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Performance Enhancement and Environmental Impact Analysis of a Solar Chimney Power Plant: Twenty-four-hour Simulation in Climate Condition of Isfahan Province, Iran

P. Karimipour-Fard, H. Beheshti*

Department of Mechanical Engineering, Faculty of Engineering, University of Isfahan, Hezar Jarib Ave., Isfahan, Iran

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A B S T R A C T

The aims of this study are to enhance the performance of a solar chimney power plant (SCPP), investigate utilization of thermal energy storage (TES) and analyze the environmental impact of the SCPP in providence of Isfahan, Iran. To achieve these goals, multi-stage numerical simulations during twenty-four hours of a day are performed in climate condition of Isfahan province (central region of Iran). Isfahan province has proper environmental condition for utilization of SCPP as a source of electricity and the environmental crises during the last decade in Iran have made utilization of green power plants a necessity. Performance enhancement of the SCPP is carried out by improvement in geometrical characteristics of collector and chimney of the SCPP. Considered factors for performance enhancement of SCPP are height, ceiling slop and radius of the collector as well as height, radius and throat shape of the chimney. Then a TES is employed to produce power in the absence of solar radiation in new proposed optimal configurations. In continue carbon dioxide emission and water consumption of enhanced configurations of SCPP are compared with shale gas, coal, hydroelectric and biomass power plants for same output power to investigate environmental impact of the SCPP. Results illustrate that improved collector of the SCPP increases the output power by almost 139% and enhanced chimney of the SCPP improves performance of the power plant by approximately 68.1%. Results also show that the SCPP with the TES would produce power during night hours in a stable range and TES has higher performance in SCPP with optimal proposed configurations. The results confirm that the SCPP is a proper choice for power generation in province of Isfahan (central region of Iran) and the enhanced SCPP with TES improves the output power range and environmental benefits considerably.

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NOMENCLATURE

C_p	Specific heat transfer coefficient *(kJ.kg^{-1}.K^{-1})*
$C_{p,v}$	Specific heat of water vapor *(kJ.kg^{-1}.K^{-1})*
g	Gravity acceleration ($m.s^{-2}$)
k	Turbulent kinetic energy
m	Relative optical air mass
$\dot{m}$	Flow rate ($kg.s^{-1}$)
Pr_t	Turbulent Prandtl number
q	Solar radiation ($kW.m^{-2}$)
R_a	Ideal air constant *(kJ.kg^{-1}.K^{-1})*
Ra	Rayleigh number
S_h	Viscous dissipation
T	Temperature (K)
u	Velocity ($m.s^{-1}$)
Greek symbols	
ε	Emissivity
ρ	Density ($kg.m^{-3}$)
τ	Shear stress (Pa)
λ	Thermal conductivity ($W.m^{-1}.K^{-1}$)
μ_t	Turbulent eddy viscosity ($kg.m^{-1}.s^{-1}$)

*Corresponding Author's Email: khbeheshti@hotmail.com (H. Beheshti)

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1. INTRODUCTION

Solar chimney is one of the new solar based power plants and utilization of SCPP is increasing in many countries. SCPP consists of collector, turbine and chimney. Collector is made up of glass or plastic that can pass solar radiation and keep its heat. Chimney is located in the middle of the collector that holds the turbine in its entrance. The heated air in the beneath of the collector ascends from the chimney and propels the turbines [1]. First prototype model of the SCPP was introduced by Professor Schlaich and tested in Manzanares, Spain, in the early 1980s [2, 3]. Then a "backyard-type" device in West Hartford, Connecticut, USA was constructed by Krisst [4] and after that Kulunk [5] built a microscale electric power plant of 0.14 W in Izmir, Turkey.

Pasumarthi and Sherif [6, 7] developed a mathematical model to study the effect of various factors on air temperature, air velocity and output power of the solar chimney. They developed three models of SCPP in Florida in order to assess their feasibility. Bernardes et al. [8] presented a new analytical and numerical model, which describes the performance of solar chimneys. Zhou et al. [9] obtained a theoretical model and found the optimal chimney height for the maximum output power.

Tingzen et al. [10] introduced a new model to evaluate performance of a SCPP system and utilized a numerical modeling to study the effect of chimney height and collector radius on output power and efficiency. Guo et al. [11] performed a numerical simulation and studied the station power output and some other output factors' variations with different solar radiation values. Sangi et al. [12] carried out a numerical simulation to study the effect of collector end curvature radius on the temperature, pressure and air velocity. Gholamalizadeh and Kim [13] applied a numerical simulation to study the greenhouse effect in SCPP that produces the upward buoyancy force in the system. Lorente et al. [14] reported that chimney height and radius and collector radius could not increase independently and indefinitely.

Patel et al. [15] studied the effect of collector outlet height, collector outlet diameter and chimney throat diameter with respect to air velocity, temperature and output power on SCPP. Tingzhen et al. [16] executed a numerical simulation to study the SCPP coupled with turbine and presented a new MW-graded power plant.

Cao et al. [17] studied the performance of a conventional SCPP and two sloped solar chimney power plants with collector oriented at 30^o and 60^o and illustrated that the maximum power is generated at about 60^0. Koonsrisuk [18] made a comparison between conventional solar chimney power plant (CSCPP) and the sloped solar chimney power plant (SSCPP) using the second law of thermodynamic analyses and revealed that SSCPP is thermodynamically more efficient than CSCPP for some configurations. Maia et al. [19] carried out energy and exergy analysis of the SCPP in a four days period and studied the specific humidity, exergy lost, exergetic efficiency and improvement potential in that case. Asnaghi and Ladjevardi [20] studied the SCPP performance in Iran to prove the advantages of using such power plants in Iran. Their results indicate that SCPP can produce from 10 to 28 MWh/month of electrical power.

