IMPACT OF DIVERGENCE ANGLE ON PERFORMANCE FIGURES OF SOLAR CHIMNEY POWER PLANTS: A COMPREHENSIVE CFD RESEARCH

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ABSTRACT

The sun ranks first among potentially renewable energy sources. Especially its different usage areas and its appeal to wide geographies increase its attractiveness. This study focuses on chimney design in solar chimney power plants, which is one of the solar energy systems. A different approach to the performance of the Manzanares pilot plant is realized with the divergent chimney design instead of the traditional cylindrical chimney with the 3D CFD model. The effect on the system is evaluated by keeping the model chimney entrance area constant, which is verified with a mesh-independent solution and experimental data, and the divergence angle towards the chimney outlet is 0.5, 1, 1.5, 2, and 2.5°. Since the chimney is the driving force of the system, it provides upward acceleration of the system air, whose kinetic energy increases under the collector. It is seen that the maximum air flow rate, which was 14.223 m/s in the reference case where the divergent chimney structure contributed to this situation, increased by 38.5% with the divergent chimney design and reached 19.7 m/s. It is determined that the chimney divergence angle, which increases after 1.5°, which is the optimum point for the chimney divergence angle, does not increase the power output of the system, on the contrary, it decreases it. The power output, which was 53.6 kW in the reference case with a cylindrical chimney, is predicted to increase by 170% at 1.5° chimney divergence and reach 146.824 kW. The same is true for the mean pressure difference at the turbine position. When the divergence angle is made 1.5°, the mean pressure difference will increase by 95% and reaches 208.083 Pa whereas it is only 106.623 Pa in the reference case.

Keywords: Solar chimney, Divergent chimney, Divergent degree, Maximum velocity

INTRODUCTION

Technological advances and their lasting effects on human habits have brought energy consumption to an incredible level in the last century. The fact that people use technology effectively in their daily life has made it inevitable to increase energy consumption. With the parallel increase in the consumption of energy resources, although there is no problem at the stage, fossil fuel-based energy production has reached a critical level for environmental pollution and human life. This makes the use of renewable energy sources inevitable. The fact that renewable energy sources are clean energy sources and that their CO_2 emissions are almost non-existent have attracted the attention of researchers in recent years. Renewable energy sources such as hydroelectric, wind, geothermal and solar are indispensable for the future of humanity and the sustainability of nature. It is the most popular among renewable energy sources with its solar energy potential (Cuce et al. 2022). Solar energy systems with different applications use the sun directly or indirectly. The use of direct sun for space heating and water heating has been in the use of humanity since ancient times. Systems in which the sun is used directly to generate electricity are photovoltaic (PV) systems (Jasim et al. 2022). PV systems can convert the solar radiation falling on them directly into electricity. In systems that indirectly generate electricity from the sun, solar energy is transferred to a working fluid. Then the energy of the fluid is converted into electricity via the turbine (Sen et al. 2021). One of the solar energy systems working with this methodology is solar chimney power plants (SCPP). SCPP systems incorporate solar energy with the translucent collector that covers a large area. Then, the air under the collector absorbs the trapped solar energy and its kinetic energy increases. System air with increased kinetic energy is drawn upwards from the collector center with the vacuum effect of the high chimney. Meanwhile, the turbine inside the chimney converts the energy of the accelerated air into electricity. The first application of SCPP systems, which are simple in structure, was established in Manzanares, Spain in the 1980s (Schlaich et al. 2005). The system has a 194.6 m high chimney and a 244 m diameter collector and gives a power output of 50 kW in the measurements obtained in September (Haaf, 1984). After this huge facility, researchers repeatedly evaluate the performance of the system at different times, taking into account different parameters. In general, the performance of the system is affected by climatic and geometric parameters (Sen and Cuce, 2020). Climatic parameters vary according to the region and it is not possible to control them beforehand. Geometric parameters, on the other hand, can be evaluated in advance at the design stage and possible performance estimates can be made. Cuce et al. (2020) claim that increasing the chimney height in SCPP systems will positively affect the performance of the system with the 3D CFD model they have developed. In their study based on the Manzanares pilot plant, they show that the power output, which is approximately 53 kW at a chimney height of 194.6 m, will increase by 152% to 134 kW if the chimney height is 500 m. Li et al. (2012) interpret the effect of chimney height and collector radius on SCPP performance based on the pilot plant with a theoretical model. They indicate that increasing the collector radius after 300 m will not affect the power output much, at this point the power output will be about 135 kW. The design of the system is as important as its

