GÜNEŞ BACASI GÜÇ SANTRALLERİNDE KOLEKTÖR YÜKSEKLİĞİNİN ETKİSİNİN SAYISAL ANALİZİ
NUMERICAL ANALYSIS OF THE EFFECT OF COLLECTOR HEIGHT IN SOLAR CHIMNEY POWER PLANTS

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ÖZET
Güneş enerji sistemleri sürdürülebilir ve temiz çevre için kaçınılmazdır. Özellikler artan insan nüfusu ile enerji tüketimindeki fazlalaşma fosil yakıtların kullanımı açısından tehlikeli boyuta ulaşmıştır. Güneş bacası güç santralleri hem düşük bakım maliyetleri hem de CO2 salınımının düşük olması bakımından popülerliğini arttırmaktadır. Yüksek bacası sayesinde oluşturduğu basınç farkı elektrik üretimi için itici güç oluşturmaktadır. Ayrıca geniş toplayıcı ile üzerine düşen güneş ışınımını bünyesine alarak altındaki sistem havasının kinetik enerjisini arttırır. Kinetik enerjisi artan sistem havası, türbin aracılığıyla elektrik üretir. Bu çalışma ilk prototip olan Manzanares güç santralini referans alarak toplayıcı yüksekliğindeki değişimin sistem havası üzerindeki etkisini yorumlamayı amaçlar. 3 boyutlu CFD modeli oluşturularak deneysel ve literatür verileri ile doğrulanır. Tüm çözümlemeler sürekli koşullar altında sabit 300 K çevre sıcaklığı ve 1000 W/m2 güneş ışınım şiddetinde elde edilir. 1,85 m yüksekliğie sahip olan pilot tesisin ideal toplayıcı yüksekliğinin daha az olması gerektiği, düşük toplayıcı yüksekliklerinde sistemin performansının arttığı görülmektedir. Ayrıca toplayıcı yüksekliğindeki artış ile sistemin debisinde belirgin bir yükselme olduğu tespit edilir. Maksimum hava akış hızının düşük toplayıcı yüksekliklerinde daha yüksek olduğu, bunun nedeninin sisteme giren toplam enerjinin sabit olmasına rağmen hava debisindeki azalmadan kaynaklandığı belirlenir.
Anahtar Kelimeler: Güneş bacası güç santralleri, Toplayıcı yüksekliği, Toplayıcı etkisi

ABSTRACT
Solar energy systems are indispensable for a sustainable and clean environment. Especially with the increasing human population, the increase in energy consumption has reached a dangerous level in terms of the use of fossil fuels. Solar chimney power plants are gaining popularity due to low maintenance costs and CO2 emissions. The pressure difference created by its high chimney creates a driving force for electricity generation. In addition, it increases the kinetic energy of the system air under it by absorbing the solar radiation falling on it with its large collector. System air with increased kinetic energy generates electricity through the turbine. This study aims to interpret the effect of the change in collector height on the system air concerning the first prototype Manzanares power plant. A 3D CFD model is created and verified with experimental and literature data. All analyzes are obtained under continuous conditions at a constant ambient temperature of 300 K and a solar irradiance of 1000 W/m2. It is seen that the ideal collector height of the pilot plant, which has a height of 1.85 m, should be less, and the system's performance increases at low collector heights. In addition, it is determined that there is a significant increase in the system's flow rate with the rise in the collector height. It is determined that the maximum air flow rate is higher at low collector heights due to the decrease in the air flow rate even though the total energy entering the system is constant.
Keywords: Solar chimney power plant, collector height, collector effect