Utilization of suitable energy storage is one of the options to improve efficiency of the solar based power plants, which is as important as developing new sources of energy [21, 22]. Thermal energy can be stored by changing internal energy of a material in the form of sensible heat and latent heat or combination of them [23]. In case of sensible TES, energy is stored by raising the temperature, but latent TES is based on heat absorption or release when storage material undergoes a phase change [24]. Sharma et al. [25] employed sodium sulfate decahydrate "$Na_2SO_4.10H_2O$" as a phase change material for latent TES in SCPP and indicated its positive effect on power generation during the night. Sensible TES has the lowest cost among the other types of TES [24]. Water is advantageous sensible TES because it is inexpensive, available and it has a high specific heat capacity. Stone is also utilized as a bed type thermal storage material for air heating applications [26, 27].

Isfahan province (central region of Iran) has a proper environmental condition for utilization of SCPP as a source of electricity. Solar chimney needs vast land space for construction and suitable climate; Isfahan region has both of these necessities for utilization of the SCPP. In addition, Isfahan has experienced massive environmental crises in the last decade; Isfahan has polluted air and soil and in recent years its famous river "The Zayandeh Rood River'' has faded. All of these facts make the SCPP a wise choice for Isfahan province that could be a substitute for conventional power plants.

In this study, performance enhancement, utilization of a TES and environmental impact analysis of SCPP are carried out. Numerous numerical simulations during twenty-four hours are carried out to improve performance of the SCPP, assess performance of TES for new proposed configurations and also illustrate and evaluate environmental benefits of the typical SCPP as well as environmental impact improvement in proposed new configuration. In enhancement part, focus is on improvement of geometrical parameters of the collector and the chimney. New configuration environmental benefit are evaluated by making a comparison with shale gas, coal, hydroelectric and biomass power plants. In the first section, numerical results are validated with experimental data and after that, three geometrical characteristics of collector and chimney including height, ceiling slop and radius of the collector as well as height, radius and throat shape of the chimney are assessed through numerous numerical simulation case studies to enhance performance of the power plant. Then in the second part, a TES is employed to generate power in the absence of solar radiation in new proposed configurations. The employed TES is inexpensive, needs low-maintenance and is installable with simple background knowledge. In the last part, environmental analysis of the SCPP is performed according to carbon dioxide emission and water consumption to evaluate environmental benefits of typical SCPP and improvement in environmental impact of the new proposed configuration. In this part, carbon dioxide emission and water consumption of proposed configurations are compared with two fossil fuel based power plants including shale gas and coal power plants as well as two renewable based power plants including hydroelectric and biomass power plants.

2. SIMULATION OF THE SCPP

Numerical simulation of the SCPP is performed in a 3-D domain and fluid flow is considered compressible. Numerical modeling is carried out for twenty-four hours of a day. The air is considered as ideal gas containing humidity. Air flows along the solar chimney due to density gradient. Commercial software ANSYS FLUENT 6.3[1] is used for numerical simulation. Because of symmetry in the geometry and the assumption that the flow is radial, a 5 degree sector plane of the power plant is considered to simulate geometry of the SCPP.

2. 1. Mathematical Formulation

2. 1. 1. Fluid Flow The general governing equations for SCPP are as follows:

Continuity equation:

$$\frac{\partial \rho}{\partial t}+\frac{\partial \rho u_i}{\partial x_j}=0 \tag{1}$$

Momentum equations:

$$\frac{\partial \rho u_i}{\partial t}+\frac{\partial \rho u_i u_j}{\partial x_j}=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j} \tag{2}$$

Energy equations:

$$\frac{\partial \rho h}{\partial t}-\frac{\partial p}{\partial t}+\frac{\partial \rho h u_j}{\partial x_j}=\frac{\partial}{x_j}\left(\lambda\frac{\partial T}{\partial x_j}+\frac{\mu_t}{Pr_t}\frac{\partial h}{\partial x_j}\right)+S_h \tag{3}$$

Ra number is a prominent factor in natural convestion system to assess that the fliud flow is laminar or turbulent. Ra number is described in Equation (4) [29]:

$$R_a=\frac{g\beta(T_h-T_c)L^3}{\alpha\nu} \tag{4}$$

where T_h and T_c are the highest and the lowest temperature of the system, respectively, and L is the characteristic length.

As shown in Equation (4), by consideration of the geometry of the power plant, the Ra number of the SCPP is higher than the critical Ra number (10^9), which means fluid flow is turbulent through the system.

The standard k-ε turbulent flow model is applied to enhance the accuracy and precision of the simulation for the SCPP [12, 15]. The equations solved for the turbulent flow are as follows [28, 29]:

$$\frac{\partial \rho k}{\partial t}+\frac{\partial \rho u_i k}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_i}\right)+G_k-\rho\varepsilon \tag{5}$$

$$\frac{\partial \rho \varepsilon}{\partial t}+\frac{\partial \rho u_i \varepsilon}{\partial x_i}=\frac{\partial}{\partial x_i}\left(\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_i}\right)+C_{\varepsilon 1}\frac{\varepsilon}{k}G_k-C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \tag{6}$$

$$G_k=\mu_t\frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j}+\frac{\partial u_j}{\partial x_i}\right) \tag{7}$$

For the standard k-ε models, the constants have the following values [27]:

$\sigma_k=1$ ، $\sigma_\varepsilon=1.3$ ، $C_{\varepsilon 1}=1.44$ ، $C_{\varepsilon 2}=1.92$

2. 1. 2. Solar Radiation Model Solar radiation in DNth day of the year on the horizontal surface of the earth is calculated by Equation (8) [30].

$$G_{0n}=1367\left(1+0.03344\,cos\left(\frac{2\pi DN}{365.25}-0.048869\right)\right) \tag{8}$$

where *DN* is the day number. In this study, parameter *DN* is set for 1st of June.