sizing. Cuce et al. (2021) analyze the effect of divergent and convergent chimney design on the performance of the SCPP system with their CFD study. They claim that the Manzanares pilot plant will outperform the divergent flue design. They emphasize that if the chimney entrance area is kept constant and the chimney outlet area is increased to 3.5 times, the power output will approach 3 times and will be 168.5 kW. Similarly, some researchers state that the divergent chimney design will provide a significant increase in the performance of the system (Hu et al. 2017). Like the chimney design, the collector design also affects the performance of the system. Hassan et al. (2018) evaluate the SCPP system with the CFD model. They claim that the collector slope will increase the mass flow rate of the pilot plant. Although the studies in the literature make different evaluations about the chimney divergence angle, there is a lack of detailed analysis. This study aims to analyze the maximum air flow rate and power output in the system at different flue divergence angles.

MATERIALS AND METHOD

The performance of SCPP systems can be evaluated by experimental, mathematical and CFD studies. The limited size variation for experimental study directs researchers to mathematical and CFD studies. In this study, a 3D CFD model is created with the student version of ANSYS engineering commercial software student version. The model created is designed to be economical in solutions by using 2 symmetry planes (XZ and YZ). The visuals of the model are given in Figure 1. Then, the network structure is constructed with the Mesh process. Finally, energy, momentum and continuity equations are solved simultaneously by making the following assumptions via FLUENT:

- The flow regime is continuous and 3-dimensional.
- The Boussinesq approximation is applied for the density of the air.
- The flow is considered turbulent throughout the system and the RNG k-ε turbulence model is applied.
- All analyzes are performed under constant environmental conditions with 1000 W/m^2 solar radiation and 300 K ambient temperature. It is assumed that these conditions do not change during the solution.
- The discrete ordinates (DO) solar ray tracing algorithm for solar radiation is adapted to the system.
- PRESTO! is preferred for pressure discretization, Coupled for pressure velocity analysis, and 2nd order discretization for other solvent options.

