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Modeling and characteristics analysis of hybrid cooling-tower-solar-chimney system

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ABSTRACT

The hybrid cooling-tower-solar-chimney system (HCTSC), combining solar chimney with natural draft dry cooling tower, generates electricity and dissipates waste heat for the coupled geothermal power plant simultaneously. Based on a developed 3-D model, performance comparisons between the HCTSC system, solar chimney and natural draft dry cooling tower were performed in terms of power output of turbine and heat dissipation capacity. Results show that compared to the traditional solar chimney with similar geometric dimensions, HCTSC system can achieve over 20 times increase in the power output of turbine. However, this huge jump in power output is at the expense of heat dissipation capacity, which may lead to the malfunction of the coupled thermal power plant. By increasing the heat transfer area of the heat exchanger, the HCTSC system can manage to recover its heat dissipation capacity.

1. Introduction

Traditional coal-fired power plants produce electricity, but they also raise several air pollution issues. In recent years, green power generation technologies, which generate sufficient electricity to meet the ever-increasing power demand but are not at the expense of environmental contamination, attract more and more attentions. The solar chimney power plant (SCPP) system harnessing abundant solar energy for electricity generation has broad application prospect in solar-energy-rich nations such as Australia and China.

Compared with coal-fired power plants, the basic structure of a SCPP system is much simpler including only chimney, solar collector and turbine (or turbines). The air is heated up inside the solar collector due to insolation. Consequently, the air pressure differential is generated between inside and outside of system. It causes continuous airflow traveling from the ambience into the chimney through the solar collector. The turbine (or turbines) set at the path of airflow converts the kinetic energy of air into electricity [1].

The first prototype of SCPP was built and run continuously from mid 1982 to early 1989 in Manzanares, Spain, which was capable to generate electricity up to 50 kW. Field tests were run and experimental data was documented and released later [2,3]. Since then, plenty of theoretical and experimental studies were conducted to elevate its application to MW level as base load source of no-carbon electricity [4–6].

Although SCPP system as a green power generation technology has promising prospect in the future, there is still some limitations to industrial application at present. SCPPs have thermal efficiencies of less than 1%, which are much less than those of traditional thermal power plants, e.g., coal-fired power plants and nuclear power plants. Hence, for a commercial SCPP with power generation capacity at MW level, the sizes of solar collector and tower must be huge, normally over 1 km in collector diameter and over 800 m in tower height [7,8]. The giant structure of SCPP at MW level lead to huge initial investment and therefore less economically competitive against its counterparts, e.g., coal-fired power plant and nuclear power plant [9]. Besides, a commercial solar chimney power plant at MW level requires a large area of land. Hence, its potential site must be far away from city to avoid high land cost. However, in that case, it will increase the cost of power transmission.

To reduce the occupied area of land and construction cost of large-scale SCPP, several proposals have been reported in the literature. Zhou et al. proposed a novel solar chimney system using man-made mountain hollow as chimney to reduce the chimney construction cost [10]. Instead of using reinforce concrete chimney, Papageorgiou proposed a floating solar chimney concept using giant plastic rings tied up to each other as chimney [11]. Zhou et al. later performed an economic analysis of floating solar chimney concept and analysis results confirmed the economic competitiveness of floating solar chimney against classic SCPPs [12]. Bilgen and Rheault

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Nomenclature

A_{fr}	heat exchanger frontal area (m^2)
C_{pa}	specific heat of air (J/kg K)
C_{pw}	specific heat of water (J/kg K)
D_{chi}	chimney diameter (m)
D_{coll}	collector diameter (m)
D_o	distance between effective solar collector and heat exchangers (m)
H_{chi}	tower height (m)
h	heat transfer coefficient based on heat exchanger frontal area (W/m^2 K)
H_{inlet}	collector inlet height (m)
h_s	convective heat transfer coefficient (W/m^2 K)
k	pressure drop coefficient of heat exchangers (–)
L_s	thickness of layer (m)
m_a	total air mass flow rate (kg/s)
m_w	water mass flow rate (kg/s)
P_e	power output (MW)
P_i	relative pressure at pressure-inlet boundary condition (Pa)
P_o	relative pressure at pressure-outlet boundary condition (Pa)
Q	heat transfer rate (W)
Q_h	heat dissipation rate (MW)
R_{base}	tower base radius (m)
s	solar radiation intensity (W/m^2)
T_{ai}	air temperature before the heat exchanger (K)
T_{ao}	air temperature after the heat exchanger (K)
T_{sky}	environmental temperature (K)
T_g	ground temperature (K)
T_{wi}	water temperature after the heat exchanger (K)
T_{wo}	water temperature after the heat exchanger (K)
V_a	air velocity flow normal to heat exchanger front area (m/s)
V_w	water velocity inside of tubes (m/s)