INTRODUCTION
The rapidly increasing human population in the world in the last century has caused energy consumption to reach incredible levels. Especially with the technological developments, the increase in energy dependency has revealed multi-faceted effects. The energy need for a short-term solution has been met from fossil fuels for many years. As this situation increased environmental pollution and harmful gas emissions, the search for

clean energy was born. The best source for this quest is renewable energy sources. Renewable energy sources are indispensable for the continuity of our planet, as they do not have harmful gas emissions and are environmentally friendly. Geothermal, solar, hydroelectric and wind energy are among the most common renewable energy sources. Of these, solar energy has an unlimited potential for humanity. Although solar energy has a wide usage area, it is widely used for space heating, hot water production and electricity generation. Solar energy can be used directly or indirectly to generate electricity. PV modules are used to generate electricity directly. PV modules can convert the solar radiation falling on them directly into electricity (Cuce et al., 2017). Indirectly, an intermediate fluid is needed to generate electricity from solar energy. Solar energy is first transferred to a fluid through some systems, and then electricity is produced from the kinetic energy of the fluid through a turbine (Cuce et al., 2022). One of the solar energy systems working with this technique is solar chimney power plants (SCPP). These systems, which receive solar energy with the semi-permeable feature of the large-scale collector, do not have harmful gas emissions. It creates a vacuum effect with the pressure difference at the inlet and outlet of the high chimney, which is the other structural element. This vacuum effect forces the system air, whose temperature and kinetic energy increase in the collector center, to upward movement. This results in the system air accelerating into the chimney and rising. In the meantime, the kinetic energy of the system air is converted into electricity with the turbine inside the chimney. SCPP systems are first installed in Manzanares, Spain in the 1980s. The system with a chimney height of 194.6 m had a collector with a diameter of 244 m and it was shown by experimental measurements that it gave a power output of 50 kW (Haaf et al., 1983). In the next process, researchers do different studies to improve the performance of the system. In general, studies can be classified under two headings as climatic and geometric parameters. Environmental temperature and solar radiation intensity are climatic parameters. For the Manzanares pilot plant, it is claimed by researchers that an increase in ambient temperature decreases the performance of the system, while an increase in solar radiation intensity increases performance (Cuce et al. 2020a). Geometric parameters can be evaluated as chimney height and diameter, collector height and diameter. The size of the collector is important as it directly affects the energy entering the system. Li et al. (2012) in their 3D CFD study for the Manzanares pilot plant, they claim that the power output is approximately 54 kW in the reference case, and if the collector radius is doubled, the power output will exceed twice that of 120 kW. The height of the chimney also affects the performance of the system like the collector. Cuce et al. (2020b) They analyze the effect of chimney height on the system with the 3D CFD model they created over the Manzanares pilot facility. They emphasize that the power output, which is 54 kW at the reference height, will increase to 134 kW if the chimney height is 500 m. It is claimed by researchers that the chimney is the driving force of the system and can provide continuous power output (Sen and Cuce, 2020).

When the studies are evaluated, it is seen that there is intense work on the collector size and chimney height, but the collector height is not adequately interpreted. In studies on the collector height, it is neglected that the air under the collector shows turbulent flow, especially after a certain height. In this study, the outputs of the system are compared by accepting both turbulent flow and laminar flow for different values of the collector height.

RESEARCH AND FINDINGS

In this study, in which the effect of collector height on the performance of the SCPP system is evaluated, a 3D CFD model is created with the student version of ANSYS engineering commercial software. The created 3D model is converted into a 90° model for economy and solved in the FLUENT interface using the boussinesq approach under constant climatic conditions. 3D CFD design, the visual and mesh image of the 90° model are given in Figure1.