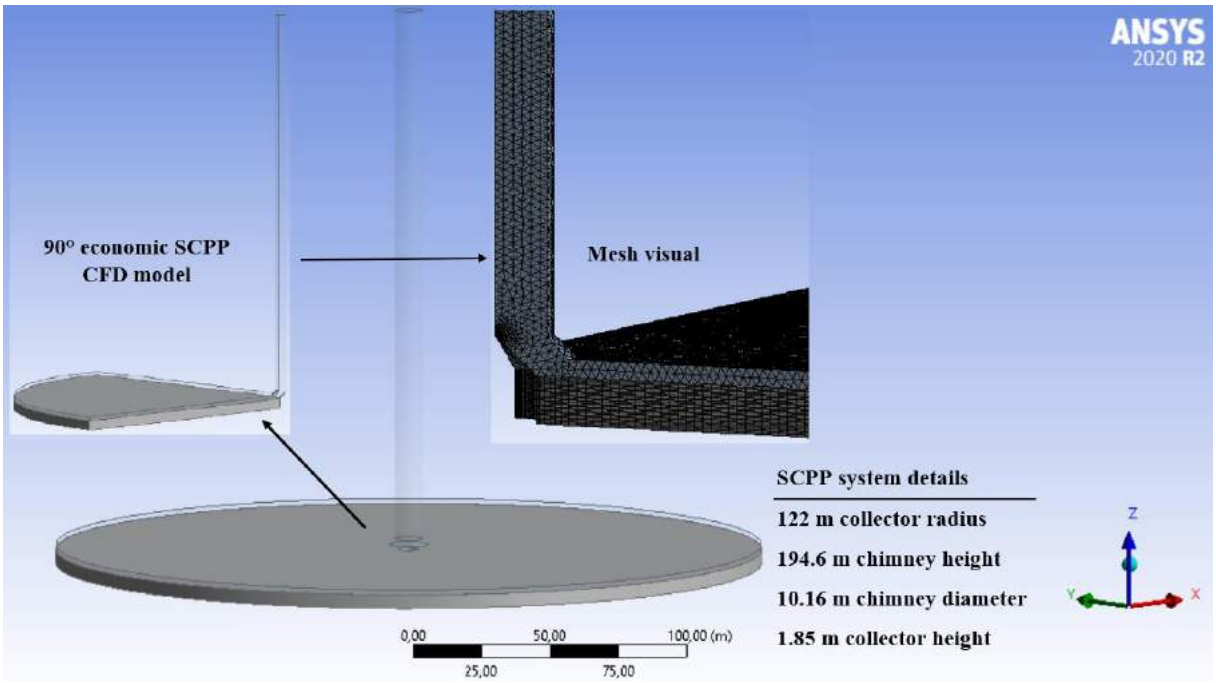


Figure 1. SCPP 3D CFD model, economic 90° model, mesh visual and geometric details of study.

In the study, composite material is used based on glass for the collector, gravel-sand mixture for the ground and pilot plant for the chimney. The thermophysical properties of the materials used in the study are given in Table 1.

Table 1. Thermophysical properties of materials used in CFD.

Material/Properties	**Density (kg/m^3)**	**Heat cap. (j/kgK)**	**Thermal con.(W/mK)**
Ground	2160	750	1.15
Glass	2700	840	0.78
Chimney	2100	880	1.4

*****Reference: Cuce et al. (2023).*

Analyzes are performed by taking the convergence criterion of 10^{-6}. First, the solution is repeated for different cell numbers to obtain a mesh-independent solution. CFD results of different cell numbers are given in Table 2. In the evaluation, it is determined that the number of 620000 cells is sufficient for the solution.

Table 2. Mesh-independent solution data over the maximum air velocity for the CFD model.

Element numbers	**V_{max} (m/s)**	**% change**
360000	15.14	-
480000	14.31	5.48
620000	14.22	-0.628
830000	14.3	-0.562

RESULTS AND DISCUSSION

After obtaining the mesh-independent solution and determining that the number of cells does not affect the solutions, the experimental data in the literature are consulted to check the reliability of the model. When the experimental data are examined at 300 K ambient temperature and 1000 W/m2 solar radiation intensity, it is seen that the system has a maximum air flow rate of 15 m/s and a power output of 50 kW (Haaf 1984). Under the same conditions, a maximum air flow rate of 14.22 m/s and a power output of 53.6 kW are obtained in the CFD model. The deviation from the experimental data is 5.2% for maximum air flow rate and 7% for power output, which is acceptable. Mesh independent solution and the verified model are then kept constant and the chimney outlet area is increased, and the outputs of the system are compared in cases where the chimney divergence angle is 0.5°, 1°, 1.5°, 2° and 2.5°.

Table 3. Effect of chimney divergent angle on system outputs.

Angle (°)	**Maximum velocity (m/s)**	**Mass flow rate (kg/s)**	**Pressure difference at turbine location (Pa)**
0	14.22	1108.46	106.62
0.5	18.01	1417.07	169.9
1	19.73	1556.39	202.74
1.5	19.6	1555.85	208.08
2	19.66	1534.25	195.27
2.5	19.11	1525.94	192.07

It is seen that the maximum air flow rate in the system increases with the increase in the chimney divergence angle, but decreases after 2°. The reason for this is that the amount of air entering the system increases with increasing mass flow rate. It is understood that the mass flow rate starts to decrease after 1.5°. The same is true for the mean pressure difference at the turbine position. It is seen that the average pressure difference at the turbine position, which is 106.62 Pa in the reference case, approaches 208.08 Pa, approaching 2 times when the flue divergence angle is 1.5°. The contours of the air flow velocity in the system for 3 different chimney divergence angles are given in Figure 2. When the images are examined, it is seen that the flue divergence angle and the upward air flow velocity at the chimney inlet increase. This is expected to increase both the pressure differential and the power output.

