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Energy and exergy assessment of solar chimney power plants: An analytical modelling

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A B S T R A C T

Solar chimney power plant (SCPP) is among the potential technologies in all over the world. In this study, a comprehensive energy and exergy analysis has been performed for SCPP. Exergy balance of the SCPP is conducted to calculate the irreversibility and exergetic efficiency of the SCPP. Influence of the effective parameters e.g. tower height, solar radiation, tower and collector radius is examined on the performance of the SCPP through the parametric study. The results show that by increasing all the effective parameters, irreversibility would increase except for tower radius. The results further indicate by increasing the collector radius, there is a maximum point from exergetic efficiency viewpoint. Eventually, increment of the effective parameters would increase the power output.

1. Introduction

Solar chimney power plants (SCPPs) are among the renewable energy systems with a good potential in all over the world.

SCPP consists of three main parts: first, solar collector to absorb solar heat, second, tower which is installed at the center of the collector, and third, turbine which can be installed inside the tower or within the collector area. Solar radiation heats up the air under the collector and thereafter air passes through the turbine and produces electricity. Unlike solar cells, SCPP can work day and night, since the pressure difference always exists between the inlet and the outlet of SCPP. Zanjan (Iran) and Manzanares (Spain) are examples of such SCPP models with the basic components.

Many researchers tried to perform energy analysis for SCPP. Haaf et al. [1] are among the first researchers who tested the SCPP prototype at Manzanares in 1983. They reported that the SCPP power output would be 50 kW at 1000 W/m^2 solar irradiance. Schlaich et al. [2] were another researchers who have tested Manzanares SCPP. The results show that the power output would be 2 kW during nighttime. In another study, Schlaich et al. [3] investigated the performance of SCPP with water bags. The concept proposes implementing water bags on the collector to prolong the power generation during nighttime. Weinrebe et al. [4] were among the first researchers who modeled SCPP and compared numerical and experimental results. Good agreement between the results was achieved by the authors. Backstrom et al. [5] modeled the turbine of the SCPP and examined the turbine characteristics. Zandian and Ashjaee [6] proposed a concept which the cooling tower of Shahid Rajaee power plant is replaced with the SCPP. The results showed that the SCPP power output would be 360 kW to 3 MW at different chimney diameters. Additionally, the authors reported that the thermal efficiency of the hybrid cycle can increase by 0.37%. In a later study, Ghorbani et al. [7] optimized geometric features of the SCPP which was proposed for the integrated Shahid Rajaee-SCPP concept. They reported that the thermal efficiency of the hybrid fossil fuel plant-SCPP can increase by 0.538% by optimizing the SCPP geometric features. Habibollahzade et al. [8] investigated power enhancement of SCPP by integrating with Tehran's waste-to-energy plant. The results showed that power increment would be 20–1200%.

To the best of our knowledge there is no comprehensive study that is performed an exergy and exergy analysis for the SCPP. In this study, we have investigated SCPP from energy and exergy viewpoints in detail. Exergy balance for the SCPP is written and exergy of fuel and products are ascertained. Exergy of fuel, exergy of products and exergy destruction rate are calculated for SCPPs. Eventually, the exergy efficiency of the SCPP is calculated for different conditions.

2. Modeling

SCPP modeling and exergy balances are described in detail. Some assumptions are made to render the analysis more traceable:

- The system is working at steady state condition.
- Heat loss from the tower of SCPP is negligible.
- Relative humidity of ambient air is negligible.
- Pressure drop inside the collector is omitted.

Total efficiency of the solar chimney can be obtained from following equation:

$$\eta_{SCPP} = \eta_{coll} . \eta_{tower} . \eta_{turbine} \tag{1}$$

where η_{coll} is the collector efficiency, η_{tower} is the tower efficiency and $\eta_{turbine}$ is the turbine efficiency. The collector efficiency is obtained from dividing the amount of heat transferred to the air through collector (Q) by the amount of solar radiation, (G) in the collector area (A_{coll}):

$$\eta_{coll} = \frac{\dot{Q}}{A_{coll} G} \tag{2}$$

By writing the energy equation for the ground which is heat absorber and also for the collector, the transferred heat can be calculated as follows:

$$\dot{Q} = \dot{m} c_p \Delta T = \alpha A_{coll} G - \beta \Delta T_0 A_{coll} \tag{3}$$

