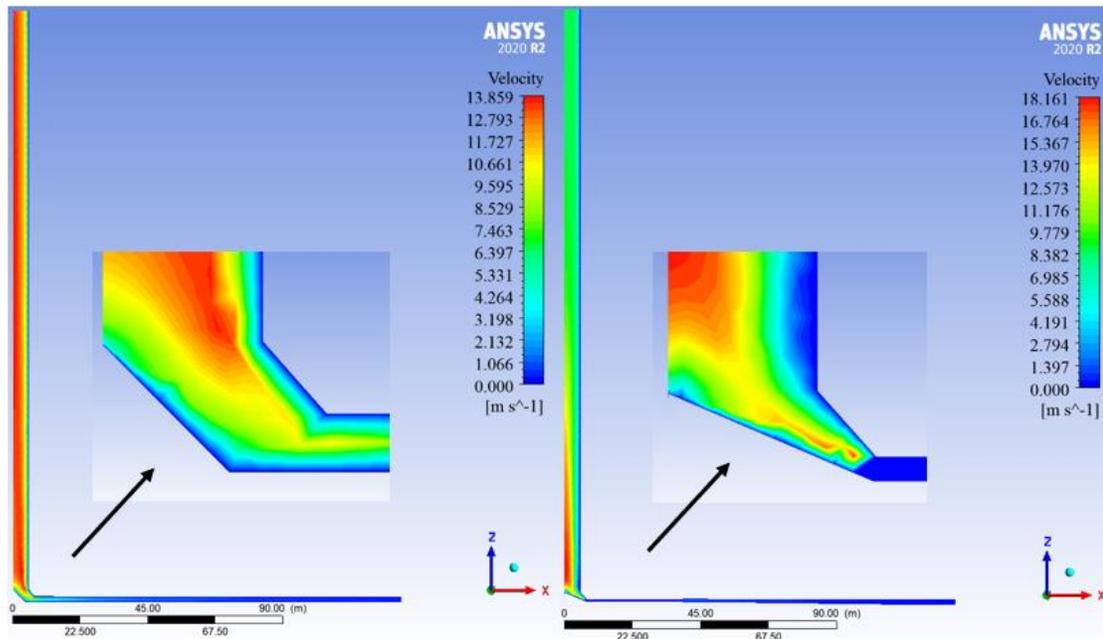


Figure 3: Air velocity contours for reference case and new design.