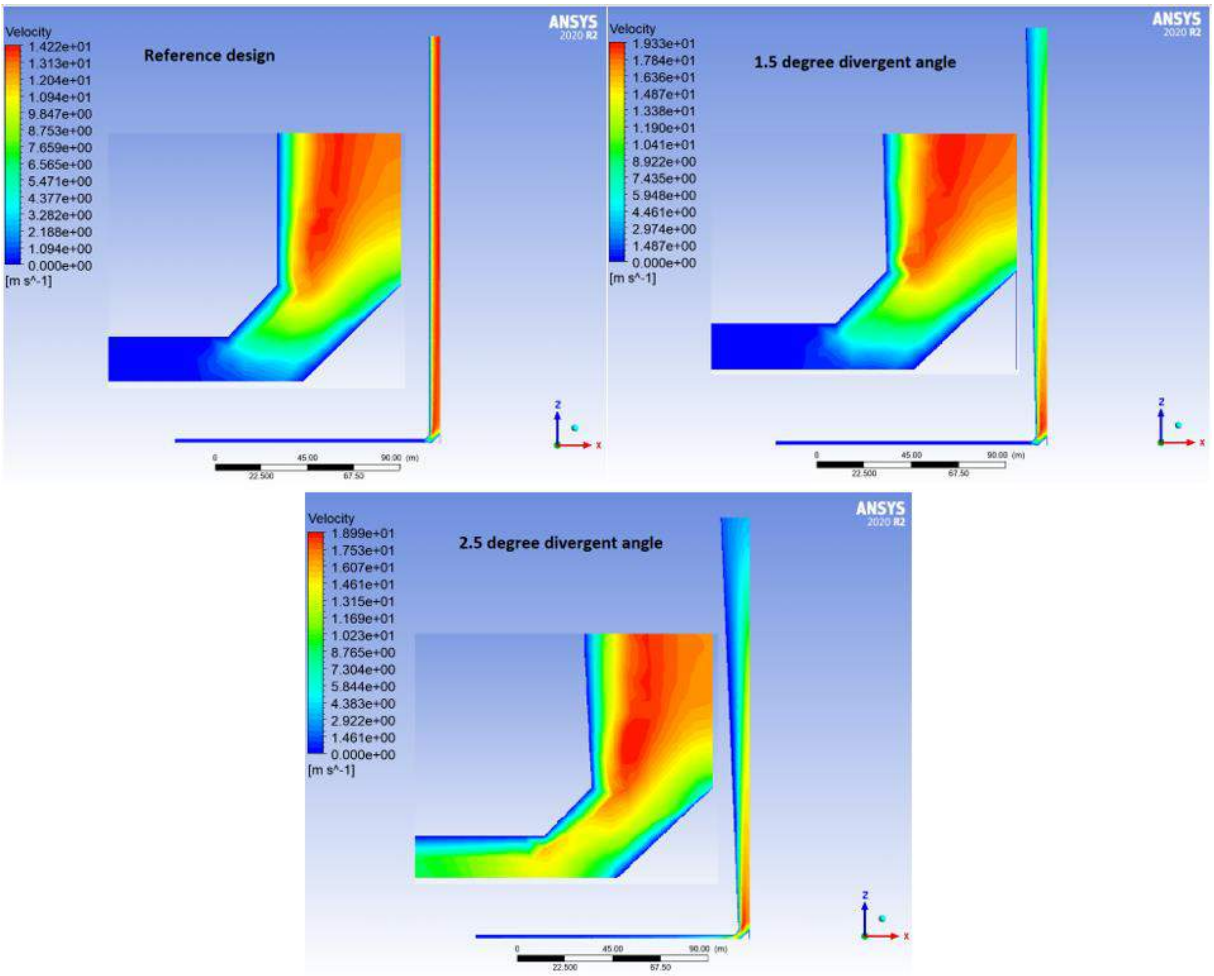


Figure 2. Velocity contours for three divergent chimney degrees.

