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Performance analysis of a solar chimney power plant design aided with reflectors

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ABSTRACT

A new design of a solar chimney power plant (SCPP) with enhanced incident solar radiation, realised using reflectors, was developed and validated. A detailed thermodynamic analysis was performed to access the performance of the new SCPP design, and its performance was compared with a conventional SCPP. All the formulated energy and exergy balance equations were solved simultaneously using engineering equation solver software. Study reveals that the increase in incident solar radiation using reflectors enhances the efficiency and power output by 22.61% and 133%, respectively. The improvement in power output is due to the higher mass flow rate. Furthermore, a laboratory scale working model of an SCPP aided with reflectors was built to determine how well the empirical results agree with the results obtained using the analytical model developed in the present study. The model developed predicts the empirical values of temperature with an accuracy of 5%. The proposed model was evaluated in Dhahran, Saudi Arabia to be used as an illustrative example. For solar irradiation data of 2017, the average energetic efficiency and the power output for the SCPP design aided with reflectors are 0.641% and 230 kW, respectively. Moreover, the power output, energy efficiency, variation of the temperature of the floor and air, variation of the mass flow rate and inlet velocity of the turbine, and the density variation of air in the collector for each month of the year are reported. Also, the results of the comparative study with a conventional SCPP are presented.

1. Introduction

The operation of a solar chimney power plant (SCPP) is based on one of the solar thermal technologies and it is one of the less efficient among them. However, considering that it is a cheap source of electricity, the technology is economically feasible. In an SCPP the natural draft is guided through a chimney, utilizing the solar radiant energy to impart an ascending thrust on air to run a turbine. An SCPP is constructed by the combination of three devices traditionally used for energy conversion; namely a greenhouse, a lengthened chimney at the centre of the greenhouse, and a wind turbine placed inside the chimney. Such a setup allows the transformation of radiant energy from the sun into electrical energy in two steps. In the first step, the collector transforms radiant energy into thermal energy by the greenhouse effect, and the design of the collector allows the heated air to flow radially towards the chimney at its centre. In the next step, the chimney transforms the thermal potential into kinetic energy, and the wind turbine converts the kinetic energy into electricity using a generator. A simple model of an SCPP consists of a film of glass or plastic drawn evenly above an area of the ground. Consequently, when the radiation is incident on the floor, the temperature of the air between the ground and the cover above it rises. The height of the cover of the collector above the ground gradually increases towards the centre of the SCPP. This design allows the continuous smooth passage of heated air, which flows through the long tubular chimney without turbulence, thereby diminishing the eddy losses. A collector with these characteristics can transform a considerable fraction of the radiant energy into thermal energy.

Many detailed research articles have been published on the operation of an SCPP based on analytical, numerical, and experimental analysis since the inception of the concept of an SCPP in Manzanares, Spain [1]. However, only a very few published attempts of enhancing the performance of the system are available. One of the attempts was to extend the operation of an SCPP to periods without solar radiation by introducing water-filled tubes for thermal energy storage as reported by Kreetz [2]. The water-filled tubes were placed on the ground so that the incident solar radiation will heat the water when solar radiation is available. During night time when the temperature of the air in the

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Nomenclature

A	area
C_P	specific heat at constant pressure
D	diameter (m)
d	height of the mirror from ground
E	energy rate
H	height (m)
h	convective heat transfer coefficient
I	solar irradiation
L	length of the reflector
m	distance of reflector from center of SCPP
$\dot{m}$	mass flow rate
Nu	Nusselt number
P	pressure
R	gas constant
$R1$	reflector
S	solar insolation
T	turbine
T_x	temperature of the component 'x'
w	velocity
X	exergy rate
ΔX	exergy destruction rate

Subscripts representation

x-y	from component x to y
Mn	mode of energy content (enthalpy, kinetic or potential) at state points (0,1,2,3) E.g., a1 (enthalpy at location 1)

