Performance assessment of solar chimney power plants with natural thermal energy storage materials on ground: CFD analysis with experimental validation

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Abstract

This study interprets the effect of using sand or gravel as energy storage unit in solar chimney power plants. The effect of using low-cost materials is evaluated. Based on the Manzanares pilot plant, a 3D CFD model is created. Geometric parameters are kept constant in simulations performed with ANSYS FLUENT engineering commercial software. By simultaneously solving DO (discrete ordinates) solar ray tracing algorithm and RNG k-ε turbulence model, the outputs of the system are examined at 290 and 300 K temperatures. The temperature distribution and power outputs of the use of sand and gravel as soil material at different temperatures and solar radiation are compared. It is understood that the use of both materials does not significantly affect the performance of the system and can be used economically instead of each other. It is seen that the system will give a power output of approximately 41.636 kW with both storage materials at a radiation intensity of 800 W/m^2 and an ambient temperature of 300 K. It is seen that the ambient temperature affects the temperature increase in the system, and the temperature increase is higher at 290 K.

Keywords: efficiency; power output; sensible heat storage; solar chimney power plants

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1 INTRODUCTION

Energy has been used by people in different ways since ancient times. There are many methods used by researchers to obtain energy. While obtaining energy, it has recently become the common effort of all humanity to be clean and not harm the environment. The reason for this is the permanent negative effects of fossil fuels used to obtain energy for many years. The most ideal method for clean energy is renewable resources. One of the renewable energy sources is solar energy. Solar energy, which can be used all over the world, is very attractive with its endless source. The energy of the sun can be used in different forms. With the opportunities developed in recent years, studies on products with high energy efficiency continue. The most widely used solar energy method is electricity generation with photovoltaic (PV) systems. PV systems are systems that produce electricity directly from the sun with some equipment [1]. Systems that indirectly generate electricity from the sun mostly transfer the solar radiation it receives into its structure to the fluid in it. The kinetic energy of the fluid is then converted into electrical energy by means of a turbine generator. One of the systems that operate in this way is solar chimney power plants (SCPPs). These systems, which are not as popular as PV systems and have low efficiency, have attracted the attention of researchers in recent years. The work of the researchers on this subject draws attention with the power output of the Manzanares prototype, which was first installed and has a chimney height of 194.6 m [2]. After the first prototype, SCPP received a lot of attention from researchers. Mullett [3] evaluates the performance of SCPP with a mathematical model. He claims that a power plant to be established must have a height of 1000 m in order to be economical. It also states that the efficiency of the system with a chimney height of 1000 m will be 1%. The Manzanares pilot plant was giving a power output of 50 kW in September with a collector radius of 122 m [4]. Researchers analyze climatic parameters that affect the performance of the Manzanares pilot plant [5, 6]. Apart from the climatic parameters, the geometric parameters and design of the system are also decisive in its performance. Cuce *et al.* [7] claim that increasing the chimney height of the Manzanares pilot plant will increase the performance of the system. They claim that the power output, which was 54.33 kW in the reference case, would reach 134 kW, reaching 2.5 times if the chimney height was 500 m. The collector where the solar radiation enters the system is another parameter that affects the performance. Li *et al.* [8] claim that if the collector radius of the Manzanares pilot plant is made 200 m, the system will give a power output of 100 kW. Similarly, some researchers emphasize that increasing the collector radius will improve the performance of the system [9, 10]. The performance of the system can be predicted by predetermining the geometric parameters. Design parameters such as geometric parameters are also important in the performance of the system. The design of the collector, chimney and floor also has an impact on the performance of the system. The collector and chimney are inclined in standard condition. The collector is usually horizontal whereas the chimney is cylindrical. Researchers claim that inclined designs compared to standard design collectors and chimneys can increase the performance of the system [11–14]. Another design that affects the performance of the system is the ground slope. The ground of the pilot plant is horizontal and without slope. Researchers emphasize that soil design is an important parameter in improving the performance of the system [15–17]. Ground is more important for SCPP than for other solar energy systems. Because the solar radiation reaching the ground during the daytime is stored here and transferred to the system during the absence of the sun, power output can be obtained independently from the sun. In this aspect, it differs from other systems. Although SCPP provides energy storage feature and provides power output even when there is no sun, this aspect of the system has not been adequately analyzed. Attig-Bahar *et al.* [18] examine the effect of land use as an energy storage unit on the performance of SCPP and evaluate the 12-month performance of the system if the Manzanares pilot plant is set up in Tunisia. In addition, they interpret the differences that can be seen in the use of soil, gravel and sand as energy storage material on the ground. They claim that the use of energy storage material gives 50% more power output than when not in use. Sedighi *et al.* [19] study the porosity of the energy storage layer, taking into account the turbine pressure drop. In their work, which references the Manzanares pilot plant, they show the ideal point for turbine pressure drop. They claim that with the increase in soil porosity, the losses at the chimney outlet decrease. They indicate that the efficiency and power output of the system change below 5% when they reduce the soil porosity value from 0.4 to 0.1. Ming *et al.* [20] evaluate the SCPP with energy storage layer by numerical analysis. They claim that the energy storage rate first decreases and then increases with the radiation intensity. They also emphasize that gravel has a higher storage rate than soil at different irradiation intensities. They also indicate that the air flow rate in the system increases with the radiation intensity. Xu *et al.* [21] analyze the SCPP with energy storage unit with the CFD model, taking the Manzanares pilot plant as a reference, and interpret the pressure, temperature and velocity distributions in the system for different radiation intensities at 293 K ambient temperature. They state that the turbine pressure drop is the ideal value for different radiation intensities. They claim that after this value, the power output will decrease. Senbeto [22] evaluates the effect of the energy storage unit on the system in the CFD study that references the Manzanares pilot plant and interprets the effect of using soil and gravel as storage material on temperature and velocity distribution in the system. When the temperature distribution is examined along the ground at a radiation intensity of 800 W/m^2, they emphasize that the temperature of the gravel ground is 20 K higher than the sand ground. It claims that with the energy storage unit, a power output of 10–20 kW can be obtained during the hours when there is no sun. Guo *et al.* [23] use soil in SCPP as heat storage area and performs thermodynamic analysis of the system. They evaluate the 24-hour performance of the SCPP system with reference to the Manzanares pilot plant. Similarly, they interpret the effect of materials with different thermophysical properties on power output. In the system with energy storage area, the power output will be low during the hours when the solar radiation is high.