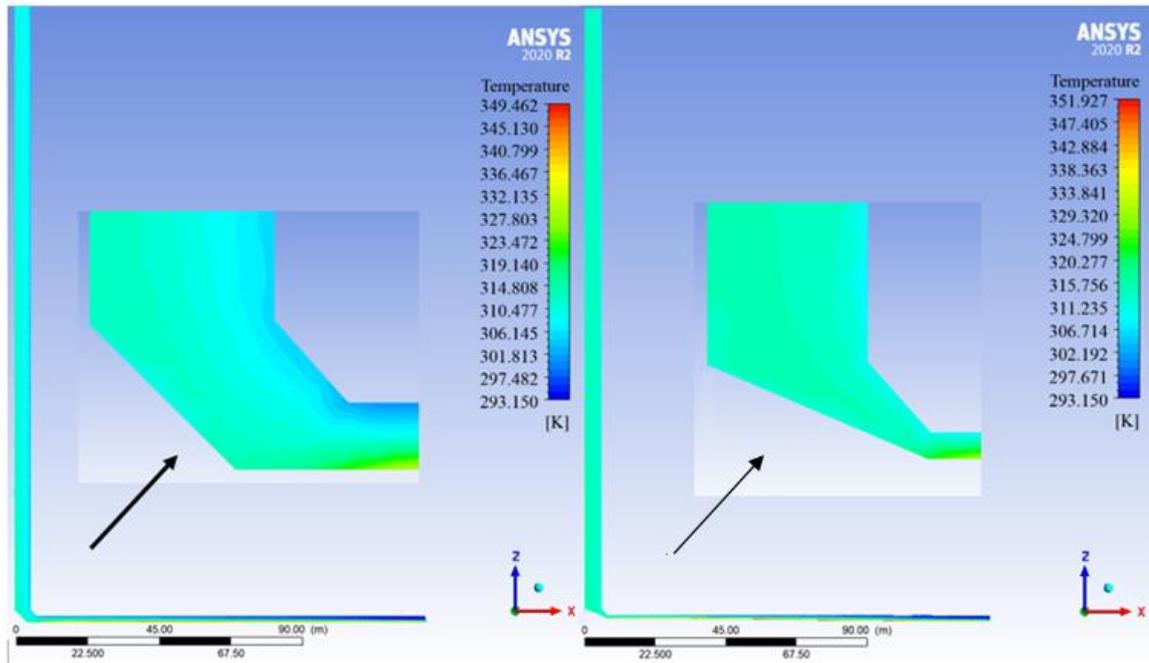


Figure 4: Temperature contours for reference case and new design.

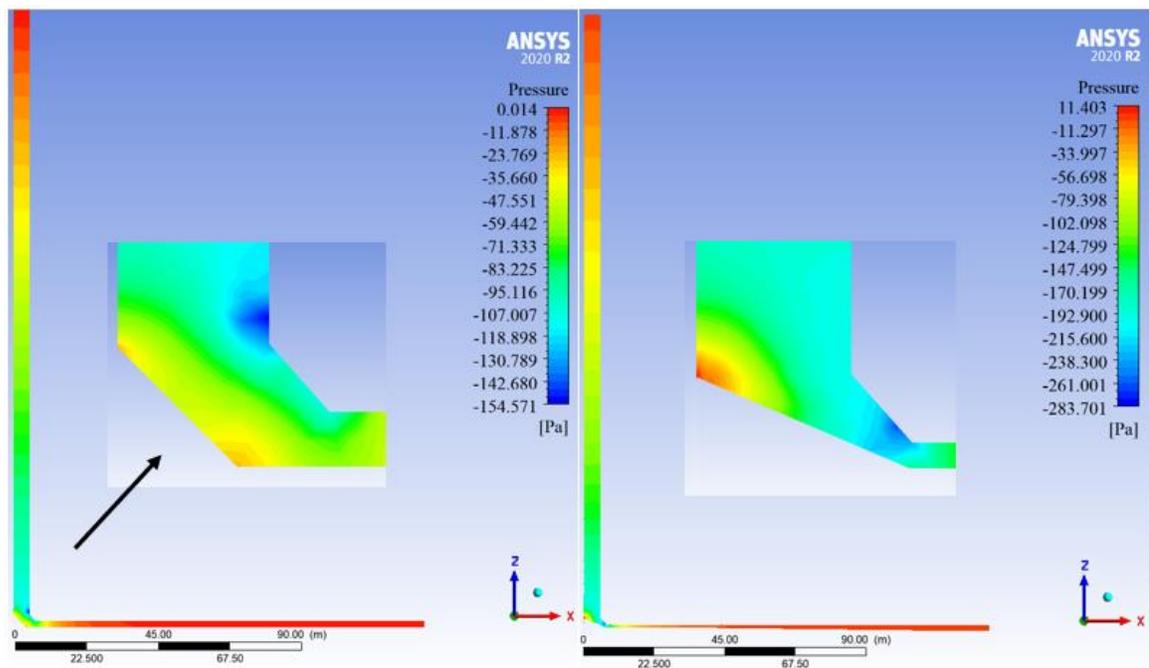


Figure 5: Temperature contours for reference case and new design.

volumetric flow rate of air in the system and the pressure drop in the turbine. With the new design, it is seen in Figure 5 that the pressure difference in the system remarkably increases in comparison with the reference case. In the new design having slope in the ground, it is concluded that the power output is improved by 23.04% compared to the horizontal ground and rises from 54.333 to 66.855 kW. With the slope

adapted to the ground, the air entering the system at the collector inlet is forced upward movement after a certain distance due to the design aspects and temperature increase. This yields to an increase in power output. Comparison of the power outputs of the reference state and the new design is depicted in Figure 6.

