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A Hybrid Solar Chimney Power Plant for Electricity Generation: Al Ain Case Study

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ABSTRACT

The research effort made in this paper is to present a new novel design of Solar Chimney Power Plant (SCPP). The SCPP, inherently, operates only when the solar radiation present intensively. The disadvantage of such energy system is the limited hours of operation with high levelized cost of energy. Therefore, we retrofitted the design of the SCPP to operate as a cooling tower in the night while maintaining its functionality during the solar radiation. The novel hybrid design produced 599 MWh/annually leading to reduction of 425 metric ton CO2. The novel design will contribute to the efforts of reducing the GHG, and energy security in remote areas.

Keywords: water distillation, solar chimney, solar chimney power plant, SCPP

NOMENCLATURE

Symbols	
q_c	Convective heat transfer rate
q_r	Radiative heat transfer rate
gls	Glass
abs	Absorber
ch	Chimney
out	Outside the chimney
$c_{p,air}$	Specific heat capacity (J/kgK),
$\underline{m}_{air}$	Mass airflow
ω	Relative humidity
r	The radius of the collector
α	Absorptivity
τ	Transmissivity
I	Solar irradiation (W/m^2)
T	Temperature (K)

1. INTRODUCTION

Fossil fuel utilization for power production emits quite large amount of GHG [1]. Moreover, it bound countries to fossil fuel dependencies and threaten the energy security [2]. Renewable energy technologies are essential to reduce dependency on fossil fuels [3-5]. These technologies provide sustainable and secure energy production and meet the continuous demand on energy. One of these technologies is the solar energy system. In energy solar system, the solar radiation is transferred into another energy form, mostly in the form of heat or electricity. There are quite different range of solar technology such as photovoltaics, concentrated solar power, solar heating & cooling, solar storage, and solar chimneys. Solar chimney is one of the promising technologies that can be utilized in remote areas and participate in energy mix strategies [6].

Solar Chimney Power Plant (SCPP) introduced early in the 80s with simple design configuration. The design utilizes the natural convention of changing air velocity when there is a variation of pressure between two regions. The main problem associated with SCPP its large size relative to the amount of produced power. Additionally, the initial capital cost and dependency on the solar radiation. There are several studies attempted to optimize the operation of SCPP to increase the power capacity, reduce the levelized cost of energy and search for new ovel materials. Fluri and Von Backstrom et al [7] studied the SCPP operation and created a performance model. In the same study, they proposed several design configurations and compared based on their efficiency and energy production. Tingzhen et al. [8] studied the fluid mechanics behavior pf the SCPP and the ability with energy storge. Tingzhen et al. [8] reported that the increase in the solar radiation, reduced the air velocity and relative static pressure inside the chimney. Alkasrawi et al [9], utilized the excess from PV to heat up the air before entering the PV-SCPP design configuration. This design alternative enhanced the overall energy production rate and increased the efficiency of the PV. Abdelsalam et al [10-12] developed several hybrid systems of SCPP in attempt to increase the operating hours.

In this work, we retrofitted the SCPP with minor design modifications. These modifications allow the SCPP to operate as a cooling tower (CT) at the night. The new Hybrid Solar Chimney Power Plant (HSCPP) operates twenty-four hours. The novel HSCPP provides continuous electrical and desalinated water production. The HSCPP is independent of solar radiation, and thus maximizes the power capacity of this technology.

2. METHODS

2.1 Methodology and Description

The HSCPP system integrates the operating principles and technologies of a traditional SCPP and a CT. As illustrated in Fig. 1, the system's novel design consists of three main components: a solar chimney, a collector, and a bi-directional turbine; the component that enables a unique hybrid configuration without the need for a base structural foundation for the CT.

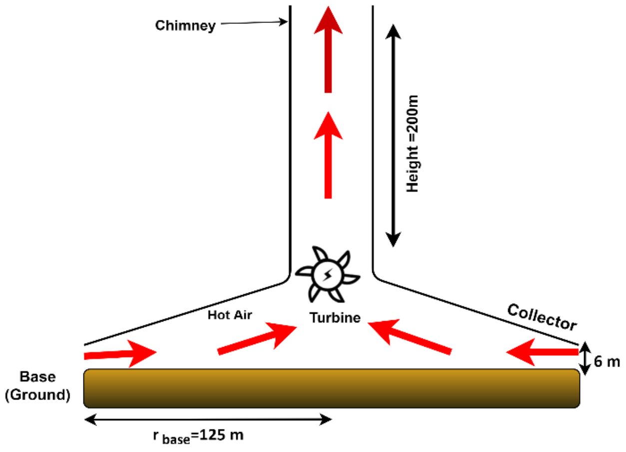

Fig. 1. Cross section view of the HSCPP.

