Thermal and energy analysis of a novel solar updraft tower design with divergent chimney and convergent collector concept: CFD analysis with experimental validation

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Abstract

The fact that energy sources are heavily dependent on fossil fuels increases the need for alternative energy day by day. Solar energy is the most popular alternative energy source with massive potential. Solar chimney power plants (SCPP) are one of the systems of interest based on solar energy. SCPP systems are rare systems that can provide 24-hour power output. Their performance has been the subject of constant research since the first pilot plant in Manzanares. Design is crucial for performance figures of SCPPs, and the limitation of climatic parameters causes the system to be approached with different designs. This study makes a 3D CFD model by combining the divergent chimney and convergent collector structure based on the first pilot plant. The solar ray tracing algorithm and the RNG k-e turbulence model are applied and the model equations are solved under dynamic conditions with the reliable software ANSYS FLUENT. After the mesh-independent solution of the model is complete, it is validated with experimental data. The two cases are compared for solar radiation of 1000 W/m^2 and environmental temperature of 293 K. A power output of 50.51 kW is achieved for standard pilot sizing. With the new model, the power output rises to 146.34 kW. It is seen that the divergent chimney and convergent collector affect the airflow in the system, increasing the maximum air velocity to 19.363 m/s. In parallel with the experimental data, it is seen that the temperature on the ground exceeds 360 K in the CFD results.

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1. INTRODUCTION

Energy sources have been dependent on fossil fuels for many years. This situation both revealed environmental pollution problems in the long term and started to reveal issues of reserves. When the rapidly increasing human population and the emergence of more energy needs combined with these problems of fossil fuels, the orientation to alternative energy sources became inevitable all over the world. Renewable energy sources are sufficient to be an alternative to fossil fuels when used efficiently. Solar energy as a leading renewable energy source is a favorite of researchers with its potential and ease of use. Solar energy can be harnessed in different forms to generate energy. Electrical power production directly through PV modules has been widely used in recent years [1]. Indirectly, solar energy has been used for water and space heating since ancient times. Apart from PV systems, electricity can also be produced indirectly from solar energy. There are mechanisms, also known as systems, in which solar intensity passes into the system fluid and the energy of the fluid is converted to electricity by a turbine. Solar chimney power plants (SCPPs) are one example of these systems. With the transparent collector in the SCPPs, it uses the solar energy trapped in its structure to heat the system air. The plant air, whose temperature and accordingly its speed and kinetic energy increase, is directed to the high chimney located in the center of the collector [2]. As a consequence of the pressure gradient at the inner and outer sections of the high tower, it creates a vacuum effect and accelerates the incoming air upwards [3]. With the turbine at a certain height, the energy content of plant air is transformed to electricity [4]. A simple schematic of the system is given in Figure 1.

SCPPs consist of three structural elements, namely collector, chimney, and turbine, and with this simple structure, they are attractive systems for generating electricity from the sun. The biggest disadvantage of the system is the high initial setup cost. Despite this, the low maintenance cost and low CO_2 emissions after installation have been effective in attracting researchers to these systems. Its first application was carried out in Spain in the 1980s. The system is located in the Manzanares region with a R_{coll} of 1.22×10^2 m and a H_{ch} of 1.946×10^2 m. In the first data received from the plant, it is reported that V_{max} of 15 m/s and 50 kW electricity are received [5]. After the results from the first facility, researchers' interest in the system increased. The biggest criticism brought to the system is at the point of efficiency. Mullet [6] claims that with a R_{coll} of 4750 m, the system efficiency will reach 1% level only at a H_{ch} of 900 m. It is also stated that in order to evaluate the system economically, it is necessary to design a 1000 m high chimney.