This is because the energy is transferred to the ground storage area. In the following hours, with the decrease of the radiation intensity, the stored energy is transferred to the system and the power output becomes higher than the system without storage. In addition, the thickness of the storage space also affects system performance. The thick storage area gives lower power output during the daytime and higher power output during the evening hours. Materials with high specific heat and thermal conductivity can be used for turbine operation and less fluctuation in power output.

SCPP differs from the other solar energy systems in some aspects. SCPP systems can run irrespective of solar radiation owing to the design features. Compared to other systems, SCPP can provide power output with a continuous pressure difference thanks to its high chimneys. However, this would be possible in case of notable higher chimney structures. On the other hand, SCPPs can provide power output even when there is no sun with energy storage on the ground. In this study, the effect of soil and gravel, which are accessible materials for energy storage, on the SCPP system performance is analyzed. The power output differences that may occur in the use of both materials are interpreted for different temperatures and solar radiation. The research is carried out for various ambient temperatures and solar radiation levels in order to assess the dependence of system behaviour on environmental conditions.

1.1 CFD model and system details

SCPP are systems in which solar radiation is absorbed through the collector and transferred to the system air. Not all of the solar radiation transferred to the system air is captured here and reaches the ground. Some of this energy reaching the ground is absorbed here and some is reflected. Unlike other solar energy systems, this energy reaching the ground is stored and transferred back to the system when the effect of solar radiation decreases. For this reason, it is important to store the energy on the ground and then transfer heat to the system. In this study, the effect of the use of soil and gravel materials, which are costly and easy to obtain, on the system in SCPP is interpreted. For the study, the geometry of the Manzanares pilot plant is based and a CFD model is created. With the model created, the performance of the two materials at different radiation intensities is interpreted. In CFD analysis, some assumptions are made and the solution is facilitated. These assumptions are listed as follows:

- The flow regime is constant in all cases, 3D and turbulent throughout the system.
- Environmental conditions are constant during each simulation.
- Air, which is the system fluid, is incompressible.
- Boussinesq approximation is used for density variation.