Subscripts

a	air
a	enthalpy
amb	ambient
ch	chimney
d	deck
E	effective
e	inlet
f	floor
gr	ground
m	mirror or reflector
p	potential energy
$power$	power produced by a turbine
sky	sky
s	sun
w	kinetic energy
0, 1, 2, 3	state points

Greek symbols

α	angle of reflector
ε	emissivity
η	efficiency
κ	thermal conductivity
ρ	reflectivity or density
σ	Stefan-Boltzmann constant
τ	transmissivity
φ	shape factor

collector drops, thermal energy stored in water inside the tubes during daytime is released. However in a thorough study, Bernardes [3] found that the power produced during the peak hours of sunshine is decreased as part of the heat is absorbed by the water-filled tubes. Nevertheless, a uniform power output is produced throughout day and night by an SCPP with water-filled tubes. The power output is approximately 40% of the peak power of a conventional SCPP, depending on the depth of water stored.

Pasumarthi and sherif [4] proposed a mathematical model to estimate the air temperature and power output of an SCPP. They examined the effects of the ambient conditions and the geometry on the overall power output. They also performed an experimental analysis of an SCPP and proposed the following designs to enhance the power output; (i) A design with a collector of greater slope, and (ii) A design with an absorber plate introduced between the ground and the glass cover. Both designs enhanced the power output by 10–15% compared to a conventional SCPP. Bilgen and Rheault [5] designed a sloped SCPP for hills at high latitudes and evaluated its performance. As natural hills are used as the collector field, the chimney height is reduced by 90%, thereby reducing the construction and maintenance costs. However, the cost of construction of a sloped collector is higher as it involves extra civil work. The authors claim an efficiency of 0.48%, which is slightly better than that of a conventional SCPP.

Balijepalli et al. [6] investigated a prototype of solar chimney power plant and determined the performance of the prototype by evaluating the pressure drop in the chimney and power output of the turbine. They also performed the detailed study on selection of appropriate materials for solar collectors, chimney, turbine and heat storage materials. Koonsrisuk and Chitsomboon [7] performed the dynamic similarity of solar chimney power plant and proposed the guide for experimental study of flow in the prototype of solar chimney power plant. Moreover, they performed the CFD analyses for three geometrically similar cases and obtained similarity by using their proposed dimensionless variables for plants of various sizes. Further the authors in their article [8] proposed the single dimensionless variable to establish a dynamic similarity between a prototype and its scaled models and found that, if the proposed dimensionless number is equal to one then the temperature distribution of the prototype to the real models is similar.

Asayesh et al. [9] optimized the solar chimney for desalination and power generation by developing a one dimensional code for simulation. Owing to very low efficiency of solar chimney power plant, solar desalination pond has been added under the collector of a solar chimney power plant. By optimising they found that the desalination system may only be installed in some regions of the collector instead of completely covering the ground. Habibollahzade et al. [10] proposed an integrated renewable system by performing the numerical study, for enhanced power generation by integrating waste-to-energy (WTE) and solar chimney power plant. The combination is performed by exploiting the warm air of the condensers outlet of WTE plant in to the SCPP. By combining these systems it was found that power output of SCPP was increased by 7%.

Papageorgiou [11] proposed a new design for the chimney, which is the component of an SCPP with the highest construction cost. He initiated the use of the cost-effective idea of floating solar chimneys (FSCs). An FSC is made up of successive balloon tubes filled with gases lighter than air, which allows the chimney to float in the air. Due to construction difficulties and the cost, the height of a conventional SCPP chimney has to be limited. For a similar power output of a conventional SCPP, the height of an FSC can be reduced by three times, making the power produced 5 to 6 times cheaper. He also stated that constructing SCPPs using 5% of the existing desert land in all the continents can cater up to 50% of the global electricity demand.

Zhou et al. [12] proposed a novel concept for producing power by integrating a solar collector with a man-made cavern in a mountain. A mountain cavern, formed by an excavation in a mountain at a high elevation, eliminates the necessity of constructing concrete chimneys, which reduces the usage of material and the construction cost. Alrobaei [13] has proposed a hybrid geothermal/SCPP/PV system in the