ANALYSIS OF THE EFFECT OF THE ENERGY STORAGE UNIT ON THE PERFORMANCE OF THE SOLAR CHIMNEY POWER PLANT WITH DIVERGENT CHIMNEY DESIGN THROUGH THE MANZANARES PILOT PLANT

E. CUCE
Department of Mechanical Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize – Turkey
erdemcuce@gmail.com

P. M. CUCE
Department of Architecture, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize – Turkey
mertcuce@gmail.com

H. SEN
Department of Mechanical Engineering, Faculty of Engineering and Architecture, Recep Tayyip Erdogan University, Zihni Derin Campus, 53100 Rize – Turkey
harun.sen6169@gmail.com

EXTENDED ABSTRACT

OVERVIEW

The increasing use of fossil fuels for the increasing energy demand in the world in the last century has caused serious environmental pollution. One of the energy sources needed to correct this situation is the sun. It is a renewable energy source that can be an alternative to fossil fuels in terms of solar potential. The sun, which has different uses, has had an important place in human life since ancient times. In recent years, the usage areas of solar energy have been increasing, and researchers have been carrying out intensive studies on this subject. It is seen that researchers use solar energy effectively, except for indoor heating and water heating purposes only with traditional methods. Some of these are solar cookers, fruit dryers and natural ventilation [1-3]. In these methods, it is mainly used in the form of absorption of solar radiation. Unlike these purposes, solar energy can be used to produce electricity directly or indirectly. Electricity generation with direct solar energy is PV systems that have been very popular in recent years. PV systems are solar energy systems that directly convert the solar radiation falling on them into electrical energy with the special materials in their structure [4]. Systems that indirectly convert solar energy into electrical energy are different from PV systems. These systems transfer solar energy to the air in their structures. This increases the kinetic energy of the air in the system. The kinetic energy of the air is converted into electrical energy by means of a turbine [5-6]. Solar chimney power plants are one of the solar energy systems that work in this way. These systems, which consist of 3 structural elements, turbine, collector and chimney, have attracted the attention of researchers in recent years with their simple structures [7]. Solar radiation reaches the ground

through the semi-transparent collector. In the meantime, some of the solar energy is absorbed by the system air. The rest causes an increase in temperature on the ground. The increase in the energy of the system air leads to an increase in its velocity. It is the only outlet of the air with high chimney velocity placed in the collector centre. Therefore, the system air is discharged from the chimney. Meanwhile, the air hitting the turbine, which is at a certain height in the chimney, generates electricity. Although it was first introduced a long time ago, the first application of solar chimney power plants was in the 1980s. The Manzanares facility established in Spain is considered the first application in this field. The system, which has a chimney height of 194.6 m, has a collector in a radius of 122 m [8]. In the first experimental studies on the system, it is seen that it gives a power output of about 50 kW at noon in the summer months [9]. Solar chimney power plants attract great attention after the first application. The reason for this is the pressure difference created by the high chimney in its structure [10]. With this pressure difference, the possibility of generating electricity during the hours when the sun is not present makes the system very attractive. Initial studies after the Manzanares pilot plant mostly focus on power output and efficiency depending on the geometric parameters of the system. However, it is shown by researchers that design changes have significant effects on the system in later periods. It is aimed to increase the performance of the system with the integration of different energy sources and hybrid systems. The geometric and design parameters affecting the performance of the system are given in Table 1.

Table 1. The geometric and design parameters affect the performance of the system.

References	Effects of geometric and climatic parameters	References	Design effects
[11-13]	Since the chimney is the driving force of the system, the increase in the height of the chimney directly increases the performance of the system.	[16-17]	Floor design and slope affect the performance of the system. The rise of the ground towards the chimney for the pilot plant causes a 17% increase in the performance of the system.
[14,6]	Collector size affects the amount of energy entering the system. Therefore, increasing the collector radius improves the performance of the system. However, after a certain point, enlarging the collector does not affect the performance of the system.	[18-19]	The collector slope improves the performance of the system to a certain extent. However, after a certain point, it affects the system negatively.
[7,15]	Environmental temperature and solar radiation intensity have a determining effect on the performance of the system. The solar radiation intensity increases the power output of the system linearly.	[19-21]	The divergent flue design doubles the performance of the system compared to the reference situation (for the Pilot plant). Increasing the chimney inclination angle after a point has a negative effect on the

			performance of the system.

By integrating other systems into solar chimney power plants, their performance can be increased. Researchers try to increase the performance of the system by creating hybrid systems with methods such as ground energy storage, using geothermal energy sources, heat exchanger integration, and adding PV. Some examples of energy storage integrated and hybrid systems are given in Table 2.