Solar radiation attenuated by the cloudless atmosphere is calculated by Equation (9):

$$G_{0c}=G_{0n}\,exp(-0.8662\,T_{lk}.m.d_R) \tag{9}$$

where, the term -0.8662 T_{lk} is the air mass atmospheric turbidity factor, m is the relative optical air mass and the parameter d_R (m) is the Rayleigh optical thickness at air mass m [31].

Solar radiation on a horizontal surface is calculated by Equation (10):

$$G_{bh}=G_{0c}sin\alpha \tag{10}$$

where α is the solar altitude angle. Solar altitude angle is calculated for the city of Isfahan.

By manipulating above mentioned equations and applying the constant values for the city of Isfahan [32], Equations (11) and (12) are developed for solar radiation in this study.

For the first 8 hour period of daytime:

$$q=1.32344[0.4367-0.3367Cos\left(\frac{\pi t}{57600}+\frac{\pi}{2}\right)] \tag{11}$$

For the second 8 hour period of daytime:

[1]http://www.ansys.com/Products/Simulation+Technology/Fluid+Dynamics/Fluid+Dynamics+Products/ANSYS+Fluent

$$q = 1.32344[0.4367 - 0.3367Cos\left(\frac{\pi t}{28800} - 2\pi\right)] \quad (12)$$

For time periods beyond these limits the q value is zero.

2. 1. 3. Power and Efficiency The output power is calculated by Equation (13) [10] where, Δp is the highest difference between the internal and ambient pressures, A is the chimney area, V is the updraft velocity and η_T is the efficiency of turbine-generators that is considered 0.35 [27] in the SCPP. The energy efficiency (η_U) of the system is defined by Equations (14) and (15). In Equation (15), $\dot{Q}_s$ is the energy rate released from the TES during the night.

$$P_{out} = \eta_T \Delta p V_{updraft} A \quad (13)$$

$$\eta_U\ (\text{day}) = \frac{P_{max}(daytime)}{Incident\ solar\ energy} \quad (14)$$

$$\eta_U\ (\text{night}) = \frac{P_{max}(night-time)}{\dot{Q}_s} \quad (15)$$

2 .2. Numerical Modeling Method Numrical modeling in this study consists of two main parts including the SCPP without TES and the SCPP with TES.

2. 2. 1. SCPP without Thermal Energy Storage In this part, numerous numerical case studies are carried out to find the optimum configuration of the SCPP in the province of Isfahan, Iran. All of the numerical simulation stages are tabulated in Tables 1 and 2 that contain numerical case studies for chimney and collector enhancement. The basic geometrical dimensions of this part of simulations are shown in Figure 1.

TABLE 1. Numerical modeling details for chimney enhancement

Stage	Enhancement parameter	Value range	Number of steps
1	Chimney height	100-1100 m	16
2	Chimney radius	3-10 m	16
3	Chamfered throat chimney	5-8 m	4

TABLE 2. Numerical modeling details for collector enhancement

Numerical modeling stage	Enhancement parameter	Value range	Number of steps
1	Collector height	1.8-4 m	16
2	Collector ceiling slope	2 degree	1
3	Collector radius	65-300 m	16

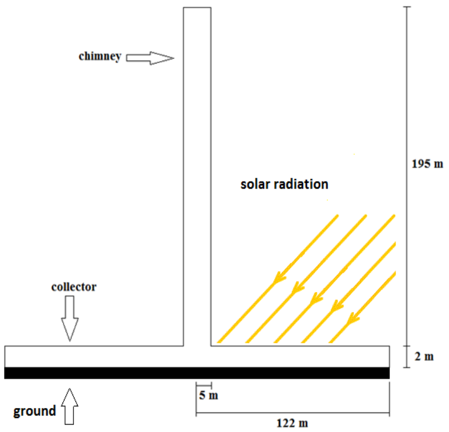

Figure 1. Typical solar chimney power plant [3]

Also basic geometrical dimensions for sloped ceiling collector and chimney with chamfered throat are shown in Figure 2. Boundary conditions for all numerical modeling case studies in this section are tabulated in Table 3.

A grid refinement investigation is conducted on typical SCPP, by calculating the generated power for different grid element quantities in order to establish the necessary grid density in the computational domain for solution convergence.

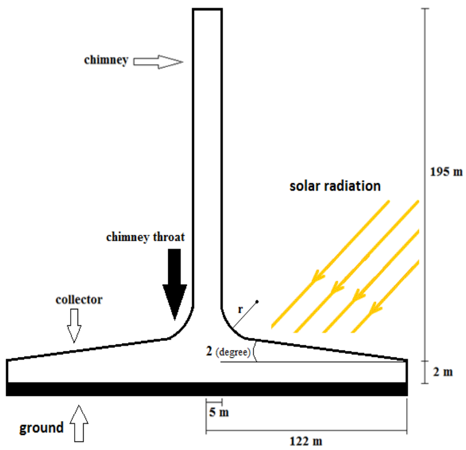

Figure 2. SCPP with chamfered throat chimney and sloped ceiling

TABLE 3. Boundary conditions

Boundary conditions	
Bottom of the power plant	Adiabatic
Chimney's body	Adiabatic
Relative pressure	Zero
Solar radiation	Solar radiation during the day on 1st of June in Isfahan
Ambient temperature	Average temperature of June in Isfahan [34]

As shown in Table 4, the numerical simulations are executed with three refinements of 3497, 5213 and 7835 structured cells. Based on the percentage of change in output power results, the grid density requirement is achieved with 5213 elements. Therefore, the mesh distribution generated with 5213 cells is used for all numerical simulations.

2. 2. 2. SCPP with TES The SCPP with TES (water and stone-bed) is assessed to continue power generation in the absence of solar radiation for proposed optimum configurations. The utilized TES consists of 15 cm depth water containers (almost 4700 m^2 totally) and a stone-bed with thickness of 1 m. The geometry dimension for numerical analysis of SCPP with TES is shown in Figure 3. Water as a TES medium is utilized in plastic bubble containers that are located beneath the power plant's collector.