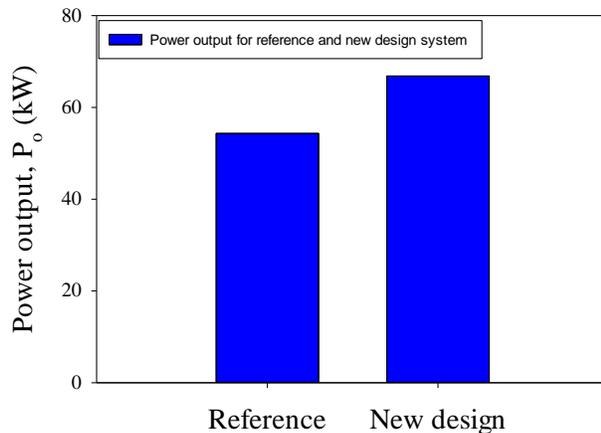


Figure 6: Power output for reference case and new design with sloping ground.

Pressure distributions in the entire system for the conventional and novel ground design are given in Figure 5. It is unequivocal from the results that minimum pressure in the horizontal ground case is -154.6 Pa whereas this is improved to -283.7 Pa in the case of sloping ground. The aforesaid enhancement yields to notably greater power output figures in the novel design which is desirable. In addition, it is seen in Figure 6 that the power output of the reference case (54.333 kW) is enhanced by 23.04% to 66.855 kW through the novel sloping ground configuration.

4. CONCLUSIONS

There are many parameters that affect the performance of SCPP systems. It is very limited to work by determining climatic parameters beforehand. However, the possible outputs of the system can be predicted by analysing the design parameters in advance. Changes in geometric dimensions bring some challenges, difficulties and cost problems. In this study, a special design is developed for the ground and the performance of the system is tried to be increased. With the design proposed, a significant increase in the performance of the system is achieved without any cost and with simple design changes. It is concluded that the maximum air velocity, which is 14.202 m/s for the horizontal ground, is enhanced by 34.1% in the sloping ground to 19.046 m/s. Moreover, it is observed that the power output of the reference design (54.333 kW) is improved by 23.04% to 66.855 kW, which is noteworthy. Sloping ground design notably improves the momentum effects around the chimney inlet, and noticeably greater pressure differences are achieved compared to the conventional horizontal ground. This phenomenon results in improved mass flow rates and

thus electrical power outputs in the plant. Sloping ground design also improves the thermal effects in the power plant. About 2.5 °C rise in maximum temperature values is obtained in the novel design.

NOMENCLATURE

ρ = Density (kg/m³)

ρ_a = Ambient air density (kg/m³)

T = Temperature (K)

T_a = Ambient air temperature (K)

η_t = Turbine-generator efficiency

g = Gravitational acceleration (m/s²)

β = Thermal expansion coefficient (1/K)

G = Solar radiation (W/m²)

P_o = Power output (W)

Q_v = Volumetric flow rate (m³/s)

P_t = Average pressure at the turbine location (Pa)

α = Thermal diffusivity coefficient (m²/s)

ν = Kinematic viscosity (m²/s)

REFERENCES

- [1] E. Cuce, H. Sen and P. M. Cuce, "Numerical performance modelling of solar chimney power plants: Influence of chimney height for a pilot plant in Manzanares, Spain," *Sustainable Energy Technologies and Assessments*, vol. 39, pp. 100704, 2020.
<https://doi.org/10.1016/j.seta.2020.100704>
- [2] H. Sen and E. Cuce, "Dynamic pressure distributions in solar chimney power plants: A numerical research for the pilot plant in Manzanares, Spain," *WSSET Newsletter*, vol. 12(1), pp. 2-2, 2020.
- [3] J. Schlaich, "The solar chimney: electricity from the sun," Edition Axel Menges 1995.
- [4] W. Haaf, K. Friedrich, G. Mayr, and J. Schlaich, "Solar chimneys part I: principle and construction of the pilot plant in Manzanares," *International Journal of Solar Energy*, vol. 2(1), pp. 3-20, 1983.
<https://doi.org/10.1080/01425918308909911>
- [5] W. Haaf, "Solar chimneys: part ii: preliminary test results from the Manzanares pilot plant," *International Journal of Sustainable Energy*, vol. 2(2), pp. 141-161, 1984.
<https://doi.org/10.1080/01425918408909921>
- [6] E. Cuce, P. M. Cuce, and H. Sen, "A thorough performance assessment of solar chimney power plants: Case study for Manzanares," *Cleaner Engineering and Technology*, vol. 1, pp. 100026, 2020.
<https://doi.org/10.1016/j.clet.2020.100026>