Table 2. The geometric and design parameters affect the performance of the system.

References	Energy storage	References	Hybrid systems
[22-23]	By using different soil and material types on the ground, energy can be stored here during the day, and power output can be obtained even when the sun is not present.	[26-27]	A hybrid system is created with PV modules to be integrated into different parts of the system. In this way, additional power output is obtained from the PV system while the power output is taken from the system. In addition, the PV system works more efficiently with the cooling effect of the air-fluid.
[24-25]	The use of additional water for energy storage on the ground reduces power output during sun hours. However, it provides power output during the hours when there is no sun, thus providing more total power output in the 24-hour period.	[28-30]	Some researchers create a hybrid system to obtain clean water and desalinate seawater. It is stated that while obtaining clean water from the system, an increase in performance is also observed.

Although there are many studies on solar chimney power plants, some points are open to improvement. Especially unlike other solar energy systems, the fact that it allows power output during the hours when the sun is not present makes these systems privileged. In this study, this feature is emphasized by using natural materials as an energy storage unit. In addition, a new design is created by using the divergent flue design that improves the power output instead of the standard cylindrical chimney. Performance evaluation of a system with a divergent chimney with an energy storage unit is presented.

METHODS

This study is based on the geometric dimensions of the Manzanares pilot plant. Geometric data of the pilot plant are given in Table 3. The chimney outlet radius is taken as 10.16 m while the work is being carried out. The reason for this is that the maximum power output range in divergent chimney design from previous studies is 3.5-5 AR [21]. The AR expression expresses the ratio of the chimney outlet area to the chimney entrance area. In this study, the AR value is taken as 4. In addition, experimental measurements show that the temperature value remains almost constant throughout the day from 0.5 m below the ground

[9]. For this reason, a floor thickness of 2 m is considered sufficient. The engineering commercial software ANSYS is used for the study. The schema, 3D view and mesh image of the model are given in Figure 1.

Table 3. Geometric data and working dimension details of the Manzanares pilot plant [8].

Geometric parameter	Value
Chimney height	194.6 m
Chimney inlet radius	5.08 m
Chimney outlet radius	10.16 m
Collector radius	122 m
Average collector height	1.85 m
Energy storage unit thickness	2 m

During the analysis, the flow is considered to be continuous and constant. It is assumed that environmental conditions do not change in each analysis. Conservation equations are solved simultaneously, and each equation can be given as:

- Continuity equation

$$\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\partial w)}{\partial z}=0. \quad (1)$$

- Momentum equation

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

$$\frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=\frac{-\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right); \quad (3)$$

$$\frac{\partial(\rho wu)}{\partial x}+\frac{\partial(\rho wv)}{\partial y}+\frac{\partial(\rho ww)}{\partial z}=\frac{-\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g\beta(T-T_a); \quad (4)$$

- Energy equation

$$\frac{\partial(pcuT)}{\partial x}+\frac{\partial(pcvT)}{\partial y}+\frac{\partial(pcwT)}{\partial z}=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right). \quad (5)$$

The boundary conditions of the system are given in Figure 1. The flow regime is considered turbulent [21]. The bossiness approximation is used for density. The convergence criterion is taken as 10^{-6}.