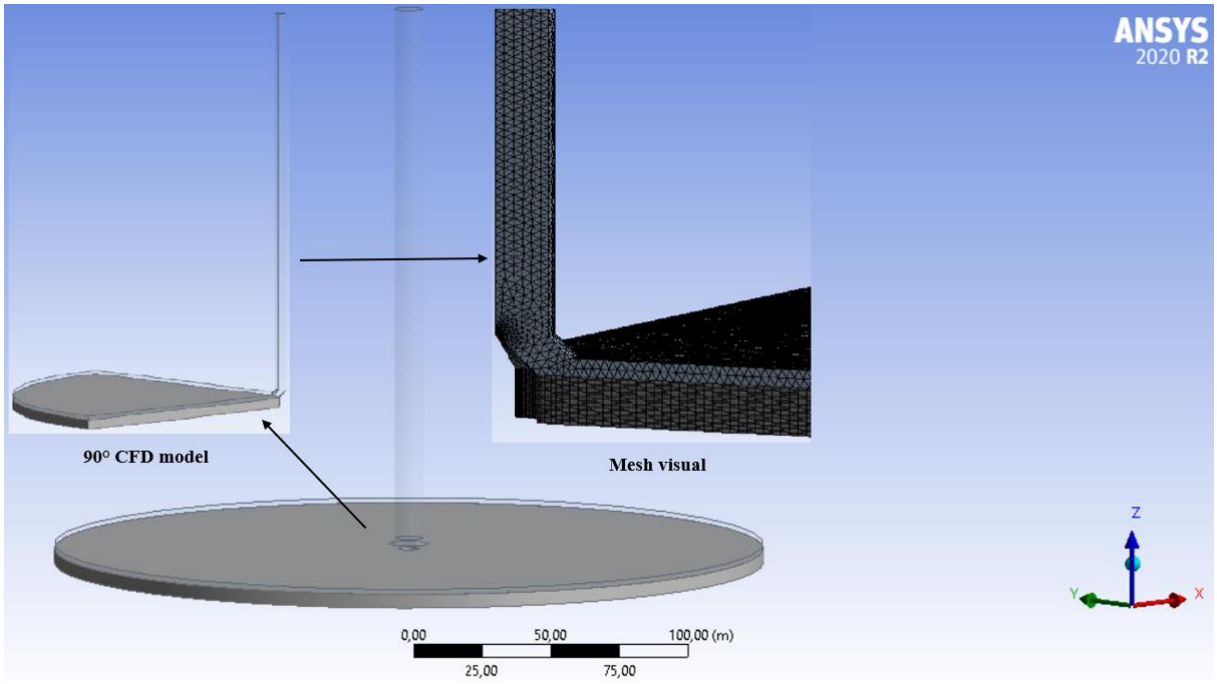


Figure 1. Images of 3D CFD model, 90° model and mesh image.

In the analysis, mesh-independent solution is performed to reach the ideal number of cells. The detailed comparison of the mesh independent solution is given in Table 1. When the table is examined, since the % change in the number of elements for 0.8 m element size is negligible, it is considered sufficient for the solution. CFD and geometric data of the system are given in Table 2. For the mesh-independent solution, the maximum air flow rate (V_{max}) in the system is taken as reference.

Table 1. Mesh independence solution and details.

Element size (m)	Element numbers	V_{max} (m/s)	%change
1	367857	15.145	-
0.9	482518	14.311	-5.506
0.8	625305	14.223	-0.614
0.7	838257	14.301	0.548

Table 2. Gometric data of the system and CFD details (Haaf, 1984).

Collector height (m)	0.5 – 2.5	Collector Radius (m)	122
Chimney height (m)	194.6	Chimney diameter (m)	10
Air density (kg/m^3)	1.176	Atmospheric pressure (Pa)	92930
Ambient temperature (K)	300	Solar radiation (W/m^2)	1000

In the CFD model, 5 m is considered sufficient since the temperature does not change in the experimental data from a depth of 1 m on the ground (Haaf, 1984). Soil and gravel mixture is used as the ground material based on the pilot plant. The floor and chimney are defined as opaque and the collector as semi-permeable. Material properties are given in Table 3. In the solvent options, coupled is used for pressure-velocity analysis, PRESTO! for pressure discretization, and a 2nd order solution for other discretizations. The convergence criterion is taken as 10^{-6} for all cases.

Table 3. Material properties used in the CFD model (Pandey et al., 2021; Abdelmohimen and Algarni, 2018).

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

After determining the applicability of the CFD model with the mesh-independent solution, experimental data and literature are used to validate the model. In the study based on the pilot plant, it is seen that the maximum air flow rate (Vmax) is 14.223 m/s and the power output is 53.6 kW. These results are consistent with experimental data. Detailed comparison is given in Table 4.

Table 4. Verification of the CFD model with the literature (Schlaich et al., 2005).