Engineering commercial software ANSYS FLUENT is used for CFD analysis. The continuity, energy and momentum equations carried out through the program are as follows, respectively [24]:

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

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

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

In SCPP, the heat transfer between the air, which is the system fluid, and the collector and the ground occur by convection. Convection within the system is natural convection. The Ra number, which determines the natural convection characteristic, can be found by gravitational acceleration g, thermal expansion coefficient β, temperature change under the collector ΔT, collector height H_{coll}, thermal diffusion coefficient α and kinematic viscosity ϑ as follows:

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

The critical value for the Ra number is 10^9. For larger values, the flow is taken as turbulent [16]. The flow for the Manzanares pilot plant is turbulent [5, 7, 13, 14]. As the turbulence model, the RNG k-ε model in ANSYS FLUENT engineering commercial software is followed. The equations of the model are as follows [24]:

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

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

When the experimental data of the Manzanares pilot plant are examined, it is seen that the temperature increase in the system is maximum 20°C [4]. In this case, the Boussinesq approach can be used to calculate the density change for the CFD study carried out, and its equation is as follows [25]:

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

ρ and T in the equation represent density and temperature, respectively. The subscript α indicates the initial state. There are different uses for calculating the power output (P_o) of the system. In this study, turbine pressure drop (ΔP_t) and volumetric flow ($\dot{Q}_v$) are used. The power output can be calculated by the equation [13]:

$$P_o = \eta_t \Delta P_t \dot{Q}_v \tag{8}$$

Here, η_t is turbine-generator efficiency and 0.8 is taken in the study [13]. CFD results are used to calculate the turbine pressure drop. In the pilot plant, the turbine is located 9 m above the ground [2]. The average pressure difference (P_t) in the system 9 m above the ground is found from the CFD results. The turbine

Table 1. *Structural details of the pilot plant in Manzanares [26]*

Parameter	Value (m)
Average collector height	1.85
Average collector radius	122.0
Chimney radius	5.08
Chimney height	194.6
Ground thickness	2

pressure drop ratio (r_t) is taken as 2/3 and the calculation is made with the following equation [13]:

$$\Delta P_t = r_t \, P_t \tag{9}$$

The geometric dimensions of the system are taken according to the pilot plant and the details are given in Table 1 [26]. When the experimental results are examined, it is seen that the temperature does not change during the day starting from 0.5 depth of the ground [4]. In this study, the floor thickness is taken as 2 m in order to better observe the temperature distribution on the ground. With the existing geometric data, a 3D model is created in the ANSYS commercial software 'Design models'. For the sake of economy in calculations, a 90-degree design is obtained by applying two plane symmetry (YZ and XZ) in the model. The 3D model and mesh view are given in Figure 1. All simulations with the model are performed with the CORE i7 16 GB RAM workstation. RNG k-ε turbulence model is used in simulations. To incorporate solar radiation into the system, the DO (discrete ordinate) solar ray tracing algorithm is included in the system. The pilot plant location is used for the solar beam direction vector [14]. It is a semi-transparent collector that transfers solar radiation to the system. The solar radiation passing through the collector reaches the ground. Solar radiation reaching the ground is stored here. The materials used in the system are based on the pilot plant and the details are given in Table 2.

SIMPLE is preferred for pressure and velocity discretization. The PRESTO technique is used for pressure interpolation. The Boussinesq model is considered suitable for the change in the density of the air. Details of the CFD used in the solver are given in Table 3. As convergence criteria, 10^{-6} for energy and radiation and 10^{-3} for other options are considered sufficient.

Details of the scheme and boundary conditions of the system are given in Figure 2. It is assumed that there is no pressure change at the collector inlet, which is the inlet of the system, and the chimney outlet, which is the outlet of the system.