- [7] L. B. Mullett, "The solar chimney overall efficiency, design and performance," *International journal of ambient energy*, vol. 8(1), pp. 35-40, 1987.
<https://doi.org/10.1080/01430750.1987.9675512>
- [8] X. Zhou, J. Yang, B. Xiao, and G. Hou, "Experimental study of temperature field in a solar chimney power setup," *Applied Thermal Engineering*, vol. 27(11-12), pp. 2044-2050, 2007.
<https://doi.org/10.1016/j.applthermaleng.2006.12.007>
- [9] A. Bugutekin, "Experimental study of temperature field in a solar chimney plant in Adiyaman," *Isi Bilimi ve Teknigi Dergisi/Journal of Thermal Science & Technology*, vol. 32(2), pp. 73-80, 2012.
- [10] D. Eryener, J. Hollick, and H. Kuscu, "Thermal performance of a transpired solar collector updraft tower," *Energy Conversion and Management*, vol. 142, pp. 286-295, 2017.
<https://doi.org/10.1016/j.enconman.2017.03.052>
- [11] A. Ayadi, A. Bouabidi, Z. Driss, and M. S. Abid, "Experimental and numerical analysis of the collector roof height effect on the solar chimney performance," *Renewable energy*, vol. 115, pp. 649-662, 2018.
<https://doi.org/10.1016/j.renene.2017.08.099>
- [12] E. Cuçe, A. Saxena, P. M. Cuçe, H. Sen, S. Guo, and K. Sudhakar, "Performance assessment of solar chimney power plants with the impacts of divergent and convergent chimney geometry," *International Journal of Low-Carbon Technologies* 2021.
<https://doi.org/10.1093/ijlct/ctaa097>
- [13] S. Kalash, W. Naimeh, and S. Ajib, "Experimental investigation of the solar collector temperature field of a sloped solar updraft power plant prototype," *Solar energy*, vol. 98, pp. 70-77, 2013.
<https://doi.org/10.1016/j.solener.2013.05.025>
- [14] A. Koonsrisuk and T. Chitsomboon, "Effects of flow area changes on the potential of solar chimney power plants," *Energy*, vol. 51, pp. 400-406, 2013.
<https://doi.org/10.1016/j.energy.2012.12.051>
- [15] M. Najmi, A. Nazari, H. Mansouri, and G. Zahedi, "Feasibility study on optimization of a typical solar chimney power plant," *Heat and Mass Transfer*, vol. 48(3), pp. 475-485, 2012.
<https://doi.org/10.1007/s00231-011-0894-5>
- [16] S. Amirkhani, S. Nasirivatan, A. B. Kasaeian, and A. Hajinezhad, "ANN and ANFIS models to predict the performance of solar chimney power plants," *Renewable Energy*, vol. 83, pp. 597-607, 2015.
<https://doi.org/10.1016/j.renene.2015.04.072>
- [17] Y. Ohya, M. Wataka, K. Watanabe, and T. Uchida, "Laboratory experiment and numerical analysis of a new type of solar tower efficiently generating a thermal updraft," *Energies*, vol. 9(12), pp. 1077, 2016.
<https://doi.org/10.3390/en9121077>
- [18] E. Cuçe and H. Sen, "Dünden bugüne güneş bacası güç santralleri: Sistem güç çıkışına etki eden performans parametreleri," *Avrasya 7. Uygulamalı Bilimler Kongresi*. 21-22 August 2020, Trabzon, Turkey, pp. 256-262.
- [19] M. Ghalamchi, A. Kasaeian, M. Ghalamchi, "Experimental study of geometrical and climate effects on the performance of a small solar chimney," *Renewable and Sustainable Energy Reviews*, vol. 43, pp. 425-431, 2015.
<https://doi.org/10.1016/j.rser.2014.11.068>
- [20] A. Koonsrisuk, S. Lorente, A. Bejan, "Constructal solar chimney configuration," *International Journal of Heat and Mass Transfer*, vol. 53(1-3), pp. 327-333, 2010.
<https://doi.org/10.1016/j.ijheatmasstransfer.2009.09.026>