	Experimental	CFD	% Error
Maximum velocity (V_{max}) (m/s)	15	14.223	5.18
Power output (P) (kW)	50	53.6	7.2

The solutions are repeated by changing the collector height in the range of 0.5 – 2.5 m with the verified model. In all analyses, the flow is considered turbulent. It is seen that reducing the height of the ball increases the performance of the system in general. In the reference case, the maximum air flow rate in the system at 1.85 m collector height is 14.223 m/s, while if the collector height is 0.5 m, it is seen that the maximum air flow rate increases by 70% and exceeds 24 m/s. The same is true for the mean pressure difference at the turbine position. It is seen that the average pressure difference, which is 106,623 Pa for the reference situation at the turbine position, increases by 160% to 277,721 Pa when the collector height is made 0.5 m. There is no similar situation for mass flow. It is seen that the mass flow rate, which is 1108.6 kg/s at the reference height, decreases by 43% and becomes 631.46 kg/s if the collector height is made 0.5 m. The power output graph of the system at different collector heights is given in Figure 2. It is noteworthy that the power output decreases with the collector height. Reducing the collector height after a point may affect the flow characteristics and cause the conversion from turbulent flow to laminar flow. In this case, the air flow rate in the system will decrease, so the power output will also decrease. For this, the performance data of the system for both laminar and turbulent flow at low collector heights are evaluated. Detailed data are given in Table 5.

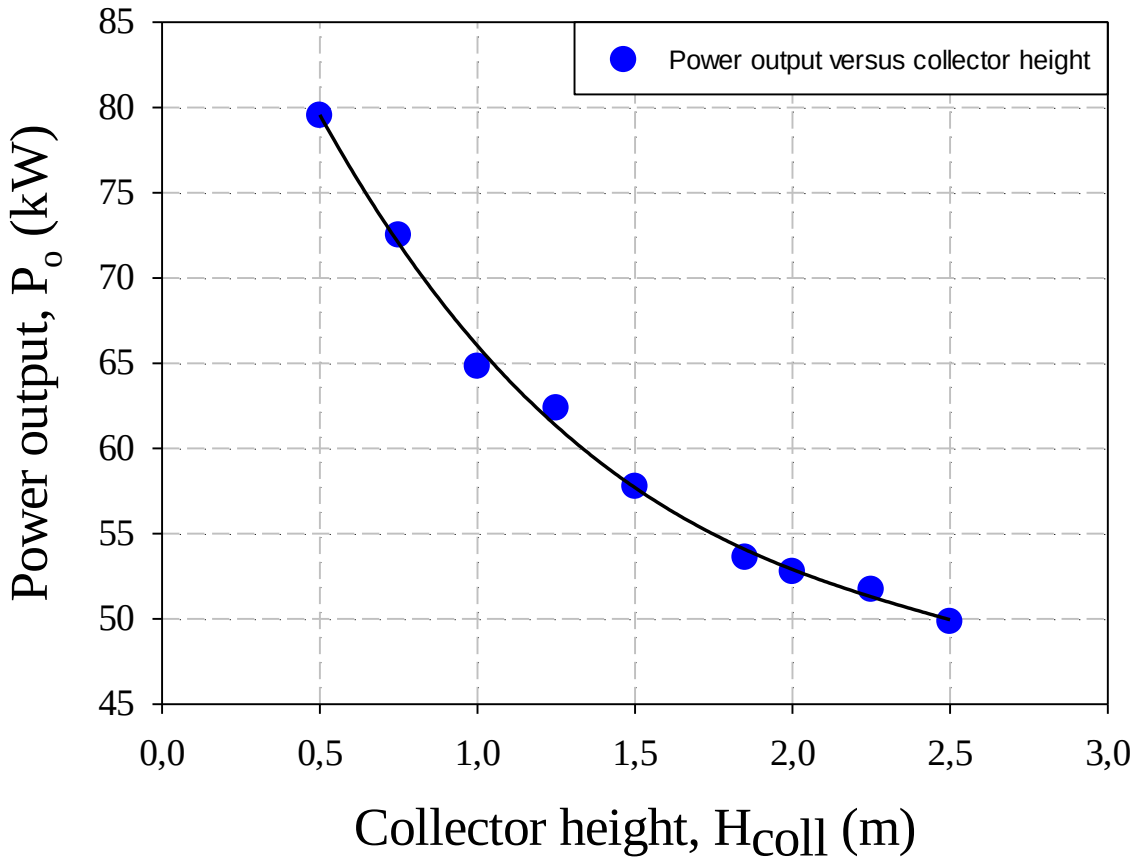


Figure 2. Effect of collector height on SCPP power output.