2 RESULTS AND DISCUSSION

In the study, in which the effect of soil or gravel use on the ground on the performance of the system is examined, the analysis is made with the 3D model created on the basis of the pilot plant. First, a mesh-independent solution is made by considering the maximum air flow rate in the system. Details are given in Table 4. When the table is examined, it is seen that the number of 1.78 m cells is sufficient for the solution. Experimental results are used to validate the model. Previous studies are also considered for consistency with the literature. Comparison of CFD results with experimental data and other studies in the literature for solar radiation varying in the range of 200–800 W/m² is given in Figure 3. When the graph is examined, it is seen that the results are consistent.

The study is carried out with the model whose mesh-independent solution is made and verified. For soil and gravel that can be used as a natural storage area on the ground, a comparison is made at 300 K. These materials were chosen because they are easily available and ubiquitous. The temperature distribution in the system with radiation intensity of 800 W/m² at an ambient temperature of 300 K is as in Figure 4 for two different storage materials. It is seen that the use of sand or gravel as the ground

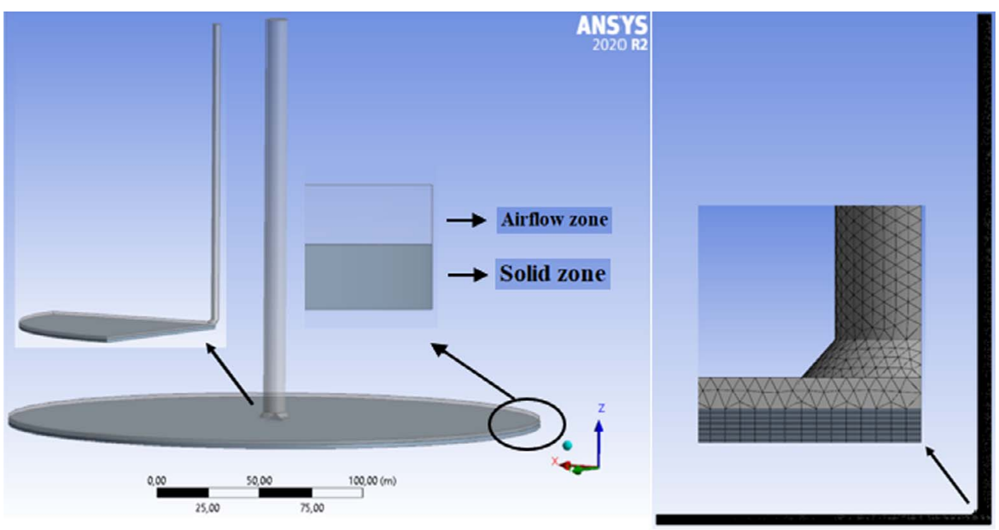

Figure 1. *Model and mesh view.*

Table 2. *Physical properties of the materials used in the CFD research [18, 27, 28]*

Physical property (unit)	Glass	Soil	Gravel	Chimney
Density (kg.m^{-3})	2700	1900	2555	2100
Thermal conductivity (W.m^{-1} K^{-1})	0.78	1.83	2	1.4
Specific heat capacity (J.kg^{-1} K^{-1})	840	2200	814	880
Transmissivity	0.9	Opaque	Opaque	Opaque
Absorption coefficient	0.04	0.8	0.8	0.6
Refractive index	1	1	1	1
Emissivity	0.1	0.9	0.9	0.71
Thickness (m)	0.004	2	2	0.00125

Table 3. *CFD parameters and climatic characteristics [7, 29]*

Solar radiation (W.m^{-2})	600–800
Atmospheric pressure (Pa)	92930
Ambient temperature (K)	300
Ambient air density (kg.m^{-3})	1.0795
Gravitational acceleration (m.s^{-2})	9.81
Air conductivity (W.m^{-1} K^{-1})	0.0264
Ideal gas constant (J.kg^{-1} K^{-1})	287
Kinematic viscosity of air (m.s^{-2})	1.8×10^{-5}
Air heat capacity (J.kg^{-1} K^{-1})	1006.24
Turbine pressure drop ratio	2/3
Stefan–Boltzmann constant (W.m^{-2} K^{-4})	5.667×10^{-8}