The effect of the change in the flue divergence angle on the power output of the system is given in Figure 3. The flue divergence angle increases the power output of the system, but this is not sustained. The power output, which is 53.6 kW in the reference case, increases by 170% and becomes 146,824 kW when the flue divergence angle is 1.5°. After this point, increasing the chimney divergence angle reduces the power output of the system rather than increasing it. The optimum flue divergence angle for the Manzanares pilot plant is 1.5°. In addition, the power output of the system for the values between the reference state and the chimney divergence angle of 2.5° can be found with the following equation:

$$P_o = 53.5804 + \frac{206.9292}{\beta} e^{\left[-0.5\left(\frac{\ln(\beta/3.6613)}{0.9961}\right)^2\right]}$$

In the equation, P_o represents the power output and β represents the chimney divergence angle.

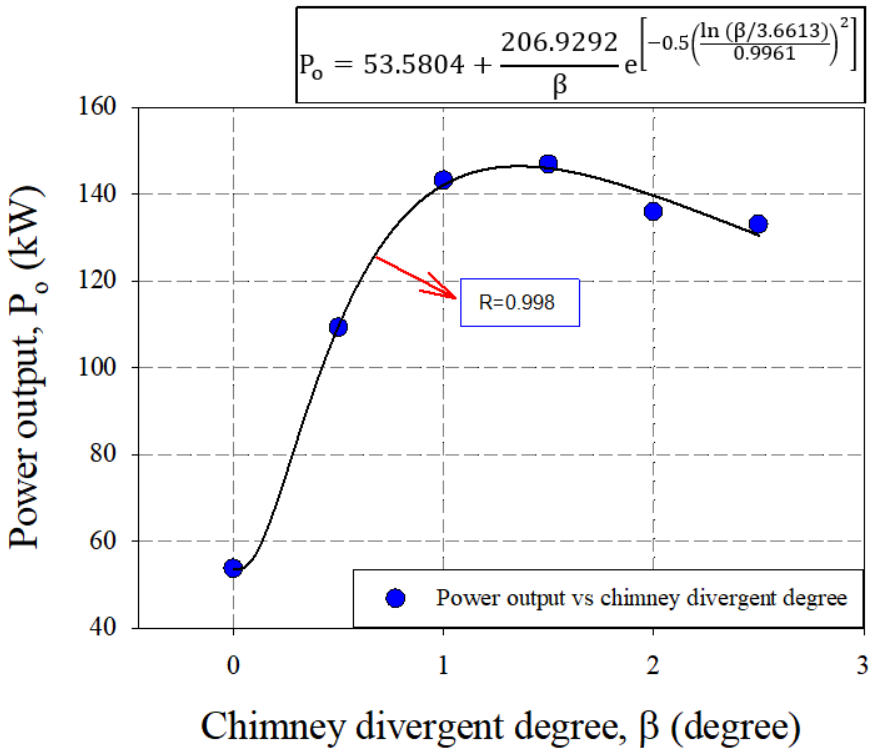


Figure 3. Graphic for power output for different chimney divergent degree.

CONCLUSION

In SCPP systems, the chimney divergence angle is evaluated with a 3D CFD model. The 90° economic model created based on the Manzanares pilot plant is verified with experimental data after the mesh-independent solution is provided. By keeping the chimney entrance area fixed, the chimney outlet area is increased. The effect of this change made depending on the chimney divergence angle on the outputs of the system can be given as follows:

- To model SCPP systems, the 3D CFD model provides results consistent with the experimental data with the turbulent flow approach.
- 53.6 kW power output is obtained at 300 K ambient temperature and 1000 W/m^{2}K solar radiation intensity.
- An increase in the chimney divergence angle increases the performance of the system up to 1.5°, but if the increase continues, the performance begins to decrease.
- At 1.5° chimney divergence angle, the system gives 170% more power output than the reference situation (146.824 kW).
- In SCPP systems, much more power output can be obtained from smaller systems with divergent chimney design rather than large-scale systems. For this, more modeling with divergent chimney design is required.

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