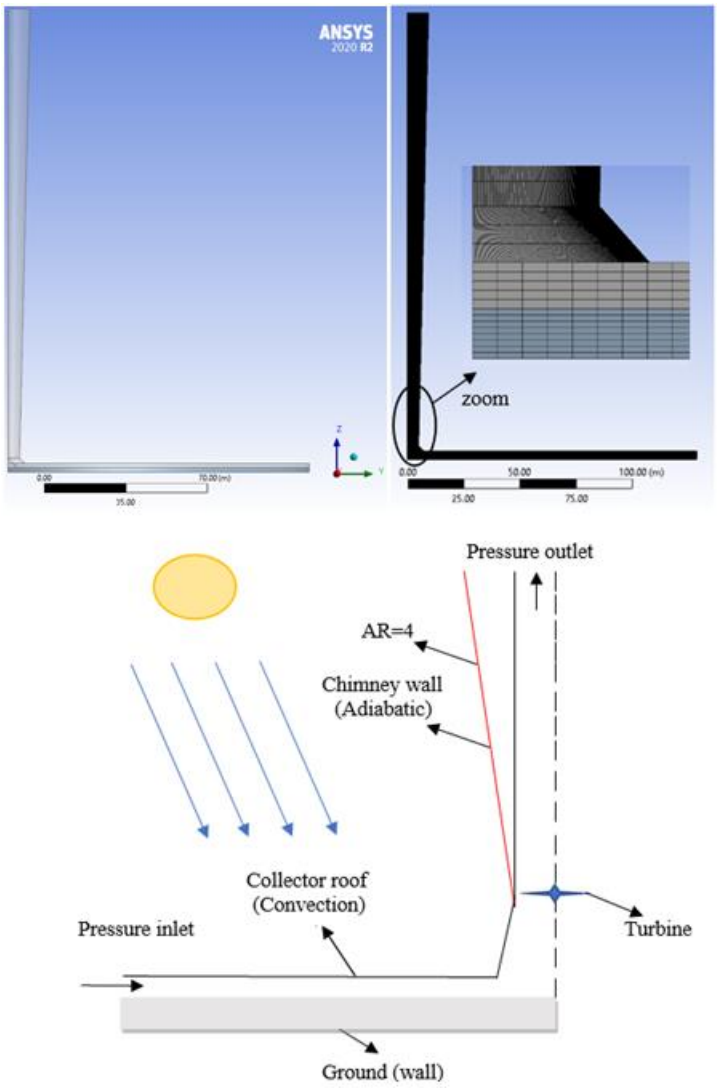


Fig. 1. Solar chimney power plant model and boundary conditions, 3D visual and mesh view.

RESULTS

Before starting the analysis, a mesh-independent solution is made for the model. For the accuracy of the model, experimental data from the pilot plant is taken as a reference. It has been shown in the previous study that the divergent chimney design gives more power output than the cylindrical chimney [21]. In the study, in addition to the divergent chimney design, the possibility of the system to give power output is interpreted by using an energy storage unit during the hours when there is no sun.

CONCLUSIONS

Solar chimney power plants differ from other solar energy systems in terms of their dependence on the sun. This study highlights the importance of energy storage in the ground, in addition to the fact that the divergent flue design improves the performance of the system.

Keywords: Energy storage, divergent solar chimney power plants.

REFERENCES

1. CUCE, E.; CUCE, P.M. A comprehensive review on solar cookers. *Applied Energy*, 2013, Vol. 102, p. 1399-1421.

2. FERREIRA, A.G.; MAIA, C.B.; CORTEZ, M.F.; VALLE, R.M. Technical feasibility assessment of a solar chimney for food drying. *Solar Energy*, 2008, Vol. 82, No. 3, p. 198-205.

3. KONG, J.; NIU, J.; LEI, C. A CFD based approach for determining the optimum inclination angle of a roof-top solar chimney for building ventilation. *Solar Energy*, 2020, Vol. 198, p. 555-569.

4. CUCE, E.; CUCE, P.M. Optimised performance of a thermally resistive PV glazing technology: An experimental validation. *Energy Reports*, 2019, Vol. 5, p. 1185-1195.

5. CUCE, P.M.; SEN, H.; CUCE, E. Impact of Tower Diameter on Power Output in Solar Chimney Power Plants. *Gazi Mühendislik Bilimleri Dergisi*, 2021, Vol. 7 No.3, p. 253-263.

6. SEN, H.; CUCE, P.M.; CUCE, E. Impacts of Collector Radius and Height on Performance Parameters of Solar Chimney Power Plants: A Case Study for Manzanares, Spain. *Science and Engineering*, 2021, Vol. 2, No. 2, p. 83-104.s

7. CUCE, E.; CUCE, P.M.; SEN, H. A thorough performance assessment of solar chimney power plants: Case study for Manzanares. *Cleaner Engineering and Technology*, 2020, Vol. 1, 100026.

8. SCHLAICH, J.R.; BERGERMANN, R.; SCHIEL, W.; WEINREBE, G. Design of commercial solar updraft tower systems—utilization of solar induced convective flows for power generation. *Journal of Solar Energy Engineering*, 2005, Vol. 127, No. 1, p.117-124.

9. HAAF, W. Solar chimneys: part ii: preliminary test results from the Manzanares pilot plant. *International Journal of Sustainable Energy*, 1984, Vol. 2, No. 2, p. 141-161.

10. SEN, H.; CUCE, E. Dynamic pressure distributions in solar chimney power plants: A numerical research for the pilot plant in Manzanares, Spain. *WSSET Newsletter*, 2020, Vol. 12, No. 1, p. 2-2.

11. ZHOU, X.; YANG, J.; XIAO, B.; HOU, G.; XING, F. Analysis of chimney height for solar chimney power plant. *Applied Thermal Engineering*, 2009, Vol. 29, No.1, p. 178-185.