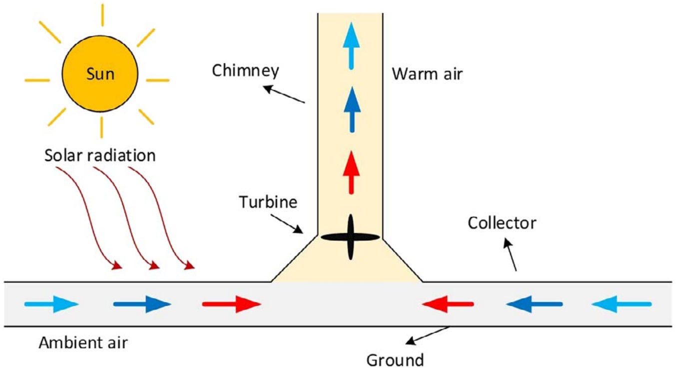

Figure 1. *Schematic of a solar chimney power plant.*

Although SCPPs have three basic structural elements, there are many parameters that have influence on the performance of the updraft tower. These can be classified into two parts as climatic and geometric parameters in general. Climatic parameters are radiation intensity and ambient temperature and are uncontrollable parameters. While the increase in ambient temperature decreases the performance of the system, the increase in radiation intensity notably enhances the performance figures of the plant [7]. The effect of outdoor temperature and solar intensity on the system is studied by researchers mainly with mathematical and CFD studies. The reason for this is that it is limited to obtaining data at the desired temperature and radiation values with experimental measurements. Bahrainirad *et al.* [8] set up an experimental system with a H_{ch} of 5.9 m and a R_{coll} of 4.13 m. They state that the V_{max} in the plant is 6 m/s and a temperature difference of 15°C is achieved. Using theoretical calculations from small-scale experimental studies, researchers try to estimate the performance of massive systems. Azizi *et al.* [9] evaluate the influence of H_{ch} on the operation of the system with an experimental prototype. Then, with the CFD model confirmed by experimental data, they claim that the boost in system height increases electricity production and system efficiency. Mekhail *et al.* [10] measure the performance with an experimental setup at a height of 6 m. Then they increase the H_{ch} to 20 m and observe the change in the outputs of the system. Similarly, they boost the diameter of the chimney. They state that the system will generate more electricity when the height of the chimney is increased. They also determine that radiation intensity and ambient temperature have a serious effect on system performance. Each of the geometric dimensioning and design parameters affects the system, and these effects have been interpreted by researchers in different ways. System height and collector size have been examined with different techniques and methods. Cuce *et al.* [11] evaluate the influence of chimney height on the performance of the pilot plant with a 3D CFD technique they proposed. They show that if the H_{ch} of the standard facility is 500 m, the power output will rise from 50 to 130 kW. They state that the height of the chimney will also increase the efficiency of the system. Toghraie *et al.* [12] propose a 3D CFD model with 100 m chimney height and 100 m collector radius to analyse the effect of geometric parameters on the performance of the SCPP system. They state that increasing the chimney height with the 5° CFD model will lead to an improvement in the performance of the system. They emphasise that the same is true for the collector radius. Boost in collector size handle more energy input and more direct electricity. Therefore, boosting the collector size is expected to rise the system's electricity production. Li *et al.* [13] develop an extensive theoretical technique based on the first pilot plant. They claim that boosting the collector diameter above 700 m will not increase the electricity production of the system and that a maximum power of 145 kW can be obtained. They show that the same is not true for the height of the chimney, increasing the height of the chimney continuously increases the power output and the power output will reach 425 kW at a chimney height of 2000 m. You *et al.* [14] assess the influence of collector radius and height on the SCPP with a 3D CFD study based on the first pilot plant. Researchers claim that the plant, which yields an electrical power of about 55 kW in the reference case, will give a power output of 95 kW when the R_{coll} is configured to 175 m, and if the collector height is reduced to 1.1 m, the power output will exceed 60 kW. Al-Kayiem *et al.* [15] try to estimate the performance of the facility mounted on a pitched roof. For this purpose, they develop a one-dimensional mathematical model. They emphasised that the performance of the system increases with the collector area, but the system is not viable when the solar radiation is less than 400 W/m^{-2}. As well as its height, the diameter of the chimney, which is the core of the system, is an important parameter. An increase in chimney diameter means more air is evacuated from the system. By doing so, the volumetric flow rate of the system increases, and the power output increases accordingly.

Cuce *et al.* [16] investigate the impact of the change in chimney diameter on the performance of the SCPP facility with a 3D CFD analysis. When they refer to the first pilot plant, they see that the enhancement in chimney diameter does not continuously increase the electricity production of the system. Researchers claim that when the chimney diameter is 10.16 m in the reference state, the power output is at the level of 53 kW, and if the chimney diameter is 24.325 m, the electrical power will increase by 47% and exceed 100 kW. They also argue that making the chimney diameter larger than this value will reduce the power output.