In Eq. (3), $\dot{m}$ is mass flow rate calculated as follows:

$$\dot{m} = \rho_{coll} A_c V_c \tag{4}$$

In Eq. (4), V_c is upwind air speed obtained as following:

$$V_c = \frac{\alpha A_{coll} G - \beta \Delta T_0 A_{coll}}{\rho_{coll} A_c c_p \Delta T} \tag{5}$$

where ρ_{coll} denotes the density of output air from solar collector and A_c represents cross-sectional area of the tower. By substituting Eq. (3) in Eq. (2), the collector efficiency is calculated by:

$$\eta_{coll} = \alpha - \frac{\beta \Delta T_0}{G} \tag{6}$$

where ΔT_0 stands for temperature difference between surface (heat absorbent) and ambient temperature and β is heat loss coefficient from solar collector. The above equation indicates that the collector efficiency is reduced by increment of temperature difference. Tower efficiency is obtained by:

$$\eta_{tower} = \frac{P_{tot}}{\dot{Q}} \tag{7}$$

Another equation that can help to calculate efficiency in an easier way is as follow:

$$\eta_{tower} = \frac{g.H}{c_p.T_0} \tag{8}$$

Eq. (8) shows the tower efficiency is dependent on the height of the tower i.e. tower efficiency can be increased by increasing the height of the tower. According to the Eq. (7), P_{tot} can be calculated by multiplying the transferred heat in tower efficiency. Now, the following valuable equation is achieved by placing tower efficiency from Eq. (8) and the transferred heat from combining Eqs. (3) and (4).

$$P_{tot} = \eta_{tower} \dot{Q} = \frac{gH}{c_p T_0} \rho_{coll} . c_p . V_c . \Delta T . A_c \tag{9}$$

As Eq. (9) indicates, P_{tot} (total power) is dependent on different parameters such as the height of the tower and the density of collector exhaust air. The above equation can be changed into the following form:

$$\Delta P_{tot} = \rho_{coll} . g . H_{tower} . \frac{\Delta T}{T_0} \tag{10}$$

Eq. (10) can be used to calculate the amount of power generation by SCPP which is dependent on collector efficiency, turbine efficiency and height of the tower as well as collector surface.

Eventually, an useful equation can be expressed as follows [1]:

$$P_{tot} = \eta_{coll} \eta_f \eta_T \frac{2}{3} g \frac{H_{tower} \pi R_{coll}^2 G}{c_p T_a} \tag{11}$$

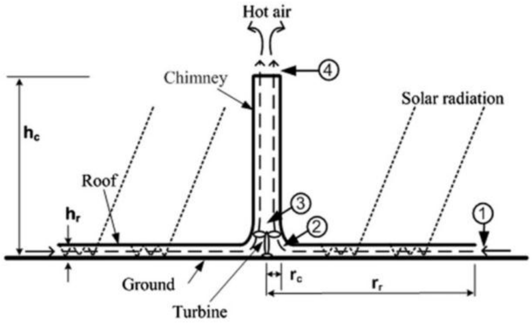


Figure 1. Schemtaic of a conventional SCPP

Exergy balance for the SCPP can be written as follows:

$$\dot{E}_4 - \dot{E}_1 + \dot{E}_{sun} = P_{tot} + i \quad (12)$$

$\dot{E}_4$–$\dot{E}_1$+$\dot{E}_{sun}$ is the exergy of fuel, P_{tot} is exergy of product and i is the exergy destruction rate. $\dot{E}_{sun}$ is the exergy of solar radiation which can be defined as [9]:

$$\dot{E}_{sun} = \dot{Q}_{sun} \times \left(1 + \frac{1}{3}\left(\frac{T_1}{T_{sun}}\right)^4 - \frac{4}{3}\left(\frac{T_1}{T_{sun}}\right) \right) \quad (13)$$

And $\dot{Q}_{sun}$ is the amount of absorbed solar radiation on the surface of the collector and T_{sun} is the temperature of sun's surface and is equal to 5770 K.

Accordingly, exergetic efficiency of the SCPP is defined as:

$$\eta_{II} = \frac{P_{tot}}{\dot{E}_4 - \dot{E}_1 + \dot{E}_{sun}} \quad (14)$$

For calculating the exergetic efficiency of SCPP, it is necessary to define the exergy of fuel. $\dot{E}_4$–$\dot{E}_1$ can be expressed as:

$$\dot{E}_4 - \dot{E}_1 = \dot{m}_{coll} \times \left(h_4 - h_1 - T_0\left(s_4 - s_1\right) + \frac{V_4^2 - V_1^2}{2} + gH_{tower} \right) \quad (15)$$

Additionally, for calculating the enthalpy of states 1 and 4, it is necessary to determine the amount of pressure drop across the chimney tower. For this purpose following equation is implemented [10]:

$$\frac{P_4}{P_1} = \left(1 - \frac{\lambda H_{tower}}{T_1} \right)^{\frac{g}{\lambda \bar{R}}} \quad (16)$$

Where λ is the lapse rate and is equal to 0.0065 K/m and $\bar{R}$ is the ideal gas constant.