In this stage, air inlet temperature and air relative humidity are considered as average value on first of June and the average of the last 60 years in Isfahan, Iran, respectively. Solar radiation in SCPP with TES is calculated for first of June in Isfahan. Boundary conditions for this stage are tabulated in Table 5.

TABLE 4. Grid refinement (solar radiation: 1100 Wm^{-2})

Grid element quantity	3497	5213	7835
Output power (kW)	47.7894	49.95687	50.1435

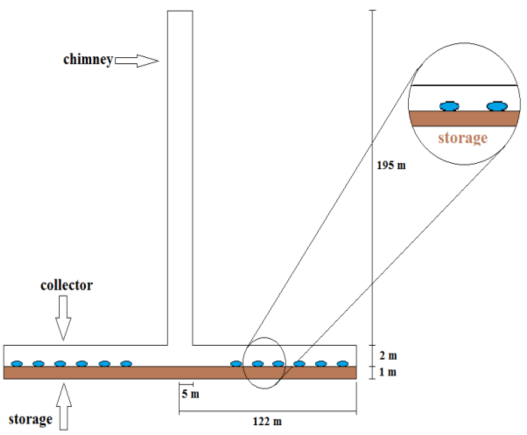

Figure 3. SCPP with thermal energy storage

TABLE 5. Boundary conditions in the SCPP with TES

Boundary conditions	
Bottom of the TES	Adiabatic
Chimney's body	Adiabatic
Air inlet temperature	Temperature of June 1st in Isfahan during a day
Relative pressure	Zero
Solar radiation	Solar radiation during the day on 1st of June in Isfahan

3. RESULTS AND DISCUSSIONS

3. 1. Results Validation The output power variations versus solar radiation variations for numerical results and experimental data are shown in Figure 4. Numerical results are presented output power for sixteen different solar radiation intensities and they show that the output power has a direct correlation with solar radiation intensity. A comparison between numerical results and experimental data shows the power and solar radiation correlations are in a same manner and values are extremely close to each other. Hence, the numerical results are in an acceptable agreement with experimental data obtained by Haaf et al. [3].

3. 2. Performance Improvement Performance improvement of the SCPP is in direct relationship with enhancement of collector and chimney impact on output power. Therefore, enhancement of collector and chimney by investigating 6 effective factors on their impact on SCPP performance are assessed. Figure 5 shows output power of typical SCPP. In this part, it is tried to improve range of power generation by enhancement of chimney and collector of the SCPP.

3. 2. 1. Chimney Enhancement In this section, chimney's geometrical features including its height, radius and throat shape impact on power plant performance are assessed.

Output power increases by adding to chimney height until 685 m that is optimal height of the chimney, as shown in Figure 6. This optimal point happens because in constant air flow density due to small temperature variations, the output power is directly related to the chimney height and mass flow rate. Through an increase in the height, mass flow rate passing the chimney is decreased and these two facts make an optimal point for chimney height.

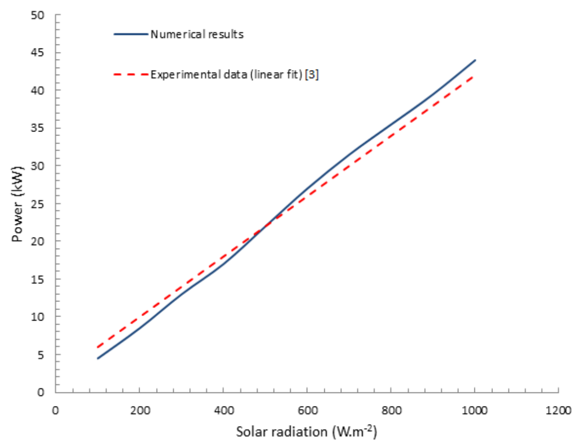

Figure 4. Output power versus solar radiation variations (numerical results and experimental data [3])

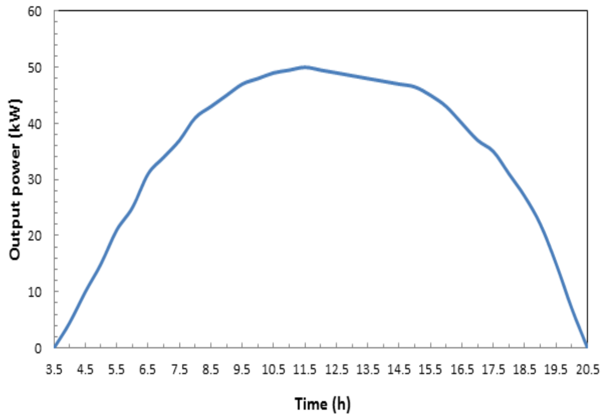

Figure 5. Output power of the typical SCPP

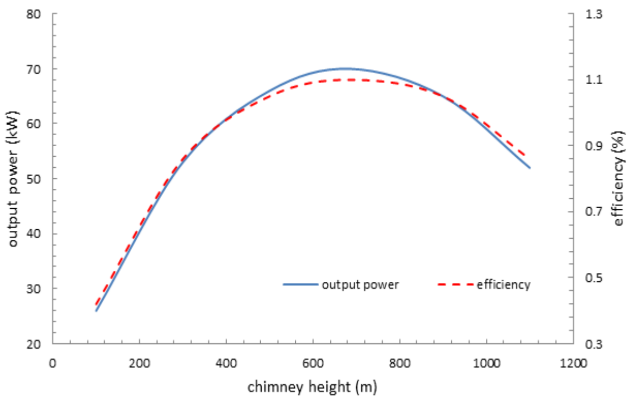

Figure 6. Output power and efficiency versus chimney height variations

Even though maximum output power increment happens in 685 m, chimney height has architectural limitation and except its impact on power output it should be in reasonable dimensions. Very high towers in dry regions like in the Middle East have average height of 400 m; also according to Figure 6 output power changes between 400 and 685 m are small and this fact makes 400 m a theoretical and practical optimum point. Efficiency changes are in agreement with output power changes and confirm the conclusions.