The design of the collector and chimney is as important as the sizing of the system. The inclination of the collector by raising it from the air inlet to the chimney entrance was handled by the researchers and its effect on the system was investigated. Ayadi *et al.* [17] evaluate the collector effect by setting up a mini SCPP facility. They claim that by making the collector slope 2.5°, the system power can be increased by 125%. Some researchers argue that the SCPP system to be mounted on a sloping slope will perform better than the reference situation [18–20]. Like the collector, the chimney design is also important for the system. Traditional SCPP systems use a cylindrical chimney. The diameter value is constant in every part of the cylindrical chimney. However, it is suggested by the researchers that the divergent and convergent chimney design created by changing the outlet diameter by keeping the inlet diameter of the chimney constant affects the performance of the system. Hassan *et al.* [21] make a 3D CFD study to show that the divergent chimney gives better electricity production than the traditional linear chimney. They claim that for the Manzanares facility, when the divergence angle of the updraft tower is configured to 1° according to the reference situation, the power output will enhance by 108% and reach 70 kW. Similarly, some researchers change the chimney outlet radius by keeping the chimney inlet radius of the Manzanares facility constant with a 3D CFD study. In this way, they analyse the system over the AR (chimney outlet area/chimney inlet area) value. Cuce *et al.* [22] claim that $AR = 5$ for the optimum case, whereas it will be $AR = 10$ according to Hu *et al.* [23]. In general, the researchers claim that the divergent chimney structure will give more power output [24, 25].

Although it is not a design element, the system performance can possibly be enhanced with some arrangements to be made about the ground. The operational features can be improved by the slope to be given to the ground from the collector inlet to the chimney inlet [26, 27]. SCPPs are different from other solar energy systems in one way. This means that the system can be used even when there is no sun. With the storage unit to be integrated into the ground, power output can be obtained even in the hours after sunset [28–30]. Considering the performance-enhancing effects, it is striking that the efficiency of the system is within certain ranges. For this reason, SCPPs have been combined with other systems and investigated by researchers. Mokrani *et al.* [31] perform measurements of temperature and airflow rate by integrating a geothermal water source into the SCPP with the device placed on the ground through an experimental study. They accented that while the V_{max} was 5.1 m/s during the day, this speed increased to 7.1 m/s with geothermal water reinforcement. PV-integrated SCPPs are also at the centre of interest for dual energy generating purposes. Singh *et al.* [32] claim that performance can be obtained from both systems thanks to PV modules being integrated into the ground of SCPP systems with a proposed design. Some researchers have demonstrated that solar chimney systems can be used to cool PV modules by installing small-scale systems [33, 34]. Some researchers have shown that the system can be used to obtain drinking water [35].

New designs for SCPP systems continue to be proposed by researchers. It is possible to get more electricity generation and efficiency in the plant by regulating the airflow in the existing system. With some simple but effective designs, power output can be increased without major additional costs by improving the airflow and turbine pressure drop in the system. For this purpose, within the scope of this study, the collector inlet height is increased by keeping the collector outlet height constant. Thanks to this effect, which creates a nozzle influence, it is aimed to

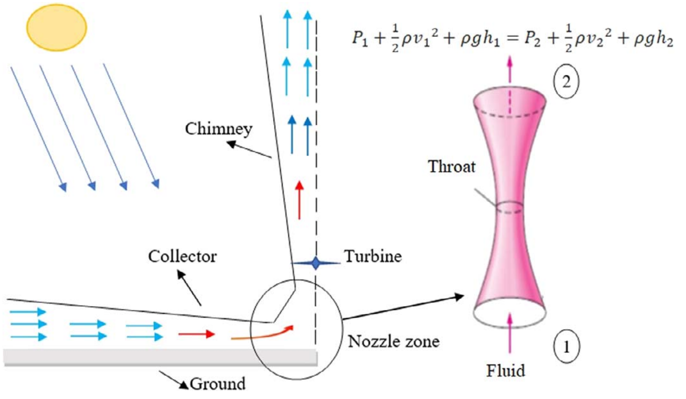

Figure 2. *Description of the newly proposed nozzle effect system [36].*

enhance the performance parameters of the pilot plant. Similarly, it is aimed to evacuate more air from the chimney by increasing the chimney outlet area. Studies in the previous literature show that chimney divergence and collector slope improve the system performance in SCPPs. Here, it is aimed to create a nozzle effect by bringing the collector closer to the floor towards the chimney entrance for improved power output and efficiency in SCPPs.

2. METHODOLOGY AND SYSTEM DETAILS

This study aims to improve performance with some design changes in SCPP systems. It is planned to accelerate the system air by creating a nozzle effect in the throat part of the chimney inlet, thus increasing the power output. For this purpose, the collector inlet height is kept constant and the floor is sloped at a certain distance from the chimney entrance. The schematic view of the newly created system design with the nozzle effect is given in Figure 2.