The SCPP's operation is typically highly dependent on solar irradiation and only operates during the day, whereas the CT's operation is independent of solar radiation and operates at all times. In the proposed design, the system operates 24 hours a day, acting as an SCPP during the day and a CT at night. Technically, the bidirectional turbine shifts its spinning direction to switch between the two operational modes, SCPP and CT modes (clockwise or counter clockwise).

When it comes to the operating principles of both configurations, the primary driving force is the air density difference between inside and outside the boundaries of the system. The main difference between the two operations is the direction of the heat flow of the air. In the SCPP mode, as shown in Fig. 1, the air under the collector is heated up from the solar radiation and from convection from the ground (base). As the air heats up, the density decreases leading to an expansion in the volume. Eventually the air rises up along the chimney causing the bi-directional turbine to rotate to generate power. On the other side, during the night whereas the CT mode, the air at the top of the chimney is cooled by a mist of water from the sprinklers at the top causing the air density to increase. Eventually the air falls downwards in the chimney causing the bi directional turbine to rotate in the opposite direction to generate electrical power, as shown in Fig. 2.This system configuration will increase the overall power output since it operates 24 hours.

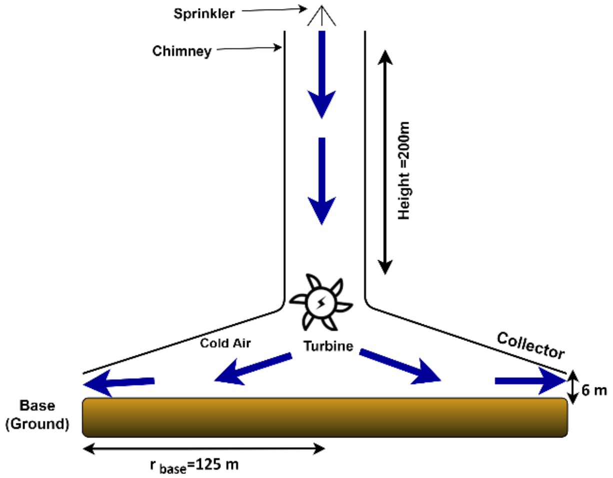

Fig. 2. Cross section view of the HSCPP during the night

2.2 Mathematical Model

The following major equations were used to build a mathematical model of the HSCPP and the suggested integration in MATLAB.

$$q_{c,gls-air} + q_{c,abs-air} = -\frac{c_{p,air}\underline{m}_{air}}{2\pi r}\frac{dT_{air}}{dr} \tag{1}$$

$$q_{r,abs-gls} + q_{c,abs-air} + q_{kabs} = \alpha_{abs}\tau_{gls}I \tag{2}$$

$$q_{c,gls-out} + q_{c,gls-air} + q_{r,gls-out} = \alpha_{gls}I + q_{r,abs-gls} \tag{3}$$

Sector 2: Water Evaporation energy balance equations for Airflow, Absorber, and Collector are:

$$q_{c,gls-air} + q_{c,wtr-air} = -\frac{c_{p,air}\underline{m}_{air}}{2\pi r}\frac{dT_{air}}{dr} \tag{4}$$

$$q_{c,abs-wtr} + q_{kabs} = \alpha_{gls}\tau_{wtr}\tau_{gls}I \tag{5}$$

$$q_{r,gls-spc} + q_{c,gls-out} = q_{c,gls-air} + q_{r,wtr-gls} + \alpha_{gls}I \tag{6}$$

Water energy balance equation is given by:

$$q_{ewtr} + q_{r,wtr-air} + q_{c,wtr-air} + c_{p,wtr}\underline{m}_{wtr}\frac{dT_{wtr}}{dr} = q_{c,abs-wtr} + \alpha_{wtr}\tau_{gls}I \tag{7}$$

The water condensation mass flow rate is given by:

$$\underline{m}_{wtr} = \underline{m}_{air}(\omega_{out} - \omega_{ch}) \tag{8}$$

2.3 Results and Discussion

Fig. 3 presents a metrological data for one day in July in the city of Al Ain, UAE. The solar radiation commenced 6:00 AM and peaked up at 12:00 PM. After 12:00 PM started to drop down in the same scale ratio when started to increase. It is interesting that the level of humidity directly proportional to the solar radiation. When the sola radio level between 400 and 900 W/m^2, we noticed dramatic decrease of the humidity. This might have an impact on the amount of the power output. Similarly, the solar radiation affects the ambient temperature increases. Overall, the solar radiation and temperature increase played a major role on the amount of produced electricity. The wind speed was almost constant during the 24 hours with low or no impact on the amount of produced electricity.