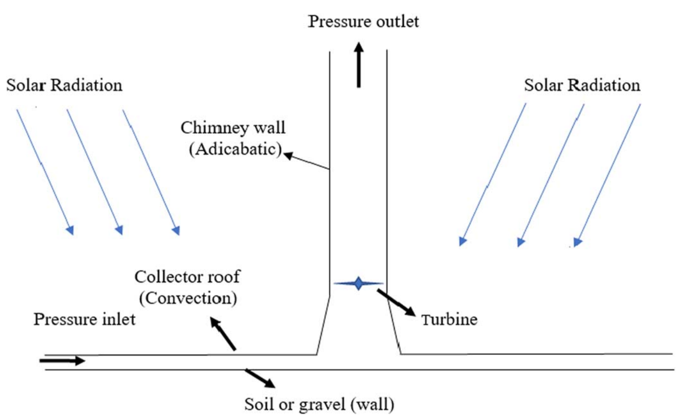

Figure 2. *SCPP scheme and boundary conditions.*

Table 4. *Mesh-independent solution over maximum air velocity*

Cell count	Maximum air velocity (m/s)	% change
1.08 m	13.56	–
1.43 m	13.55	0.07
1.78 m	13.546	0.03

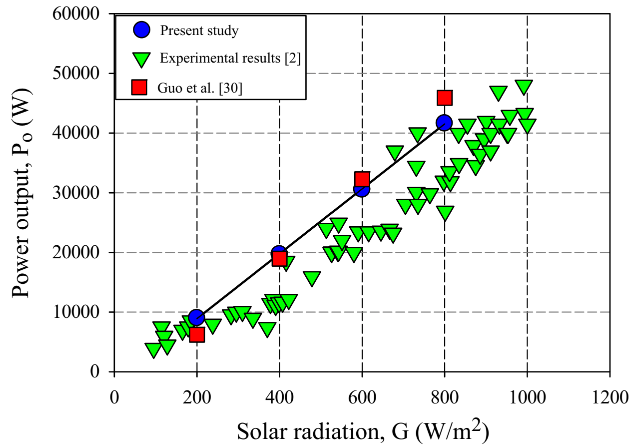

Figure 3. *Comparison of CFD results with numerical and experimental data at different radiation conditions [2, 30].*

material does not have a significant effect on the temperature distribution in the system under the same conditions.

The system is affected by the type of storage material in the ground as well as by the ambient temperature. When sand is used as the ground material, the temperature distribution in the system for two different ambient temperatures at 800 W/m^2 constant solar radiation is given in Figure 5. When the ambient temperature rises, it is seen that the temperature increases directly in the system and on the ground. Although there is a 10-K increase in the ambient temperature, it is seen that the maximum temperature in the system has increased by about 7 K. For two different ambient temperatures, the temperature increase in the system is examined. At a constant radiation intensity of 800 W/m^2, at 290 K ambient temperature, the temperature increase in the system is 67.305 K, while at 300 K ambient temperature it is seen that the temperature increase in the system is 64.880 K. More temperature rise means more kinetic energy increase in system air. In this case, it is expected that the system will give more power output at an ambient temperature of 290 K.

It is seen that the use of different materials on the floor does not have a significant effect on the system. This situation can be understood from the contours and graphics. In this case, it is expected that the use of sand or gravel on a SCPP floor to be installed will not affect the performance of the system. It is clear that environmental temperature and solar radiation are the determining factors in the performance of the system when the geometric parameters are kept constant. Because the solar radiation directly increases the energy entering the system, it affects the air flow in the system. Transferring more energy to the system air means an increase in airflow rate and hence power output. When sand is used as the ground material, the maximum velocity of the air in the system and mass flow rate is given in Figure 6 at