A 3D CFD model of the solar chimney is created using ANSYS FLUENT software. In the analysis, a 90° system model is made and fast solution, coherency, and reliability are aimed for. The model created is structured on the dimensional characteristics of the Manzanares facility. The model is developed using two symmetry planes (XZ and YZ). The CFD technique and meshing details are depicted in Figure 3. Continuity, energy, and momentum equations are solved simultaneously for the model. The aforesaid equations are as follows:

$$\nabla.\left(\rho.\overrightarrow{v}\right) = 0 \tag{1}$$

$$\begin{aligned}\nabla.\left(\overrightarrow{v}\ (\rho E + p)\right) \\ = \nabla.\left(k_{eff}\nabla T - h\overrightarrow{j} + \left(\mu\left[\left(\nabla\overrightarrow{v} + \nabla\overrightarrow{v}^{T}\right) - \frac{2}{3}\nabla.\overrightarrow{vI}\right].\overrightarrow{v}\right)\right)\end{aligned} \tag{2}$$

$$\nabla\left(\rho.\overrightarrow{v}.\overrightarrow{v}\right) = -\nabla p + .\left(\mu\left[\left(\nabla\overrightarrow{v} + \nabla\overrightarrow{v}^{T}\right) - \frac{2}{3}\nabla.\overrightarrow{v}\,I\right]\right) + \rho\left\{\overrightarrow{g}\right\} \tag{3}$$

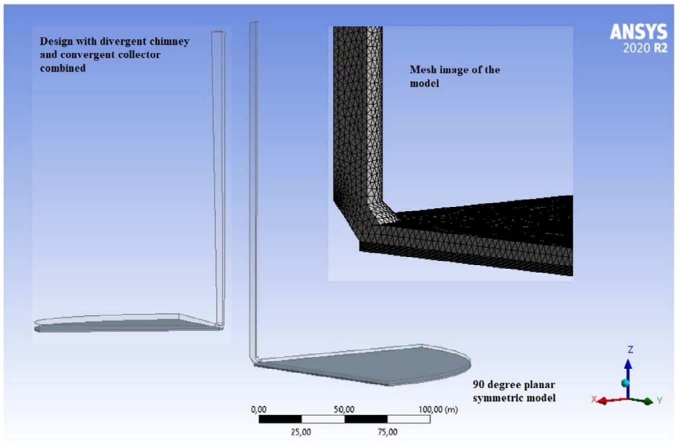

Figure 3. *3D CFD model, new design and mesh image.*

In operation, the energy of the system air increases due to both direct solar radiation and the increase in temperature of the ground. In this case, the flow characteristics of the system air are important. The dimensionless parameter for natural convection is the *Ra* number. For *Ra* number, the turbulence region starts from 10^8 to 10^{10}. Within the system, this value is more than 10^{10}. There is general acceptance in the literature that the flow in SCPP systems is turbulent [37]. The *Ra* equation is given as:

$$Ra = \frac{g\beta\Delta T H_{coll}{}^{3}}{\alpha\vartheta} \tag{4}$$

Different models are available in literature for the turbulence model. In this study, the RNG k-e turbulence model is applied to the solution. Since the temperature change is limited in the plant, the Boussinesq approach is considered appropriate to compute density. The mathematical expressions of the turbulence model and the Boussinesq approach are as follows:

$$\frac{\partial}{\partial x_i}\left(\rho k u_i\right) = \frac{\partial}{\partial x_j}\left[\alpha_k \mu_{eff}\frac{\partial k}{\partial x_j}\right] + G_k + G_b + \rho\varepsilon - Y_M + S_k \tag{5}$$

$$\begin{aligned}\frac{\partial}{\partial x_i}\left(\rho\varepsilon u_i\right) = \frac{\partial}{\partial x_j}\left[\alpha_\varepsilon \mu_{eff}\frac{\partial\varepsilon}{\partial x_j}\right] + C_{1_\varepsilon}\frac{\varepsilon}{k}\left(G_k + C_{3\varepsilon}G_b\right) \\ - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} - R_e + S_\varepsilon\end{aligned} \tag{6}$$

$$\left(\rho - \rho_a\right)g \approx -\rho_a\beta\left(T - T_a\right)g \tag{7}$$

T and ρ are the temperature and density of air in the system. Also, α denotes the initial condition. *g* is the gravitational acceleration and its value is 9.81 m/s^2. β is the coefficient of thermal expansion and its unit is 1/K. Turbine pressure drop (ΔP_t), volumetric flow ($\dot{Q}_v$) and turbine-generator efficiency (η_t) are used to calculate the power output (P_o) to be obtained from the system. The turbine pressure reduction is calculated from