Chimney radius is second important characteristic of chimney to enhance output power. Figure 7 shows output power and efficiency variations versus chimney radius and illustrates that chimney radius has an optimal point at 6.3 m and after this peak point output power decreases with a low gradient. Chimney radius optimum point would increase output power at the rate of almost 3.5%.

Chimney throat shape is the last factor in enhancement of the chimney. Chamfered throat chimney would decrease resistance of inner part of the chimney. By employing circular chamfered throat updraft velocity is enhanced and the output power increases in all cases. Radius of 6 m is considered as optimum radius because increment in output power for this radius is higher than increment for radius of 5 m and also after this value for higher radiuses, output power increment is negligible. Chamfered throat chimney with radius of 6 m increases output power by almost 25% that is a considerable enhancement in the SCPP performance.

3. 2. 2. Collector Enhancement In this section collector's characteristics including its height, slope and radius impact on power plant performance are assessed.

Figure 8 illustrates the effect of the collector height variation on the output power and efficiency. By increasing the collector height from the ground, volume of the air under the collector will increase and in the same solar radiation, solar energy entry into the collector should heat a greater amount of the air that leads to a decrease in the output power. Thus, the collector height should remain 2 m to avoid reduction of the SCPP performance.

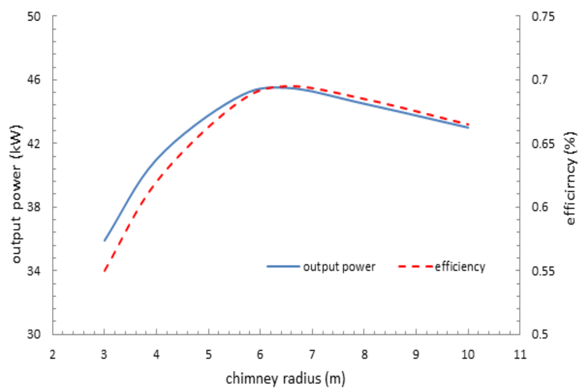

Figure 7. Output power and efficiency versus chimney radius variations

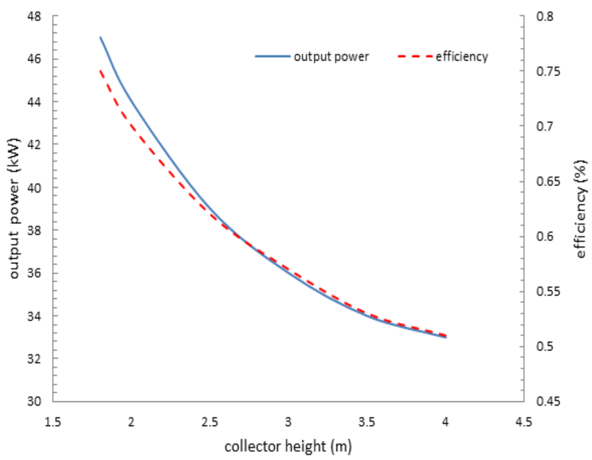

Figure 8. Output power and efficiency versus collector height variations

Second factor is collector ceiling slope. To assess this factor, SCPP is modeled with 2 degrees angle in the collector ceiling and other geometrical dimensions of the typical power plant and thermal flux are considered constant. This makes a reduction in flow resistance on the upper surface of the collector. In this configuration the maximum output power reaches to 70 kW; compared with the typical system with the maximum output power being 44 kW, the maximum output power is increased by almost 55%.

Third factor of collector is its radius that could increase solar radiation input to the SCPP. When collector radius increases, air temperature under the collector will increase and this phenomenon results in a decrease in the air density and an increase in pressure difference that leads to an increase in output power as shown in Figure 9. Because of the increase in the collector radius, solar energy absorption will rise with higher rate compared with the output power increase; therefore, efficiency decreases in higher collector radiuses. Efficiency and output power lines intersect each other on radius of 165 m as shown in Figure 9 and by considering best choice on output power and efficiency perspective it is optimum radius. Even though it is crystal-clear that without consideration of efficiency higher radiuses would make more power, the area of land for construction of power plant could not expand infinitely, therefore radius of 165 m is chosen as optimum height that increases the out put power by almost 80%.

3. 3. Utilization of Thermal Energy Storage for New Proposed Configurations

In this part performance of a TES that consists of water containers and a stone-bed is assessed to continue power generation during night hours in new proposed optimal configurations. This type of TES is chosen because it is inexpensive, needs low-maintenance and its installation needs no complicated background knowledge, also its usefulness is proved for the typical SCPP [27].

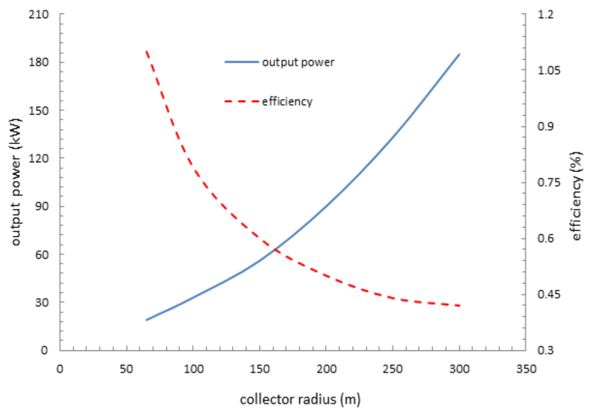

Figure 9. Output power increment versus collector radius

Figure 10 shows power generation of the SCPP in six configurations for twenty-four hours including typical SCPP, SCPP with optimal chimney and SCPP with optimal collector, with and without TES. Power generation is continued during night hours by utilization of TES and the output power range is in a stable and acceptable range. Power generation in SCPP with optimal chimney and optimal collector and no TES increases in comparison with typical SCPP and by utilization of TES they produce power with a stable range that shows this type of TES is useful for enhanced SCPP configurations as well as the typical SCPP. As shown in Figure 10, power range for SCPP with optimal collector and chimney with TES are almost 43 and 30 kW, respectively, for twenty-four hours a day that increase incredibly in comparison with typical SCPP with power range of 20 kW. In addition by utilizing optimal collector and chimney at the same time, increment in power range of the SCPP would be higher.