3. Results & Discussion

Modeling of SCPP is validated with published measured data by Haaf et al. [1] which shows a decent agreement between the results.

Parametric study has been performed to examine how each parameter can affect the performance and exergetic efficiency of SCPP. First effective parameter is collector radius. Influence of this parameter is shown in Figure 2. As the figure shows by increasing the radius, power output, velocity of the fluid inside the tower, temperature increment and irreversibility increase while there is a maximum point in aspect of exergetic efficiency. Increment in irreversibility is justified because higher radius of collector means higher absorption exergy of radiation and then higher exergy of fuel. Increase of power output can be easily justified because higher absorption of thermal energy leads to higher power output.

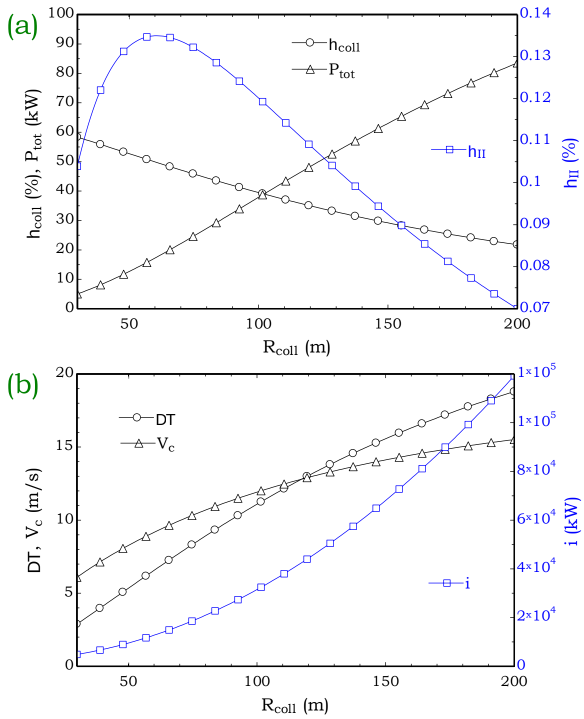
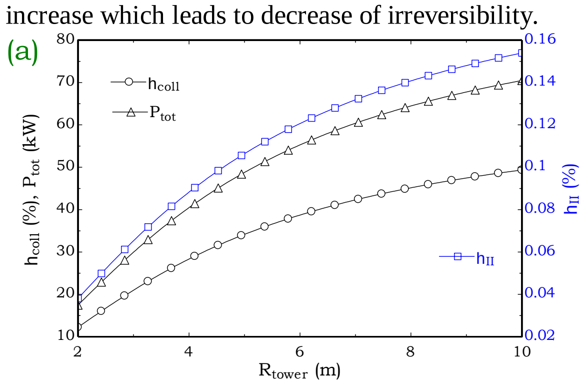


Figure 2. Influence of collector radius on SCPP performance

Tower radius can also be an effective parameter as Figure 3 shows. Inference from the figure is by increasing the tower radius, power output, efficiency of collector and exergetic efficiency increase while irreversibility, upwind velocity and ΔT, decrease. Increasing the tower radius will increase the mass flow rate inside the chimney tower which increase the power output. Additionally, increment of tower radius would not increase the pressure loss across the chimney tower and also the amount of absorption of solar radiation. Accordingly, exergy of fuel remains constant and power output (exergy of product) increase which leads to decrease of irreversibility.



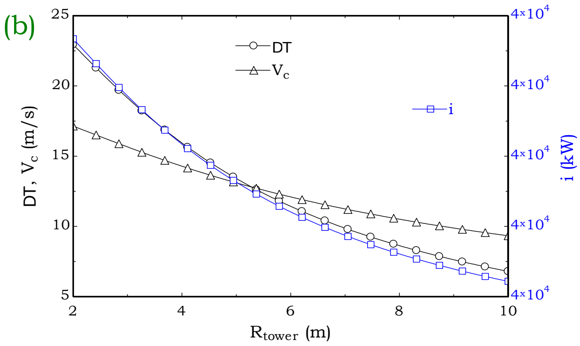


Figure 3. Effect of tower radius on the SCPP performance

Solar radiation also affects the results considerably. As Figure 4 shows, increment of solar radiation will increase all performance indicators. Increase in solar radiation clearly increases the power output since higher available radiation means higher velocity in the tower and thereafter higher power output. Also raising the solar radiation will increase the irreversibility since higher solar radiation means higher exergy of fuel and increase in denominator of Eq. (14).

