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A Smart Hybrid Solar Chimney Power Plant

Jad Sunna' [1*], Emad Abdelsalam [1], Hamza Nawafah [1], Malek Alkasrawi [1]

[1] Al Hussein Technical University
Department of Energy Engineering, Amman 11831, Jordan
*20110001@htu.edu.jo

ABSTRACT

This work presents a revolutionary design of a Smart Hybrid Solar Chimney Power Plant (SHSCPP) with a target of maximizing the power capacity and reducing the operation cost. The design combines a classic Solar Chimney Power Plant (SCPP) structure with a Cooling Tower (CT) configuration. The chimney and a bidirectional turbine are shared components of the SCPP and CT. The SHSCPP system operates as a typical CT throughout the night. However, during the daytime, the system switches back and forth between the CT and the SCPP to produce the maximum amount of electricity depending on predicted weather data. Additionally, the SHSCPP produces distilled water while the system is working as an SCPP. Aqaba city which is located in Jordan has been selected to assess the performance of the SHSCPP due to its geographical area, and weather variations. The main results showed that the SHSCPP produces 651.7 MW/year of electricity compared to 368.4 MW/year when operating as a traditional SCPP.

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
wtr	Water
ch	Chimney
out	Outside the chimney
$c_{p,air}$	Specific heat capacity (J/kgK)
$\underline{m}_{air}$	Mass airflow
$\underline{m}_{wtr}$	Mass water condensation flow
ω	Relative humidity
r	The radius of the collector
α	absorptivity
τ	Transmissivity
I	Solar irradiation (W/m^2)
T	Temperature (K)

1. Introduction

Nowadays, there is considerable growth in the need for fresh water and green power alternatives [1]-[2]. Many variables, including population increase, growing living standards, and industrial expansion, are raising the bar in this domain. As a response, research efforts have been focusing on finding new efficient, renewable, and clean energy alternatives to established models to minimize carbon emissions. Solar, wind, biomass, and hydropower are examples of alternative sources [3]. Other efforts were made to enhance a combined renewable energy resource [4][5]. Governments all over the globe were worried about creating the necessary legislation and policies to promote scientific research in this area. Also, to guarantee that the use of these clean energy resources is enabled [6]. Wind, solar, hydropower, biomass, and geothermal are just a few of the newly developed renewable energy options [7][8]. Solar Chimney Power Plant (SCPP) appears to be a viable solution. Fluri and Von Backstrom [9] investigated the performance of the SCPP power conversion unit; they developed a performance model and compared the efficiency and energy yield of three alternative configurations. They also confirmed that the power conversion unit's total-to-total efficiency is expected to be 80%. They demonstrated that the power conversion unit's efficiency declines dramatically as the diffuser area increases. Tingzhen et al. [10] analyzed the heat transmission and airflow patterns in an SCPP with an energy storage porous layer of soil or gravel where it can be numerically calculated. They also investigated the impact of solar radiation on the energy storage on the heat storage capacity of the energy storage layer. Their findings demonstrated that the heat storage ratio of the porous layer reduced as the solar radiation increased from 200 to 600 W/m^2, then rebounded to 800 W/m^2. Furthermore, when solar radiation rose, the relative static pressure and air velocity inside the chimney reduced and increased, respectively. In addition, Ghalamchi et al. [11] built an SCPP prototype to examine the influence of different chimney diameters and

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absorber materials on the system's thermal performance. The collector's diameter was three meters, and the chimney height was two meters. Their findings indicated that the heat transfer rate for the black aluminum absorber was much higher than the heat transfer rate for the iron absorber. It was also proved that the largest temperature differential between the air inside the collector and the surrounding environment was 27℃. The diameter of the chimney was discovered to be the most critical element determining the performance of the SCPP. Abdelsalam et al. [12]– [15] developed several design configurations to enhance the performance of the traditional SCPP. In this paper, a novel design of a Hybrid Solar Chimney Power Plant (HSCPP) integrated with a smart operation mechanism is presented, hence the name (SHSCPP). The design combines the Cooling Tower (CT) technology with traditional SCPP. The smart operation mechanism is established by estimating the power production between the CT mode and the SCPP mode, then selecting the mode that produces higher electric power. The estimated power output is calculated using the mathematical model and depends on the forecasted weather conditions.