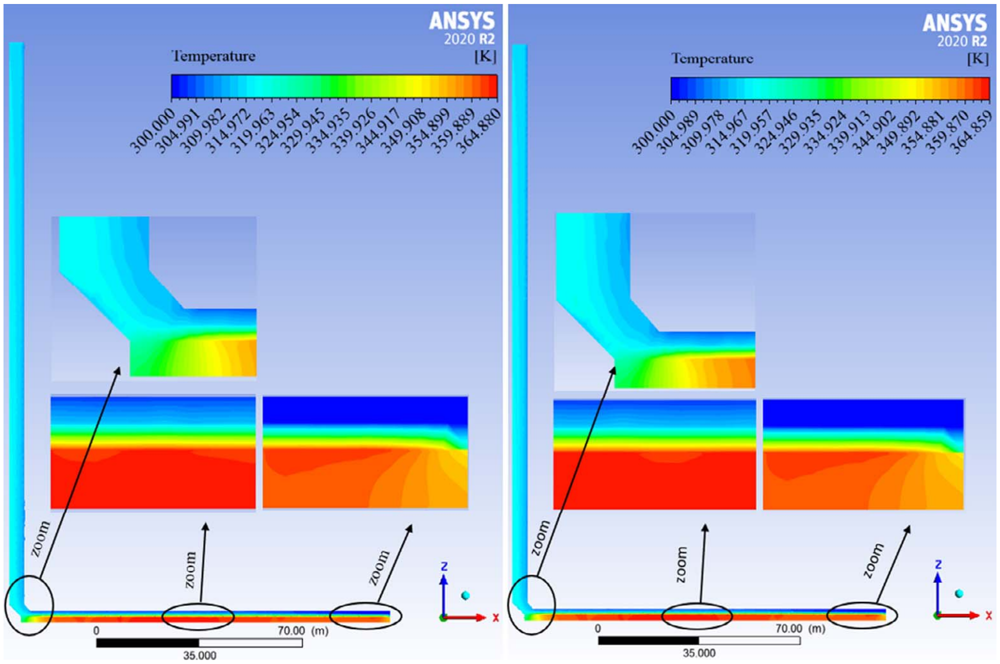

Figure 4. *Temperature distribution in the system (sand on the left, gravel on the right) when sand and gravel are used as soil material.*

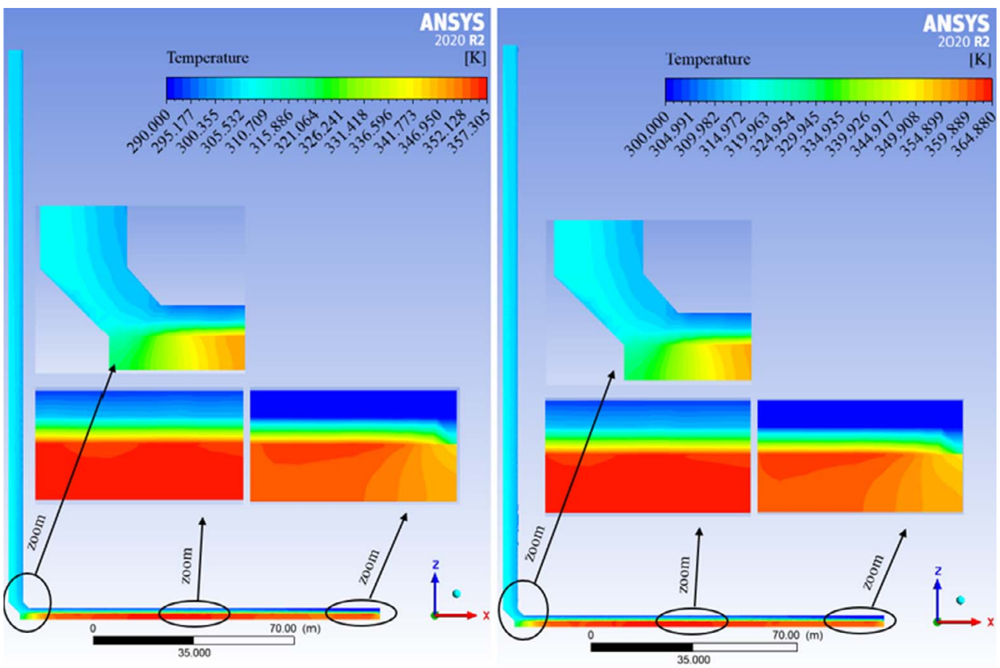

Figure 5. *Temperature distribution in the system at 290 and 300 K for sand storage material.*

an ambient temperature of 300 K and a solar radiation of 200–800 W/m^2. It is seen that the maximum air velocity in the system, which is 6.67 m/s at 200 W/m^2, exceeds 1.5 times when the solar radiation is 800 W/m^2 and reaches 11.10 m/s. Like the air flow rate, the mass flow rate of the system also increases with the increase of solar intensity. It is seen that at a radiation intensity of 800 W/m^2, the mass flow rate increases by 66.51% compared to 200 W/m^2 and becomes 962.58 kg/s.