The figure further demonstrates that by increasing the solar radiation upwind velocity and temperature difference would rise and it makes sense since higher solar radiation means higher absorption heat and then higher upwind velocity and increment of temperature.

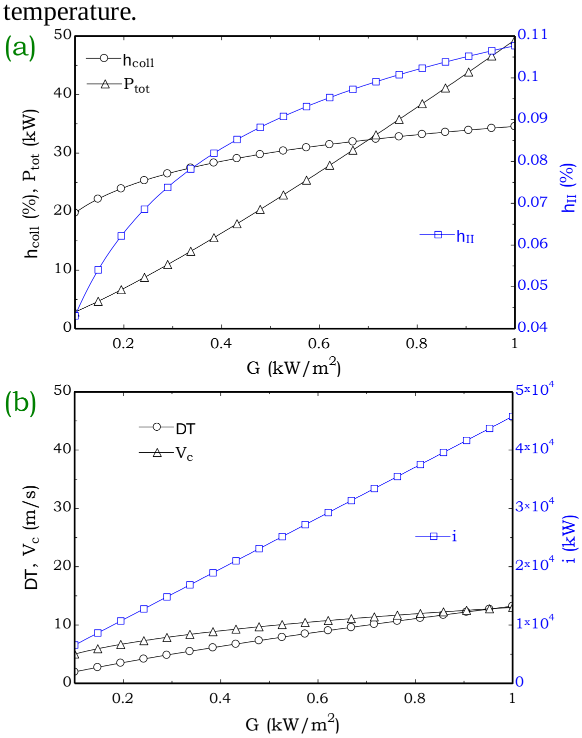


Figure 4. Influence of solar radiation on SCPP performance

Last but not least effective parameter is height of the tower. As the Figure 5 depicts, by raising the height of the tower, all the performance indicators are expected to increase except temperature difference which is expected to decrease. Increment in power output is justified because higher elevation of the tower means higher pressure drop across the tower which is clearly increase the power output. Irreversibility also increases by raising the elevation since higher pressure loss means higher exergy of fuel.

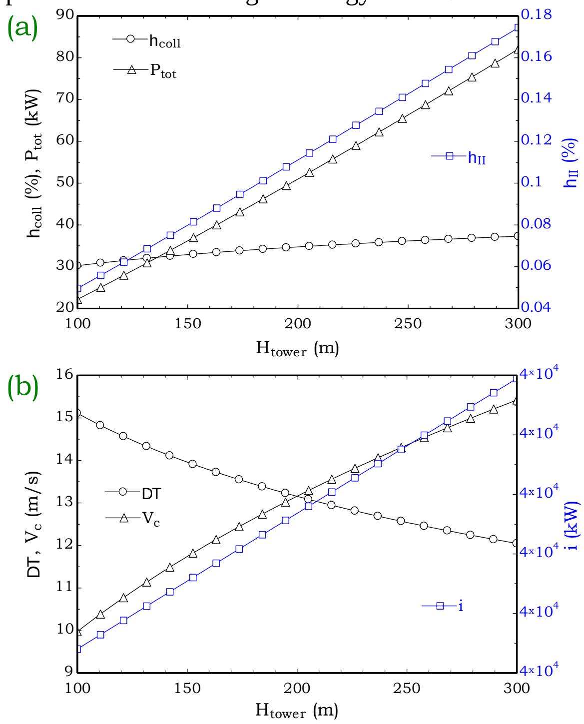


Figure 5. Effect of tower height on SCPP performance

4. Conclusion

In this study, a comprehensive energy and exergy analysis has been performed for SCPP. Exergy balance of the SCPP is conducted to calculate the irreversibility and exergetic efficiency of the SCPP. Influence of the effective parameters e.g. tower height, solar radiation, tower and collector radius is examined on the performance of the SCPP through the parametric study. The results show that by increasing all the effective parameters, irreversibility would increase except for tower radius. The results further indicate by increasing the collector radius, there is a maximum point from exergetic efficiency viewpoint. Eventually, increment of the effective parameters would increase the power output.

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Nomenclature	
A	Area
$\dot{E}$	Exergy rate
G	Solar radiation
H	Height
h	Enthalpy
i	irreversibility
$\dot{m}$	Mass flow rate
P	Pressure
P_{tot}	Power output
Q	Heat rate
s	Entropy
T	Temperature
V	Velocity
Greek letters	
η	Efficiency
λ	Lapse rate
β	Collector heat loss
α	Collector absorption coefficient
ρ	Density
Subscripts	
1, 2 ,…	State point
coll	Collector
c	Chimney

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