2. METHODS

2.1 Methodology and Description

The SHSCPP system combines the design and technology of a standard SCPP with a CT. As shown in Figures 1 and 2, the system's innovative design consists of three primary components: a solar chimney, a collector, and a bi-directional turbine. Also, a seawater pool is added at the bottom of the structure. The SCPP mode is activated when the air underneath the collector is heated by solar radiation, causing the air density to drop, expand, and rise in the chimney. As the air passes through the chimney, the turbine at the bottom of the chimney begins to generate electricity. On the other hand, the CT mode works by spraying a mist of water at the top of the chimney, which evaporates instantaneously, causing the dry air to cool; the air then gets denser, forcing it to drop owing to gravity towards the bottom of the channels. The air that exits the bottom of the chimney interacts with the turbine to generate electricity. During the daytime, Smart Operation Mode (SOM) is used to select between the SCPP and CT modes. The power production is calculated using a mathematical model based on the prediction of future weather conditions such as solar irradiation, ambient temperature, wind speed, and humidity. After the calculations are done, the SHSCPP will operate using the mode with higher calculated electrical power production. However, during the night the SHSCPP works in CT mode. Distilled water is also produced when the system operates as an SCPP; as the air under the collector is heated up it enhances the evaporation of the seawater pool, later the vapor condensates on the inner walls of the chimney and is then collected by the distilled water pipes. This configuration maximizes the power output during the daytime specifically and throughout the 24 hours of operation in general.