- [21] D. V. V. Shahi, M. A. Gupta, and M. V. S. Nayak, "CFD Analysis of solar chimney wind power plant by Ansys Fluent," *Int J Technol Res Eng*, vol. 5(9), pp. 3746-3751, 2018.
- [22] P. Karimipour Fard, H. Beheshti, "Performance enhancement and environmental impact analysis of a solar chimney power plant: Twenty-four-hour simulation in climate condition of isfahan province, iran," *International Journal of Engineering*, vol. 30(8), pp. 1260-1269, 2017.
<https://doi.org/10.5829/ije.2017.30.08b.20>
- [23] S. Larbi, A. Bouhdjar, and T. Chergui, "Performance analysis of a solar chimney power plant in the southwestern region of Algeria," *Renewable and Sustainable energy reviews*, vol. 14(1), pp. 470-477, 2010.
<https://doi.org/10.1016/j.rser.2009.07.031>
- [24] M. O. Hamdan, "Analysis of solar chimney power plant utilizing chimney discrete model," *Renewable energy*, vol. 56, pp. 50-54, 2013.
<https://doi.org/10.1016/j.renene.2012.09.047>
- [25] G. M. Ngala, M. B. Oumarou, A. B. Muhammad, and M. Shuwa, "Evaluation of solar chimney power plant in semi-arid region of Nigeria, Arid Zone," *Journal of Engineering, Technology and Environment*, vol. 11, pp. 1-12, 2015.
- [26] D. Toghraie, A. Karami, M. Afrand, and A. Karimipour, "Effects of geometric parameters on the performance of solar chimney power plants," *Energy*, vol. 162, pp. 1052-1061, 2018.
<https://doi.org/10.1016/j.energy.2018.08.086>
- [27] E. Cuçe, P. M. Cuçe, "Performance assessment of solar chimneys: Part 1 – Impact of chimney height on power output," *Energy Research Journal*, vol. 10, pp. 11-19, 2019.
<https://doi.org/10.3844/erjsp.2019.11.19>
- [28] E. Cuçe, P. M. Cuçe, "Performance assessment of solar chimneys: Part 2 – Impacts of slenderness value and collector slope on power output," *Energy Research Journal*, vol. 10, pp. 20-26, 2019.
<https://doi.org/10.3844/erjsp.2019.20.26>
- [29] M. T. Esfidani, S. Ravehi, M. Shahsavari, A. Sedaghat, "Computational study on design parameters of a solar chimney," In *2015 International Conference on Sustainable Mobility Applications, Renewables and Technology (SMART)*, pp. 1-5, 2015.
<https://doi.org/10.1109/SMART.2015.7399268>
- [30] A. A. Gitan, S. H. Abdulmalek, S. S. Dhrab, "Tracking collector consideration of tilted collector solar updraft tower power plant under Malaysia climate conditions," *Energy*, vol. 93, pp. 1467-1477, 2015.
<https://doi.org/10.1016/j.energy.2015.09.009>
- [31] A. B. Kasaeian, E. Heidari, S. N. Vatan, "Experimental investigation of climatic effects on the efficiency of a solar chimney pilot power plant," *Renewable and Sustainable energy reviews*, vol. 15(9), pp. 5202-5206, 2011.
<https://doi.org/10.1016/j.rser.2011.04.019>
- [32] P. J. Cottam, P. Duffour, P. Lindstrand, and P. Fromme, "Effect of canopy profile on solar thermal chimney performance," *Solar Energy*, vol. 129, pp. 286-296, 2016.
<https://doi.org/10.1016/j.solener.2016.01.052>
- [33] A. Ayadi, Z. Driss, A. Bouabidi, M. S. Abid, "Experimental and numerical study of the impact of the collector roof inclination on the performance of a solar chimney power plant," *Energy and Buildings*, vol. 139, pp. 263-276, 2017.
<https://doi.org/10.1016/j.enbuild.2017.01.047>
- [34] H. H. Al-Kayiem and Q. A. Al-Nakeeb, "Geometry alteration effect on the performance of a solar-wind power system" In *2006 International conference on energy and environment*, pp. 50-55, 2006.