Energy efficiency of the SCPP is listed in Table 6 for previous configurations. Efficiency in SCPP with TES decreases during day time by almost 50% in all cases; however it increases as shown in Table 6. Efficiency increases considerably in SCPP with optimal configurations in both day-time and night-time. In optimal configuration with no TES, increment in efficiency illustrates their higher ability to produce power during day time.

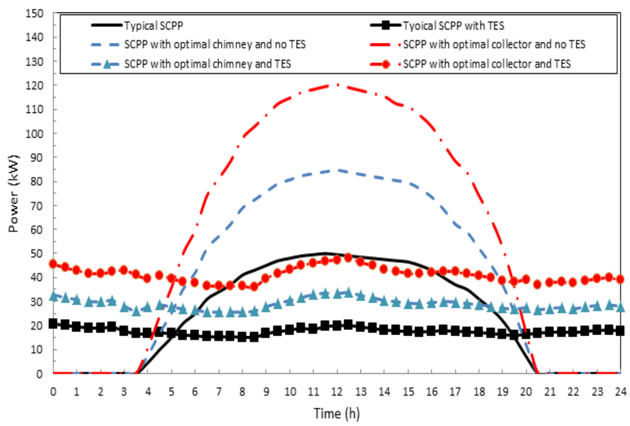

Figure 10. Output power of SCPP in twenty-four hours

TABLE 6. Energy efficiency

Different configurations	Day time (%)	Night time (%)
Typical SCPP	1.09741	-
Typical SCPP with TES	0.52487	2.33356
SCPP with optimal chimney and no TES	1.84475	-
SCPP with optimal collector and no TES	2.62281	-
SCPP with optimal chimney and TES	0.89237	3.81239
SCPP with optimal collector and TES	1.21240	5.28835

In optimal configurations with TES increase in efficiency shows that this type of TES has considerably positive performance for utilization in these proposed optimal configurations and these new proposed configurations could produce power more efficient in the absence of solar radiation in comparison with typical SCPP.

3. 4. Environmental Analysis of the New Proposed Configurations The SCPP has no water consumption and carbon dioxide production. Comparison with ordinary and some new types of power generation systems could illustrate environmental benefits of SCPP for utilization in province of Isfahan that has low air quality and shortage of water resources problems. The average rate of carbon dioxide emission and water consumption of power generation systems (for the output power range of the SCPP in a single day) are considered for comparison [33].

3. 4. 1. Enhanced SCPP Environmental Benefits Versus Shale Gas Power Plant Gas power plants in province of Isfahan are one of the most common kinds of power plants. These kinds of power plant have high water consumption due to their wet cooling towers and also they pollute air and soil massively. Reduction rate of carbon dioxide emission and water consumption in the SCPP in comparison with the shale gas power plant are shown in Table 7. Results show that the typical SCPP is greener and more beneficial in greenhouse gases emission and water consumption point of view. In the system with the optimal configuration, water consumption and carbon dioxide emission are decreased, 1780.02 and 942.56 kg per day, respectively, as shown in Table 7. Thus, SCPP has a huge environmental advantage compared with shale gas power plant by reducing water consumption and greenhouse gases emission significantly per output power.

3. 4. 2. Enhanced SCPP Environmental Benefits Versus Coal Power Plant Coal power plants are known for their high carbon dioxide emission and as shown in Table 8, typical SCPP reduces carbon dioxide emission by 533.6 kg per day in the same output power. Also water consumption of typical SCPP is considerably lower than coal power plants.

TABLE 7. Reduction of CO_2 emission and water consumption in the SCPP versus shale power plants

Type of solar chimney	Carbon dioxide (kg per day)	Water consumption (kg per day)
Typical SCPP	296.8	560.75
Optimal SCPP	942.56	1780.02

TABLE 8. Reduction of CO_2 emission and water consumption in the SCPP versus coal power plants

Type of solar chimney	Carbon dioxide (kg per day)	Water consumption (kg per day)
Typical SCPP	522.6	1401.7
Optimal SCPP	1659.642	4449.494

SCPP with optimal configuration increases the reduction rate by 1659.642 and 4449.494 kg per day for carbon dioxide emission and water consumption, respectively. Hence, SCPP has a huge advantage over coal power plant from environmental perspective and it could be a way to increase air quality and decrease waste of water in critical regions.

3. 4. 3. Enhanced SCPP Environmental Benefits Versus Hydroelectric Power Plant Even though hydroelectric power plant is a green power plant from carbon dioxide emission point of view, it has considerable disadvantage from water consumption perspective in dry regions. As shown in Table 9, typical SCPP and enhanced SCPP decrease water consumption in high quantities and the optimal SCPP could save 30116.38 kg per day water.

3. 4. 4. Enhanced SCPP Environmental Benefits Versus Biomass-Derived Power Plant Biomass-derived power plants like hydroelectric power plants have huge water consumption, however they do not produce considerable greenhouse gases. In contrast, as illustrated in Table 10, typical SCPP reduces water consumption by 13058.5 kg per day and in SCPP with optimal configuration this reduction increases by almost 200% and reaches to 41452.32 kg per day. This amount of water in industrial scale could have incredible impact on local environment in dry regions.

3. 4. 5. Impact of TES Utilization on Environmental Benefits of SCPP The TES would increase power plants stability and balance its output power range. SCPP in optimal conditions with TES, would increase environmental benefit of the power generation in same output power in comparison with shale gas power plants as shown in Table 11; in this optimal configuration, reduction rate of carbon dioxide emission and water consumption are increased by almost 265 %, compared with typical SCPP.