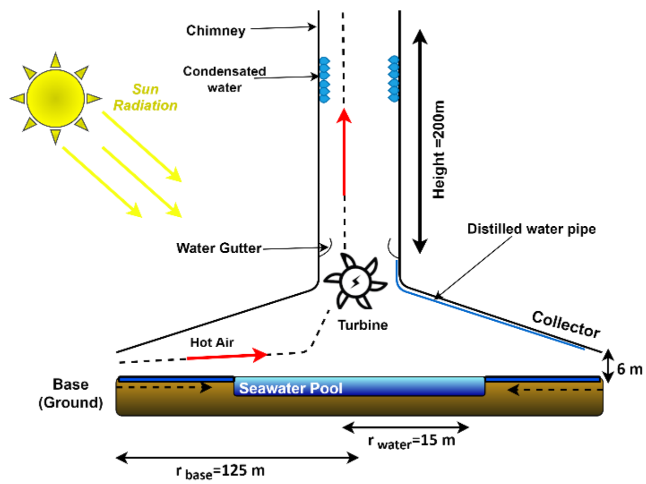

Fig. 1 Cross-section view of the SHSCPP during daytime

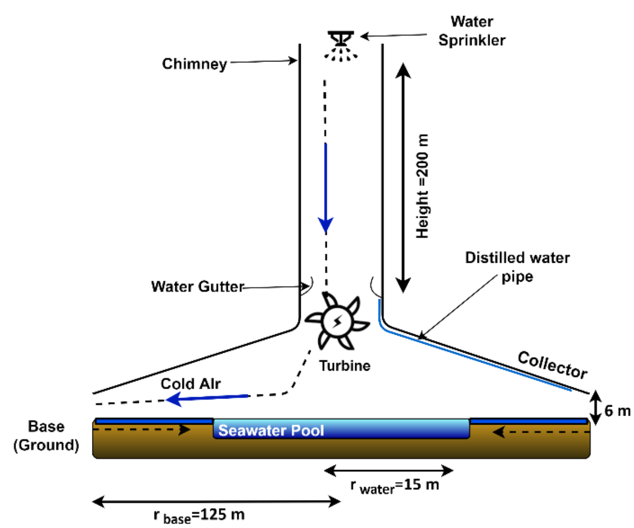

Fig. 2 Cross-section view of the SHSCPP during the night

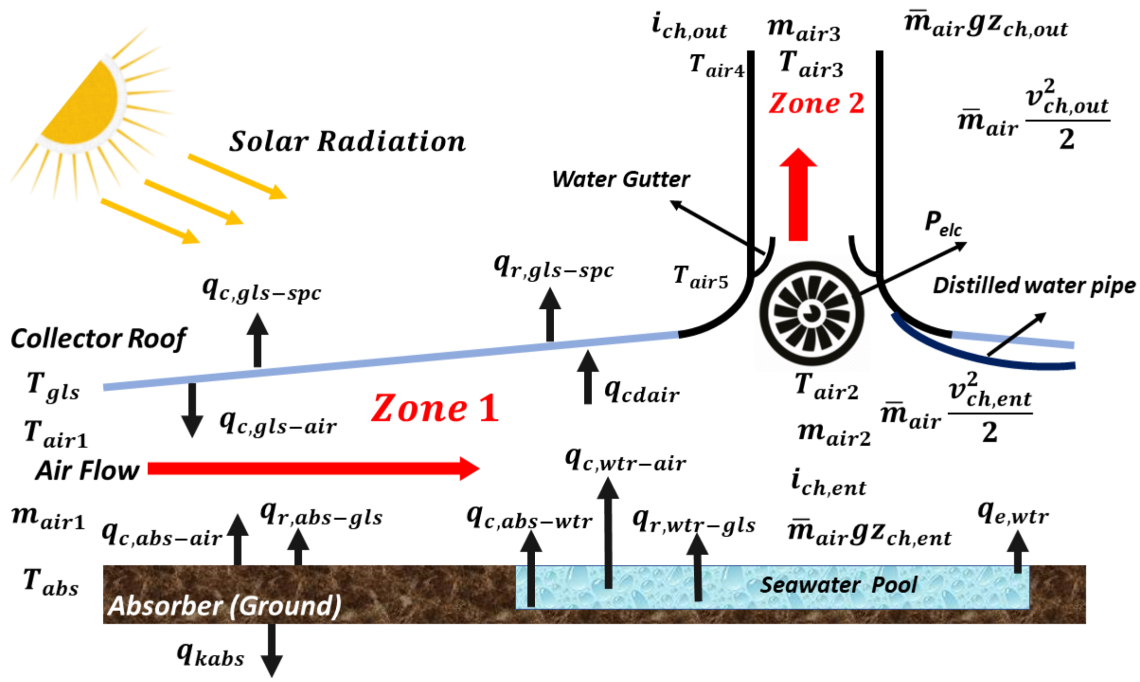

Fig. 3 Energy Balance Environment

2.2 Mathematical Model

The following major equations were used to build a mathematical model of the SHSCPP and the suggested integration in MATLAB, as shown in Fig. 3. The detailed equations can be found in our previous publications [12]–[15].

Sector 1: Air heating

$$q_{c,gls-air} + q_{c,abs-air} = -\frac{c_{p,air} m_{air}}{2\pi r}\frac{dT_{air}}{dr} \qquad (1)$$

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

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

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

$$q_{c,gls-air} + q_{c,wtr-air} = -\frac{c_{p,air} m_{air}}{2\pi r}\frac{dT_{air}}{dr} \qquad (4)$$

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

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

Water energy balance equation is given by:

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

The water condensation mass flow rate is given by:

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

2.3 Results and Discussion

Fig. 4 shows a 24-hour weather data profile on the 20th of July in Aqaba city, Jordan. The graph represents the solar radiation as it starts to increase at 5:00 AM until it reaches the peak at noon, then it starts to decrease until it reaches 0 at 6:00 PM. The average humidity is almost 37% with a peak of 60% at 5:00 AM. Wind speed had an average of 5.3 m/s before achieving the maximum value of 7.2 m/s at 8:00 PM. The overall mean value is equal to 5.44 m/s. The minimum and highest temperatures recorded for that day were 27 ℃ and 40.4

°C respectively, and the highest temperature recorded was around 5:00 PM.

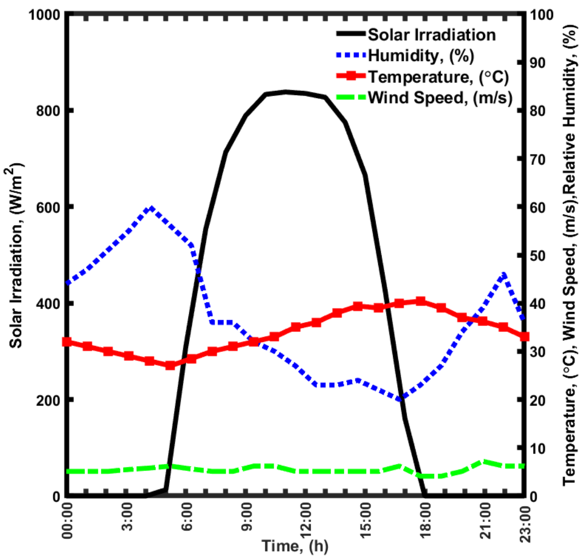

Fig. 4. A 24-hour weather profile on the 20th of July

Fig. 5 shows the electric power production during 24 hours. The solid blue line represents the CT mode which can potentially operate 24/7, while the solid black line represents the electric power production of the SCPP mode that operates during the solar irradiance. The red dots represent the SHSCPP mode. The trend shows how the smart operation selects the higher power output. The design works as CT from 12:00 AM until 1:00 AM before switching to the SCPP mode until 7:00 AM then it switches back to CT mode for the rest of the day. The SOM selected the CT mode at 10:00 AM instead of the SCPP mode, which resulted in gaining an additional 15.026 kW.