12. TOGHRAIE, D.; KARAMI, A.; AFRAND, M.; KARIMIPOUR, A. Effects of geometric parameters on the performance of solar chimney power plants. *Energy*, 2018, Vol.162, p. 1052-1061.

13. CUCE, E.; SEN, H.; CUCE, P.M. Numerical performance modelling of solar chimney power plants: Influence of chimney height for a pilot plant in Manzanares, Spain. *Sustainable Energy Technologies and Assessments*, 2020, Vol. 39, 100704.

14. LI, J.Y.; GUO, P.H.; WANG, Y. Effects of collector radius and chimney height on power output of a solar chimney power plant with turbines. *Renewable Energy*, 2012, Vol. 47, p. 21-28.

15. TAYEBI, T.; DJEZZAR, M.; GOUIDMI, H. 3D numerical study of flow in a solar chimney power plant system. Sciences & Technology, 2018, Vol. 3 No. 1, p. 17-20

16. CUCE, E.; CUCE, P.M.; SEN, H.; SUDHAKAR, K.; BERARDI, U.; SERENCAM, U. Impacts of Ground Slope on Main Performance Figures of Solar Chimney Power Plants: A Comprehensive CFD Research with Experimental Validation. *International Journal of Photoenergy*, 2021.

17. CUCE, P.M.; CUCE, E.; SEN, H. Improving electricity production in solar chimney power plants with sloping ground design: an extensive CFD research. *Journal of Solar Energy Research Updates*, 2020, Vol. 7, No. 1, p. 122-131.

18. COTTAM, P.J.; DUFFOUR, P.; LINDSTRAND, P.; FROMME, P. Effect of canopy profile on solar thermal chimney performance. *Solar Energy*, 2016, Vol. 129, p. 286-296.

19. HASSAN, A.; ALI, M.; WAQAS, A. Numerical investigation on performance of solar chimney power plant by varying collector slope and chimney diverging angle. *Energy*, 2018, Vol. 142, p. 411-425.

20. HU, S.; LEUNG, D.Y.; CHEN, M.Z. Effect of divergent chimneys on the performance of a solar chimney power plant. *Energy Procedia*, 2017, Vol. 105, p. 7-13.

21. CUCE, E.; SAXENA, A.; CUCE, P.M.; SEN, H.; GUO, S.; SUDHAKAR, K. Performance assessment of solar chimney power plants with the impacts of divergent and convergent chimney geometry. *International Journal of Low-Carbon Technologies*, 2021.

22. GUO, P.; WANG, Y.; LI, J.; WANG, Y. Thermodynamic analysis of a solar chimney power plant system with soil heat storage. *Applied Thermal Engineering*, 2016, Vol. 100, p. 1076-1084.

23. PRETORIUS, J.P.; KRÖGER, D.G. Critical evaluation of solar chimney power plant performance. *Solar Energy*, 2006, Vol. 80, No. 5, p. 535-544.

24. SEMAI, H.; BOUHDJAR, A.; LARBO, S. Canopy slope effect on the performance of the solar chimney power plant. *International Journal of Green Energy*, 2017, Vol. 14, No. 3, p. 229-238.

25. CHOI, Y.J.; KAM, D.H.; PARK, Y.W.; JEONG, Y.H. Development of analytical model for solar chimney power plant with and without water storage system. *Energy*, 2016, Vol. 112, p. 200-207.

26. SINGH, A.P.; KUMAR, A.; SINGH, O.P. Performance enhancement strategies of a hybrid solar chimney power plant integrated with photovoltaic panel. *Energy Conversion and Management*, 2020, Vol. 218, 113020.

27. RAHBAR, K.; RIASI, A. Performance enhancement and optimization of solar chimney power plant integrated with transparent photovoltaic cells and desalination method. *Sustainable Cities and Society*, 2019 , Vol. 46, 101441.

28. ZHOU, X.; XIAO, B.; LIU, W.; GUO, X.; YANG, J.; FAN, J. Comparison of classical solar chimney power system and combined solar chimney system for power generation and seawater desalination. *Desalination*, 2010, Vol. 250, No. 1, p. 249-256.

29. MING, T.; GONG, T.; de RICHTER, R.K.; CAI, C.; SHERIF, S.A. Numerical analysis of seawater desalination based on a solar chimney power plant. *Applied Energy*, 2017, Vol. 208, p. 1258-1273.

30. MENDEZ, C.; BICER, Y. Integration of solar chimney with desalination for sustainable water production: A thermodynamic assessment. *Case Studies in Thermal Engineering*, 2020, Vol. 21, 100687.