Table 1. *Geometric data of the Manzanares pilot plant [4].*

Parameter	Symbol	Value (m)
Chimney height	H_{ch}	194.6
Chimney inlet diameter	D_{ch-in}	10.16
Chimney outlet diameter	D_{ch-out}	19
Transparent cover radius	R_{coll}	122
Transparent cover inner height	$H_{coll-in}$	4
Transparent cover outer height	$H_{coll-out}$	1.85
Ground thickness		1

Table 2. *Material properties considered in the study [27, 38].*

Properties	Chimney	Glass	Ground
Thermal cond. (W/mK)	1.4	1.15	1.84
Density (kg/m^3)	2100	2500	2160
Specific heat cap. (J/kgK)	880	750	710
Transmissivity	opaq	0.9	opaq

Table 3. *Boundary conditions of the CFD model [2, 11].*

Chimney	Adiabatic wall	Heat flux = 0
Collector inlet	Pressure inlet	$P_{gauge} = 0$, $T_{\alpha} = 293$ K
Chimney outlet	Pressure outlet	$P_{gauge} = 0$
Collector	Mixed	h = 10 W.m^{-2} K^{-1}, Radiation = 1000 W.m^{-2}
Symmetric	Symmetry	
Ground	Convection	h = 0 W.m^{-2} K^{-1}

Table 4. *Mesh-free analysis based on V_{max} in the system.*

Cell number	Element size (m)	V_{max} (m/s)	% change
267 500	1.1	13.96	
381 670	0.95	14.11	1.07
426 670	0.885	14.146	0.25

Table 5. *Validation of the model by comparing CFD results with experimental data [5].*

Criterion	V_{max} in system (m/s)	Power output (kW)
Experimental data	15	50
CFD result	14.146	50.51
% difference	6.03	1.02

the overall pressure deviation at the turbine location (P_t). The equations are as follows [2]:

$$\Delta P_t = r_t \, P_t \tag{8}$$

$$P_o = \eta_t \Delta P_t \dot{Q}_v \tag{9}$$

r_t in the equation is the turbine pressure reduction value and expresses what fraction of the pressure deviation can be transferred to the turbine. Its value is 2/3. The pilot plant geometry is taken as a basis for the study. In the reference case, the data are given in Table 1. The CFD model is then revised so that the transparent cover inlet is 4 m and the chimney outlet diameter is 19 m, to perform the divergent chimney design. In the experimental data, it is seen that the temperature on the ground remains constant after 0.5 m depth [5]. For this reason, 1 m of soil thickness is considered sufficient. Glass thickness is taken as 4 mm.

In the analysis, the flow regime is considered to be continuous and turbulent. In addition, the fluid in the plant is air and the Boussinesq approach is accepted to determine the density change. Environmental conditions are taken to be constant. To simulate solar radiation, discrete ordinates (DO) are entered into the solar ray tracing algorithm program. Coupling is used for pressure–velocity discretisation and PRESTO option is used for pressure interpolation. For spatial discretisation, the gradient least squares cell-based option is preferred. For discretisations other than pressure, the second order upwind is selected. The convergence criteria are set to 10^{-6} for energy and radiation and 10^{-3} for others. The details of the materials used in the system are given in Table 2 and the boundary conditions are given in Table 3.

3. RESULTS AND DISCUSSION

In the current research where the nozzle influence is considered with a 3D CFD model in SCPP systems, a 90° model is created. The visuals of the model and the view of the new design are given in Figure 3. In order to determine that the model is independent of the number of cells in the solutions, a mesh-independent solution is conducted. In different cell counts, the ideal cell number is determined by taking the V_{max} in the system as a reference. In SCPPs, V_{max} is the main performance parameter since all the rest of the calculations are done over V_{max}. In the mesh-independent solution, it is considered sufficient since the change in the V_{max} is 0.25% in the number of 426 670 cells. Details of the mesh independent study are shown in Table 4.

After obtaining the cell number-independent model with the mesh-independent solution, the CFD results are evaluated along with the *in-situ* findings for validation. In the CFD results, the V_{max} in the system is 14.146 m/s and the power output is 50.51 kW. Experimental data for the same climatic conditions are sufficiently consistent with the CFD results. Comparison details are given in Table 5.