TABLE 9. Reduction of CO_2 emission and water consumption in the SCPP versus hydroelectric power plants

Type of solar chimney	Carbon dioxide (kg per day)	Water consumption (kg per day)
Typical SCPP	6.929	9487.4
Optimal SCPP	22.00471	30116.38

TABLE 10. Reduction of CO_2 emission and water consumption in the SCPP versus biomass power plants

Type of solar chimney	Carbon dioxide (kg per day)	Water consumption (kg per day)
Typical SCPP	51.701	13058.5
Optimal SCPP	164.189	41452.32

TABLE 11. Reduction of CO_2 emission and water consumption

Type of solar chimney	Carbon dioxide (kg per day)	Water consumption (kg per day)
Typical SCPP	296.80	560.75
Optimal SCPP (no TES)	942.56	1780.02
Optimal SCPP with TES	1083.32	1876.78

4. CONCLUSION

The objective of this study is to enhance the performance of a SCPP, investigate application of a TES for new proposed configurations and perform environmental impact assessment for typical SCPP and new proposed configuration, in Isfahan province of Iran (central region of Iran).

After multiple stages of numerical simulation, the following results are obtained from the analysis of the SCPP in climate condition of Isfahan province (central region of Iran):

- Enhanced chimney of the SCPP improves performance of the power plant by almost 68.1%. This optimal configuration of the collector has 400 m height, 6.3 m radius and a chamfered throat with 6 m radius.
- Enhanced collector of the SCPP increases output power by almost 139% that is a considerable improvement in performance of the SCPP. This optimal collector has 2 m height, 165 m radius and a sloped ceiling.
- SCPP with optimal collector and chimney by utilization of the TES produces stable power with a high range that shows this type of TES is useful for enhanced SCPP configurations as well as the typical SCPP.
- SCPP has considerable advantages over shale gas and coal power plants from carbon dioxide emission and water consumption points of view.
- SCPP has a huge advantage over hydroelectric and biomass-derived power plants from water consumption perspective.
- Employing TES would increase environmental benefits of the SCPP from carbon dioxide emission and water consumption perspective by almost 16% and 6%, respectively.

5. REFERENCES

1. Zhou, X., Wang, F. and Ochieng, R.M., "A review of solar chimney power technology", ***Renewable and Sustainable Energy Reviews***, Vol. 14, No. 8, (2010), 2315-2338.
2. Haaf, W., Friedrich, K., Mayr, G. and Schlaich, J., "Solar chimneys part i: Principle and construction of the pilot plant in manzanares", ***International Journal of Solar Energy***, Vol. 2, No. 1, (1983), 3-20.
3. Haaf, W., "Solar chimneys: Part ii: Preliminary test results from the manzanares pilot plant", ***International Journal of Sustainable Energy***, Vol. 2, No. 2, (1984), 141-161.
4. Krisst, R., "Energy-transfer systems", ***Alternative Sources of Energy***, Vol., No. 63, (1983), 8-8.
5. Kulunk, H., "A prototype solar convection chimney operated under izmit conditions", in Proceedings of the 7th Miami international conference on alternative energy sources. Vol. 162, (1985).
6. Pasumarthi, N. and Sherif, S., "Experimental and theoretical performance of a demonstration solar chimney model—part i: Mathematical model development", ***International Journal of Energy Research***, Vol. 22, No. 3, (1998), 277-288.
7. Pasumarthi, N. and Sherif, S., "Experimental and theoretical performance of a demonstration solar chimney model—part ii: Experimental and theoretical results and economic analysis", ***International Journal of Energy Research***, Vol. 22, No. 5, (1998), 443-461.
8. Bernardes, M.d.S., Voß, A. and Weinrebe, G., "Thermal and technical analyses of solar chimneys", ***Solar Energy***, Vol. 75, No. 6, (2003), 511-524.
9. Zhou, X., Yang, J., Xiao, B., Hou, G. and Xing, F., "Analysis of chimney height for solar chimney power plant", ***Applied Thermal Engineering***, Vol. 29, No. 1, (2009), 178-185.
10. Tingzhen, M., Wei, L. and Guoliang, X., "Analytical and numerical investigation of the solar chimney power plant systems", ***International Journal of Energy Research***, Vol. 30, No. 11, (2006), 861-873.
11. Guo, P.-h., Li, J.-y. and Wang, Y., "Numerical simulations of solar chimney power plant with radiation model", ***Renewable Energy***, Vol. 62, No., (2014), 24-30.
12. Sangi, R., Amidpour, M. and Hosseinizadeh, B., "Modeling and numerical simulation of solar chimney power plants", ***Solar Energy***, Vol. 85, No. 5, (2011), 829-838.
13. Gholamalizadeh, E. and Kim, M.-H., "Three-dimensional cfd analysis for simulating the greenhouse effect in solar chimney power plants using a two-band radiation model", ***Renewable Energy***, Vol. 63, (2014), 498-506.
14. Lorente, S., Koonsrisuk, A. and Bejan, A., "Constructal distribution of solar chimney power plants: Few large and many small", ***International Journal of Green Energy***, Vol. 7, No. 6, (2010), 577-592.
15. Patel, S.K., Prasad, D. and Ahmed, M.R., "Computational studies on the effect of geometric parameters on the performance of a solar chimney power plant", ***Energy Conversion and Management***, Vol. 77, (2014), 424-431.
16. Tingzhen, M., Wei, L., Guoling, X., Yanbin, X., Xuhu, G. and Yuan, P., "Numerical simulation of the solar chimney power plant systems coupled with turbine", ***Renewable Energy***, Vol. 33, No. 5, (2008), 897-905.
17. Cao, F., Zhao, L., Li, H. and Guo, L., "Performance analysis of conventional and sloped solar chimney power plants in china", ***Applied Thermal Engineering***, Vol. 50, No. 1, (2013), 582-592.