- [35] E. Cuce, "Güneş bacası güç santrallerinde toplayıcı eğiminin çıkış gücüne ve sistem verimine etkisi," *Uludağ Üniversitesi Mühendislik Fakültesi Dergisi*, 2020; vol. 25, pp. 1025-1038, 2020.
<https://doi.org/10.17482/uumfd.732862>
- [36] K. Ikhlef, and S. Larbi "Energy Performance Analysis of a Solar Chimney Power Plant with and without Thermal Storage System," In 2019 6th International Conference on Automation, Control, Engineering and Computer Science (ACECS) Istanbul, Turkey, *International Journal of Control, Energy and Electrical Engineering*, vol. 11, pp. 1-7, 2019.
- [37] A. Hassan, M. Ali, and A. Waqas, "Numerical investigation on performance of solar chimney power plant by varying collector slope and chimney diverging angle," *Energy*, vol. 142, pp. 411-425, 2018.
<https://doi.org/10.1016/j.energy.2017.10.047>
- [38] M. Motoyama, K. Sugitani, Y. Ohya, T. Karasudani, T. Nagai, and S. Okada, "Improving the power generation performance of a solar tower using thermal updraft wind," *Energy and Power Engineering*, vol. 6(11), pp. 362, 2014.
<https://doi.org/10.4236/epe.2014.611031>
- [39] H. Nasraoui, Z. Driss, A. Ayedi, and H. Kchaou, "Numerical and experimental study of the aerothermal characteristics in solar chimney power plant with hyperbolic chimney shape," *Arabian Journal for Science and Engineering*, vol. 44(9), pp. 7491-7504, 2019.
<https://doi.org/10.1007/s13369-019-03821-x>
- [40] M. J. Ahirwar and P. Sharma, , "Analyzing the Effect of Solar Chimney Power Plant by Varying Chimney Height, Collector Slope and Chimney Diverging Angle," *International Journal of Innovative Research in Technology*, vol. 6(7), pp. 213-219, 2019.
- [41] S. Hu, D. Y. Leung, and M. Z. Chen, "Effect of divergent chimneys on the performance of a solar chimney power plant," *Energy Procedia*, vol. 105, pp. 7-13, 2017.
- [42] J. S. Pattanashetti and N. Madhukeshwara, "Numerical Investigation and Optimization of Solar Tower Power Plant," *International journal of research in aeronautical and mechanical engineering*, vol. 2(1), pp. 92-94, 2014.
- [43] Y. Xu and X. Zhou, "Performance of divergent-chimney solar power plants," *Solar Energy*, vol. 170, pp. 379-387, 2018.
<https://doi.org/10.1016/j.solener.2018.05.068>
- [44] A. Zandian and M. Ashjaee, "The thermal efficiency improvement of a steam Rankine cycle by innovative design of a hybrid cooling tower and a solar chimney concept," *Renewable energy*, vol. 51, pp. 465-473, 2013.
<https://doi.org/10.1016/j.renene.2012.09.051>
- [45] M. A. H. Abdelmohimen and S. A. Algarni, "Numerical investigation of solar chimney power plants performance for Saudi Arabia weather conditions," *Sustainable Cities and Society*, vol. 38, pp. 1-8, 2018.
<https://doi.org/10.1016/j.scs.2017.12.013>

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