Design parameters are as important as environmental conditions in SCPP systems. In this study, the chimney outlet diameter is increased in order to enhance the airflow rate in the plant. In addition, the collector inlet height is increased to allow more air to enter the plant. The velocity distributions of the reference system and the newly created model in the steady regime at enviromental temperature of 293 K and a solar intensity of 1000 W.m^{-2} are given in Figure 4 from the symmetry section. The V_{max} in the system, which was 14.146 m/s in the reference state, increased by 36.88% to 19.363 m/s with the new design. With the divergent

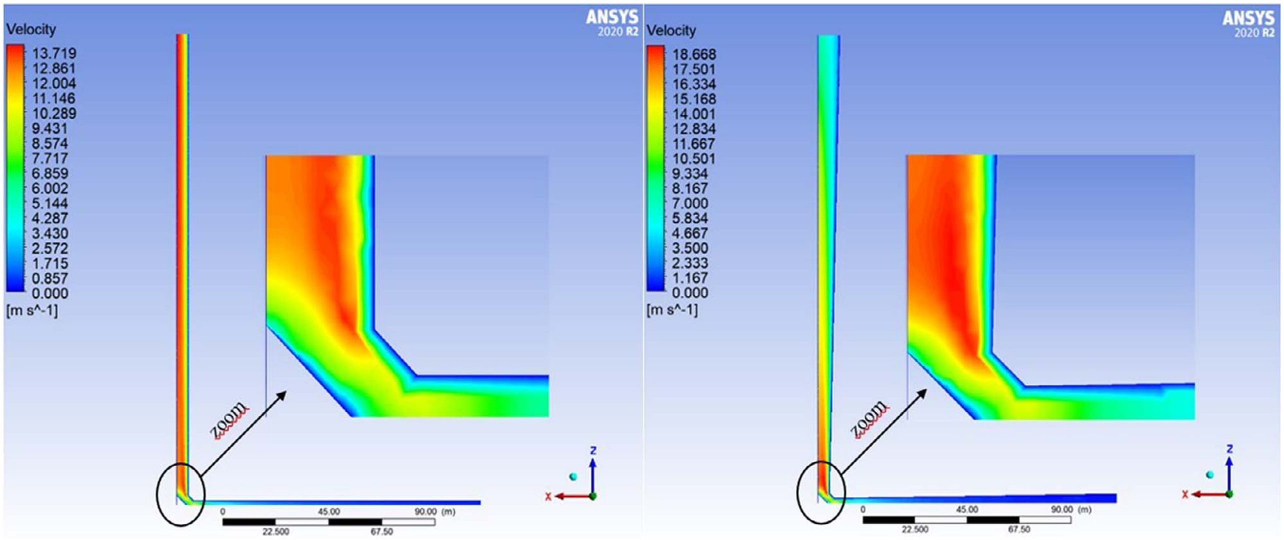

Figure 4. *The view from the symmetrical plane of the velocity distribution in the plant for the reference (on the left) and the new model (on the right).*