Fig. 4 presents electrical production for the HSCPP for 24 hours. The electrical production during the daytime was due to the SCPP functionality during the solar radiation. During the nighttime, the electricity continues to be produced since the HSCPP operates as a CT. Interestingly, and as shown in Fig. 4, the rate of electricity production varies significantly and proportional to the solar radiation when the HSCPP operates as SCPP. By contrast, the electrical production was constant when the HSCPP operates as CT. In the CT operation mood, interesting the temperature and humidity profile did not significantly affect the electricity output. This is since CT operation depends mainly on humidifying the air to the saturation point.

The overall and annual electrical production for the HSCPP presented in Table I. The annual electrical production for the HSCPP is 324 MWh when it operates as an SCPP. This value is like previous work and looks acceptable and within the range of acceptable operation of classical SCPP. However, when the HSCPP operates as a CT, the annual electrical production corresponds to 275 MWh. This will make the HSCPP operates 24 hours with annual 599 MWh. If this amount of electricity from the HSCPP, there will be a total of 425 metric ton CO^2 equivalent reduction. To develop this system further, we may include a sea water basin underneath the solar collector. This will allow the system to generate desalinated water without any modification to the main HSCPP design.

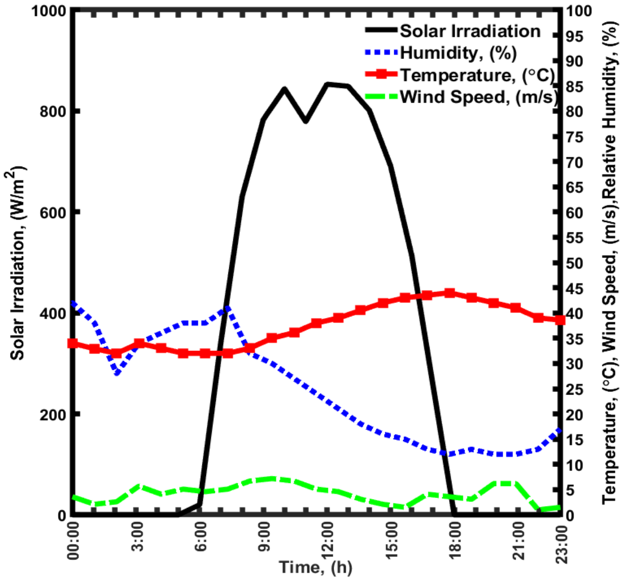

Fig. 3. A 24-hour weather profile on the 20th of August

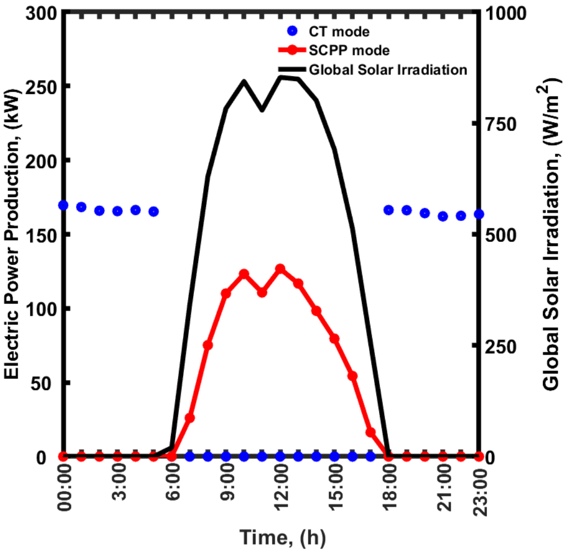

Fig. 4. A 24-hour profile of electricity production on 20th of August

TABLE I. *Annual Energy and Water Production*

Month	Avg Monthly Global Solar Irradiation (kWh/m^2)	Electric Energy, HSCPP (kWh), SCPP	Electric Energy, HSCPP (kWh), CT	Total Electric Energy (kWh), HSCPP
January	254.87	25856.26	0.00	25856.26
February	270.51	24514.38	0.00	24514.38
March	280.53	27597.18	2864.66	30461.84
April	304.05	28099.93	15822.76	43922.69
May	314.11	29504.07	39619.12	69123.19
June	307.93	27766.28	37179.91	64946.19
July	311.75	29300.34	52059.71	81360.05
August	302.01	28429.66	59803.23	88232.89
September	291.88	26999.25	43724.93	70724.18
October	283.09	27524.04	20872.78	48396.83
November	261.91	25144.20	3081.88	28226.08
December	241.33	23757.23	158.21	23915.44
Total	3423.96	324492.84	275187.18	599680.02

2.4 Conclusions

The novel design of the HSCPP developed allowed this energy system to operate 24/7 instead of only during the daytime. The HSCPP design maximize the power capacity and lead to decrease the levelized cost of energy. The retrofitting was a simple mechanical addition of nozzle in the top of the HSCPP. This adds almost nothing to the capital investment.

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