The power outputs of two different storage materials on the ground at 300 K ambient temperature at different solar radiation are given in Table 5. When the power outputs at 600 and 800 W/m^2 irradiation intensity are examined, it is seen that the power

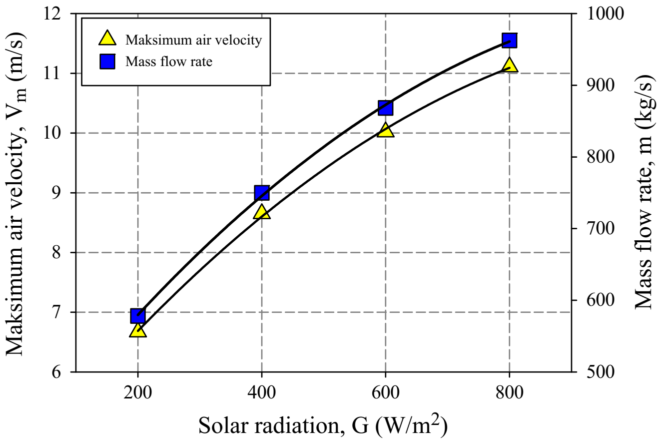

Figure 6. *Maximum air velocity and mass flow rate in the system.*

Table 5. *Power outputs of different ground materials at different solar radiation*

Ground storage material	Solar Radiation, G (W/m^2)	Power output, P_o (W)
Sand	800	41636
	600	30565
Gravel	800	41623
	600	30545

outputs increase for both materials. In this case, it is clear that the solar radiation directly increases the performance of the system.

Looking at the table, it is seen that the two materials do not have a significant effect on the power output for the same radiation. It is seen that both materials can be used interchangeably.

2.1 Future works

The DO solar ray tracing algorithm and a 3D 90-degree CFD model analysis with RNG k-ε turbulence model algorithm used in this study showed the effects of sand and gravel in terms for energy storage. As it known, the power distribution scheme is very important to ensure the balance of electricity supply and demand. For this reason, transient system simulation (TRNSYS) has been used in some studies in the literature [31, 32]. In addition, it will be useful to propose a power dispatching scheme in the specified time interval by integrating the TRNSYS, where optimum power dispatch analysis can be made, into this study. Some advantages of the TRNSYS are as follows:

- A comprehensive weather database containing all necessary weather parameters in SCPP studies is possible with TRNSYS.
- TRNSYS in the literature has a clear, visual and user-friendly structure, and has a simple and understandable structure.
- With TRNSYS, simulations up to 365 days or 8760 hours and more can be created.

In future studies, CFD-based numerical studies as in this study, in which experimental data are validated, can be integrated into numerical studies such as time-dependent TRNSYS.

3 CONCLUSIONS

There are many parameters that determine the performance of SCPP systems. Geometric parameters and climatic parameters have a decisive effect on the performance of the system. These parameters can be evaluated before the system is installed and used to estimate possible power output. In this study, the effects of the use of sand and gravel for energy storage on the performance of the system are interpreted. The results are evaluated by applying DO solar ray tracing algorithm and RNG k-ε turbulence models to the 3D 90-degree CFD model. The following conclusions can be drawn from the study:

- DO solar ray tracing algorithm and RNG k-ε turbulence model give consistent results for SCPPs.
- The solar radiation is very effective on the performance of the system. The increase in ambient temperature negatively affects the temperature increase in the system.
- In terms of cost, gravel can be used instead of sand on the ground.
- When the soil material is sand, the temperature rise in the system is 67.305 K at an ambient temperature of 290 K. The temperature rise is 64.880 K when the ambient temperature is 300 K.
- At a solar radiation of 800 W/m^2, the maximum air velocity in the system is 11.108 m/s.
- Solar radiation positively supports the mass flow rate of the system. Compared to 200 W/m^2, at 800 W/m^2, the mass flow rate increases by 66.51% and becomes 962.58 kg/s.

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