These findings obtained from the analysis made with the assumption of turbulent flow show that the collector height has a negative effect on the system. In this case, the point to be considered is to evaluate the flow characteristic in the system when the collector height decreases. For natural convection the dimensionless number Rayleigh (Ra) is decisive for laminar and turbulent flow. Since there is turbulent flow with Rayleigh number greater than 10^9, the Ra number is approximately $2.16X10^8$ for a collector height of 0.5 m. Since this value is smaller than the critical Ra number, the flow can be assumed to be laminar. In Figure 3, for 0.5 m collector height, laminar and turbulent flow, respectively, and maximum air flow velocity contours in the system are given. As can be seen from the image, since the collector height is low, the air flow rate up to the throat is low. Detailed data for laminar and turbulent flow acceptance for 0.5 m collector height are given in Table 5.

Table 5. Performance data of the system in laminar and turbulent flow for collector heights of 0.5 m.

		Mass flow rate (kg/s)		V_{max} (m/s)	Power output (kW)		
0.5 m Laminar	273.94				10.083		6.016
0.5 m Turbulent	631.46				24.222		79.53

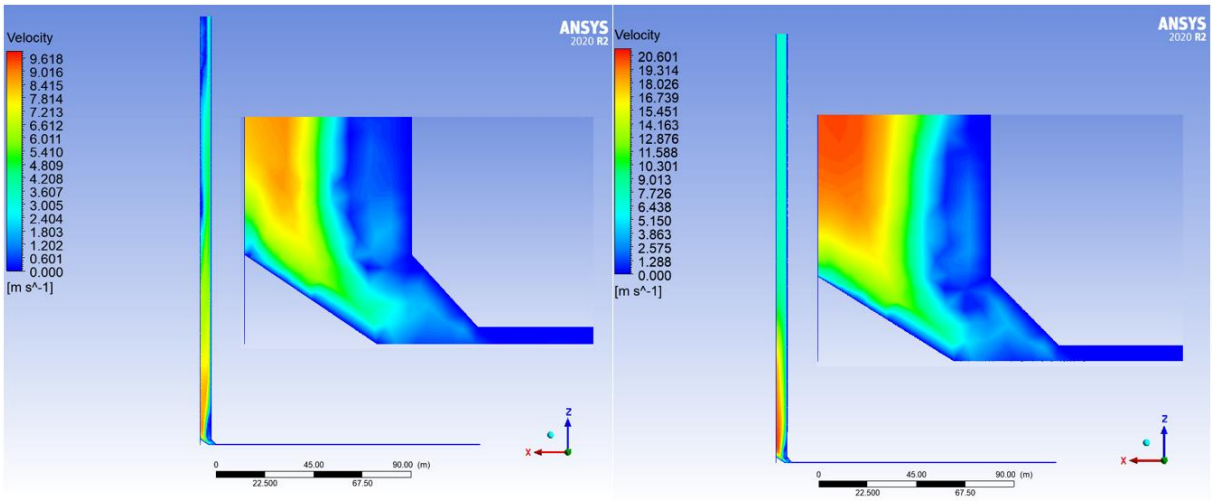


Figure 3. Velocity contours for 0.5 m collector height laminar on the left and turbulent on the right.

CONCLUSION

- CFD model gives very consistent results in experimental data for 1000 W/m^2 and 300 K ambient temperature lowering the collector height improves system performance.
- There is a minimum height for the ideal value of the collector height. In order to determine this value, the study can be expanded by evaluating the natural transport effects and evaluating the value of Ra number for different heights.
- It is possible to increase the power output, which was 53.6 kW in the reference case, to 64.8 kW by reducing the height by 20% with a collector height of 1 m.
- Since the flow characteristic is laminar at low collector heights, the collector height should not be lowered below 1 m.
- If the collector height is made 0.5 m for the pilot plant, the expected power output cannot be obtained because the flow characteristic will be laminar under the collector.

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