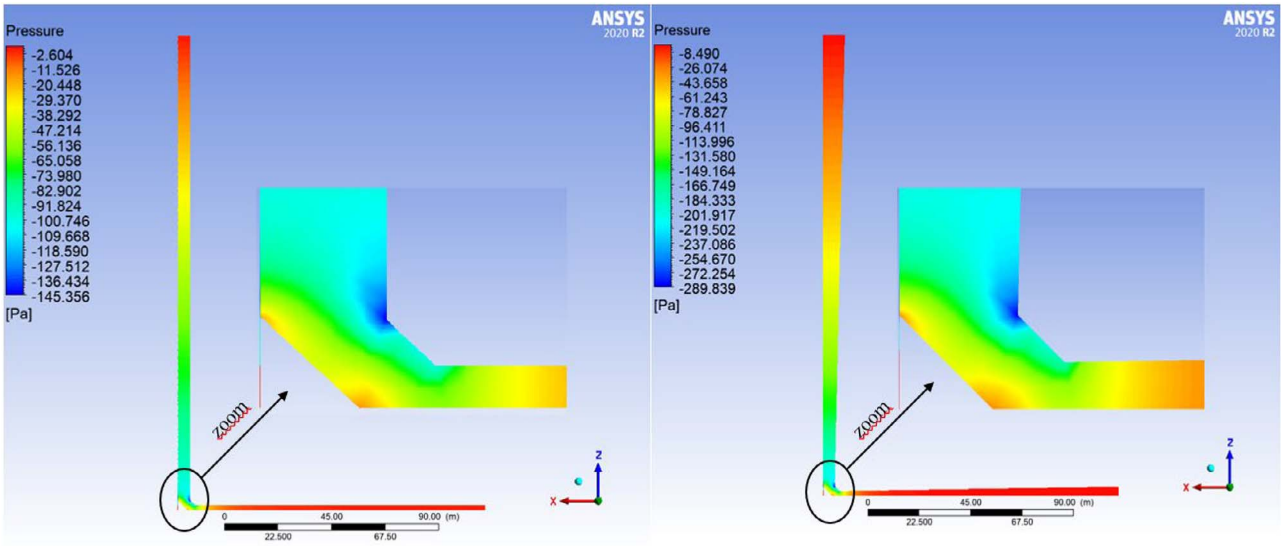

Figure 5. *The view from the symmetrical plane of the pressure distribution in the plant for the reference (on the left) and the new model (on the right).*

chimney and convergent collector design, it is seen that the air velocity starts to increase before it reaches the chimney inlet. This is because the expanding chimney increases the air movements by creating a high vacuum. The importance of airflow rate is that it increases the mass and volumetric flow rates in the system. In the reference case, the mass flow rate is 1083.25 kg/s and the volumetric flow rate is 900 m^3/s. With the new model, it is seen that the value of two increases by more than 40% to 1553.4 kg/s and 1289.54 m^3/s, respectively.

Turbine pressure drop is one of the significant parameters of electrical power production. As the pressure difference from the system increases, the power output increases proportionally. In the power output calculation, in equation 8, P_t is the overall pressure deviation at the turbine location and is taken through the simulation data. The findings reveal that the overall pressure deviation near the turbine area in the reference state is 105.315 Pa. With the new design, it is understood that this value exceeds 2 times and reaches 212.777 Pa. This is directly reflected in the power output. Pressure distribution visuals for the reference state and the new model are given in Figure 5. The pressure deviation reaches its maximum at the throat part.

Solar energy systems are dependent on the sun due to their structure. SCPP systems are easy to distinguish from other energy systems in this respect. The energy stored on the floor passes into the system air during the hours when the sun is absent or insufficient, making a performance improvement effect. Similarly, the continuous vacuum impact provided by the updraft tower allows power output for 24 hours. The temperature distribution

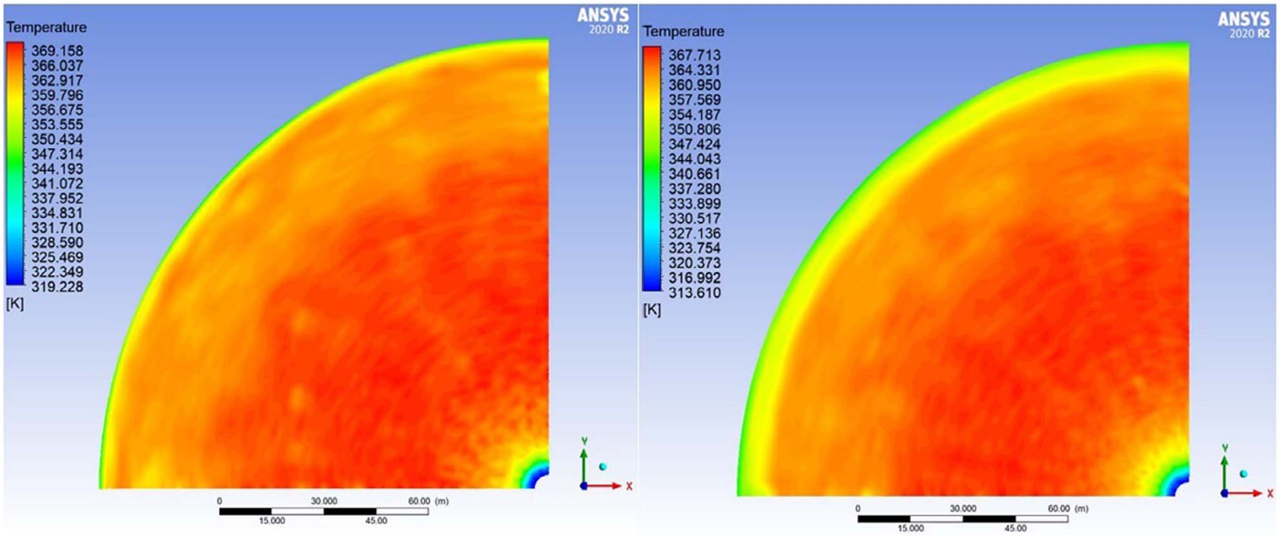

Figure 6. *Temperature distribution on the collector floor for the reference (on the left) and the new model (on the right).*

at the collector floor for the reference state and the new design is given in Figure 6. When the distributions are examined, it is understood that the temperature values are higher at the collector floor for the reference case. This is because the air velocity is higher in the new design. The high airflow rate increases the convection effects and causes the energy on the floor to pass into the plant air. When the *in-situ* findings are analysed, it is found that the temperature increase on the ground is above 70°C [5]. In the study, the maximum temperature on the ground is ∼360–370 K, on average 350–360 K. These results show that the CFD model can simulate the thermal performance characteristics of the system very well.