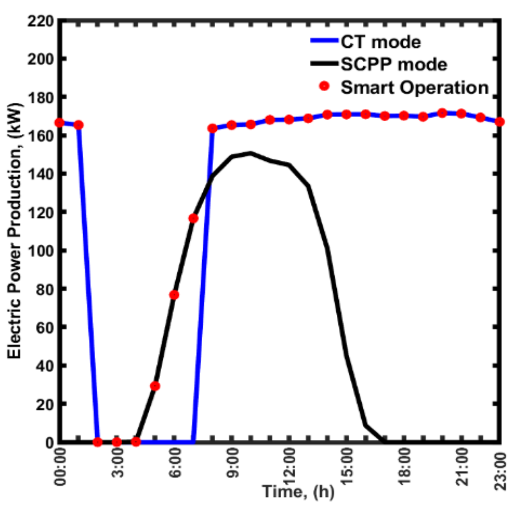

Fig. 5. A 24-hour profile of electricity production on the 20th of July

Fig. 6 is a bar chart that represents the monthly electric power production when operating as a traditional SCPP, compared to the SHSCPP production. In the first and the last two months of the year, the power production is almost the same. That is because the CT is not operating due to high humidity in winter. However, the SHSCPP mode generates higher electricity from May to October. Both modes share the same trend as production increases until it reaches the peak in July before decreasing each month. The highest power production was in July (10145.8 kW) while operating as SHSCPP compared to (37664.6 kW) as SCPP.

Table 1 summarizes the annual energy production between SHSCPP (651.75 MWH) and HSCPP (368.45 MWH). The annual production shows that the SHSCPP generates the maximum power production compared with any other operating mode.

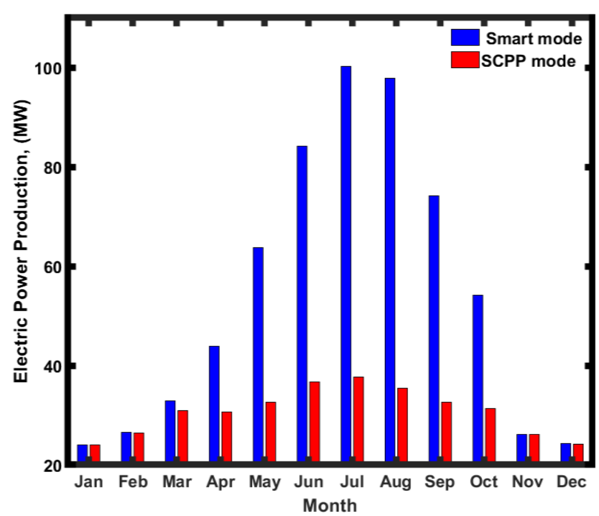

Fig. 6. Monthly electric power production

TABLE I. *ANNUAL ENERGY AND WATER PRODUCTION*

	Annual Average Global Solar Irradiation(kWh/m²)	Annual Electrical Energy, Traditional SCPP (MWH)	Annual Electrical Energy, SHSCPP (MWH)	Annual Water Production (Ton)
Total	3128.05	368.45	651.75	85750.72

2.4 Conclusions

A novel design of an SHSCPP was presented in this work. The design consists of a solar chimney, a collector, and a bi-directional turbine. The design allows the system to work as an SCPP and as a CT. A Smart operation mode was developed based on predicted weather conditions to select between the CT mode and the SCPP mode. The results showed that the SHSCPP outperformed the traditional SCPP in terms of electricity production, whereas the SHSCPP produces 651.75 MW compared to 368.45 MWH from the traditional SCPP. In addition, the SHSCPP produces 85750.72 ton of water annually. Further work will focus on assessing the design in other areas and improving the results using machine learning techniques.

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