18. Koonsrisuk, A., "Comparison of conventional solar chimney power plants and sloped solar chimney power plants using second law analysis", ***Solar Energy***, Vol. 98, (2013), 78-84.
19. Maia, C., Silva, J.C., Cabezas-Gómez, L., Hanriot, S. and Ferreira, A., "Energy and exergy analysis of the airflow inside a solar chimney", ***Renewable and Sustainable Energy Reviews***, Vol. 27, (2013), 350-361.
20. Asnaghi, A. and Ladjevardi, S., "Solar chimney power plant performance in iran", ***Renewable and Sustainable Energy Reviews***, Vol. 16, No. 5, (2012), 3383-3390.
21. Rezaie, B., Reddy, B.V. and Rosen, M.A., "Exergy analysis of thermal energy storage in a district energy application", ***Renewable Energy***, Vol. 74, (2015), 848-854.
22. Sadafi, M., Hosseini, R., Safikhani, H., Bagheri, A. and Mahmoodabadi, M., "Multi-objective optimization of solar thermal energy storage using hybrid of particle swarm optimization, multiple crossover and mutation operator", ***International Journal of Engineering***, Vol. 24, No. 3, (2011), 366-376.
23. Baylin, F., "Low temperature thermal energy storage: A state-of-the-art survey" (1979), Solar Energy Research Inst., Golden, CO (USA).
24. Lane, G.A., "Solar heat storage: Latent heat materials", (1983).
25. Sharma, S., Kotani, H., Kaneko, Y., Yamanaka, T. and Sagara, K., "Design, development of a solar chimney with built-in latent heat storage material for natural ventilation", ***International Journal of Green Energy***, Vol. 4, No. 3, (2007), 313-324.
26. Sharma, A., Tyagi, V.V., Chen, C. and Buddhi, D., "Review on thermal energy storage with phase change materials and applications", ***Renewable and Sustainable Energy Reviews***, Vol. 13, No. 2, (2009), 318-345.
27. Karimi-Pour-Fard, P., Beheshti, H. and Baniasadi, E., "Energy and exergy analyses of a solar chimney power plant with thermal energy storage", ***International Journal of Exergy***, Vol. 20, No. 2, (2016), 150-169.
28. Wilcox, D.C., "Turbulence modeling for CFD", DCW industries La Canada, CA, Vol. 2, (1998).
29. Ajay, K. and Kundan, L., "Performance evaluation of nanofluid (al2o3/h2o-c2h6o2) based parabolic solar collector using both experimental and CFD techniques", ***International Journal of Engineering-Transactions A: Basics***, Vol. 29, No. 4, (2016), 572-580.
30. Kalogirou, S.A., "Solar energy engineering: Processes and systems, Academic Press, (2013).
31. Kasten, F. and Young, A.T., "Revised optical air mass tables and approximation formula", ***Applied Optics***, Vol. 28, No. 22, (1989), 4735-4738.
32. Tolabi, H.B., Moradib, M. and Tolabia, F.B., "New technique for global solar radiation forecast using bees algorithm", ***International Journal of Engineering***, Vol. 26, No. 11, (2013).
33. Chang, Y., Huang, R., Ries, R.J. and Masanet, E., "Life-cycle comparison of greenhouse gas emissions and water consumption for coal and shale gas fired power generation in china", ***Energy***, Vol. 86, (2015), 335-343.

Performance Enhancement and Environmental Impact Analysis of a Solar Chimney Power Plant: Twenty-four-hour Simulation in Climate Condition of Isfahan Province, Iran

P. Karimipour-Fard, H. Beheshti

Department of Mechanical Engineering, Faculty of Engineering, University of Isfahan, Hezar Jarib Ave., Isfahan, Iran

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چکیده

اهداف اصلی در این پژوهش افزایش کارایی نیروگاه دودکش خورشیدی، بررسی استفاده از ذخیره کننده‌ی انرژی حرارتی و آنالیز تاثیرات محیط زیستی نیروگاه در استان اصفهان (ایران) می‌باشند. برای دستیابی به این اهداف، مراحل متعدد مدل سازی عددی در طول ۲۴ ساعت شبانه روز در شرایط آب و هوایی اصفهان انجام گرفته است. بهبود عمکرد نیروگاه با ایجاد تغییرات در فاکتورهای هندسی نیروگاه انجام شده است. این فاکتورها عبارتند از ارتفاع، شیب سقف و شعاع کلکتور به علاوه‌ی ارتفاع، شعاع و شکل گلویی دودکش. سپس یک نوع ذخیره کننده‌ی انرژی حرارتی در حالت بهبود یافته‌ی نیروگاه مورد استفاده قرار گرفته است. در ادامه ایجاد آلودگی ناشی از دی اکسید کربن و مصرف آب برای تولید برق در این نوع نیروگاه با چهار نوع نیروگاه گازی، زغال سنگ، هیدرولیک و بایومس در تولید توان یکسان مورد مقایسه قرار گرفته است تا میزان تاثیر مثبت محیط زیستی این نیروگاه مورد بررسی قرار گیرد. نتایج نشان می‌دهد که کلکتور بهبود یافته و دودکش بهبود یافته به ترتیب ۱۳۹٪ و ۶۸,۱٪ توان نیروگاه را افزایش می‌دهند. بر اساس نتایج نیروگاه با وجود ذخیره کننده‌ی انرژی حرارتی تولید توان پایداری در طول شبانه روز دارد و ذخیره کننده بیشترین کارایی را در نیروگاه بهبود یافته دارد. نتایج همچنین کارایی نیروگاه دودکش خورشیدی در استان اصفهان (مناطق مرکزی ایران) را تایید می‌کند و نشان می-دهد که ذخیره کننده‌ی انرژی دامنه‌ی توان خروجی و فواید محیط زیستی نیروگاه را به طور قابل ملاحظه‌ای بهبود می‌دهد.

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