It can be seen from the performance values that the effect of divergent chimney and convergent collector concept on SCPP performance is positive. The V_{max} in the system, the average pressure difference at the turbine position and the power output increase significantly. The electrical power of 50.51 kW in the reference situation, approaches 3 times with the new model and reaches 146.34 kW. Figure 7 gives an evaluation of the performances for the reference and the new model. The combination of divergent chimney and convergent collector impacts in the pilot plant yields remarkably better electrical power output since both design concepts improves buoyant effects, pressure difference and mass flow rate of system air. The novel nozzle influence near the turbine position notably raises the air velocity figures.

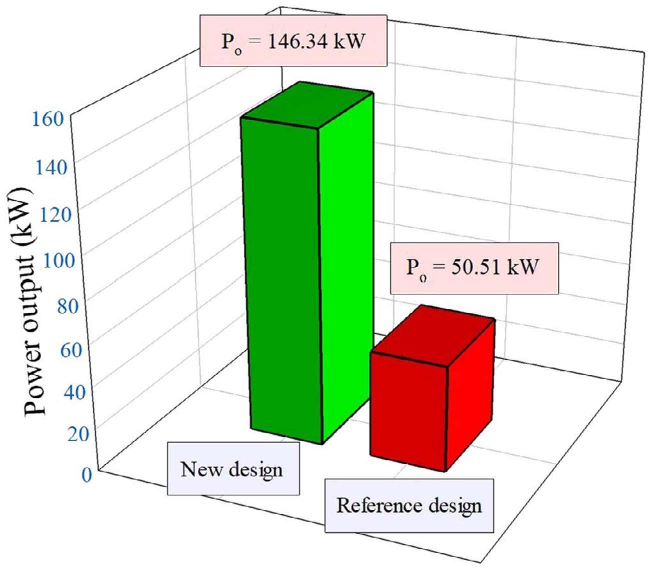

Figure 7. *Comparison of power output for reference model and nozzle design model.*

4. CONCLUSIONS

In this study, the performance of SCPP systems at 293 K environment temperature and 1000 W.m^{-2} solar radiation is evaluated with a new design. With the concept of divergent chimney and convergent collector, a new model is created with a ground thickness of 1 m. The created 3D 90° CFD model is simulated under constant environmental conditions. The discrete ordinates (DO) solar beam tracking approach option is preffered to simulate solar intensity, and the RNG k-e model for turbulence is analysed under continuous conditions. The findings drawn from the present work can be listed as follows:

- The solar beam tracking algorithm and the RNG k-e turbulence model are well-suited for modeling SCPP systems.
- The first pilot plant gives an electrical power of 50.51 kW in CFD results, this value is 50 kW in experimental data.
- The combined effect of divergent chimney and convergent collector has a contributive influence on the plant operation. The power output in the new design approaches 3 times the reference state (146.34 kW).

- The V_{max} improves by 36.8% to 19.363 m/s in the new model.
- The volumetric and mass flow rates increase by more than 40% with the new model and become 1553.392 kg/s and 1289.548 m^3/s.

In future studies, divergent and convergent designs of chimney and collector will be examined in different ways and their effects on the system will be evaluated. Energy storage on the ground will be assessed through different pond materials [39] for further enhancement in performance figures. In addition, collector area dependency [40] will be assessed for the optimal design since it is a significant part of the system cost.

Author contributions

Pinar Mert Cuce (Conceptualization [Equal], Data curation [Equal], Software [Equal], Writing—original draft [Equal]), Abhishek Saxena (Writing—review & editing [Equal]), Erdem Cuce (Investigation [Equal], Methodology [Equal], Supervision [Equal], Writing—original draft [Equal], Writing—review & editing [Equal]), Karolos Kontoleon (Writing—review & editing [Equal]), Erman Öztekin (Data curation [Equal], Methodology [Equal], Validation [Equal]), Saboor Shaik (Writing—review & editing [Equal]) and Shaopeng Guo (Software [Equal], Supervision [Equal], Validation [Equal])

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