Greek symbols

ρ	air density (kg/m^3)
ρ_{ai}	air inlet density (kg/m^3)
ε_{ext}	emissivity of sunroof (–)

proposed a novel solar chimney concept to reduce occupied area of land and construction cost [13]. It consists of a sloped collector leaning against mountainside and a short chimney at mountain top. The sloped collector not only reduces the occupied land area but also partially replaces the function of chimney therefore decreases the real size of chimney at mountain top.

To save the construction cost and enhance the capacity of power generation, Zandian and Ashjaee proposed an idea that combines solar chimney with Natural Draft Dry Cooling Tower (NDDCT) served as cooling device in thermal power plants [14]. This hybrid system, Named as Hybrid Cooling Tower Solar Chimney (HCTSC), is capable of dissipating waste heat and generating electricity simultaneously. As illustrated in Fig. 1, heat exchangers are vertically placed at the periphery of solar collector entrance to preheat airflow before it goes into solar collector. Consequently, faster airflow through turbine can be achieved and therefore more power output according to Zandian and Ashjaee. Zandian and Ashjaee also reported that the malfunction of cooling part would not happen if a proper chimney diameter is chosen.

Obviously, in terms of structure, there are some similarities between HCTSC system and Solar Enhanced Natural Draft Dry Cooling Tower (SENDDCT) proposed by Zou et al. [15–17]. Both have heat exchangers, solar collector and tower (i.e., chimney). SENDDCT aims to use solar energy absorbed by solar collector to improve the cooling performance of natural draft dry cooling towers for Australian Enhanced Geothermal System (EGS) at hot periods, whereas HCTSC system is to make use of the waste heat of heat exchangers to increase the volume flow rate through turbine and therefore increase the power output.

In the 3-D model developed by Zandian and Ashjaee, although the approach to modeling the heat transferred from heat exchangers to airflow was clearly explained, the air-side pressure drop across the heat exchanger was not considered in their model, which may not match the reality. Normally, in any dry cooling system, the air-side pressure drop due to the heat exchangers has significant influence on the pressure balance of the system and therefore the cooling capacity. Hence, the pressure drop due to the heat exchangers must be considered during simulations, and its effects on such a hybrid system need to be carefully analyzed. The present paper is to analyze the performance characteristics of HCTSC system by using self-developed numerical model in ANSYS FLUENT and verify the feasibility of HCTSC system.

2. Geometric model of NDDCT and HCTSC system

A HCTSC system was chosen as a reference case in the present study with its dimensions listed in Table 1. For the sake of comparison, the geometries were set as the same as those in the example of Zandian and Ashjaee's study except for the type of heat exchanger. 4-row finned tube bundles are designed to be vertically placed at the periphery of the solar collector. The major geometric and working parameters of this type of heat exchanger are listed in Table 2. To simplify the modeling process, the heat exchangers used flat arrangement rather than an A-frame or V-frame arrangement, which means the frontal area of the heat exchanger is equal to the inlet area of solar collector (i.e., solar collector diameter times the height of collector inlet).

3. 3-D model for HCTSC system

A 3-D model for such a HCTSC system was developed in ANSYS FLUENT. Since the numerical simulation for the entire system is computationally-expensive and time-consuming, only 30 degrees sector was cut off from the whole HCTSC system and used as the computational domain (Fig. 2). In this case, the heat transfer and air mass flow rate computed in the sector are 1/12 of the values of the entire system. Both unstructured tetrahedral and hexahedral meshes were used in the numerical simulation. Special meshing in the near-wall zone was carried out to meet the requirement of near-wall treatments for turbulent airflow under sunroof. Grid-independence has been investigated by analyzing each case at different mesh sizes (i.e., cell quantity varying from 500,000 to 1500,000) until consistent results were reached (less than 0.1% error in the present study).

3.1. Governing equations

The simulations were run in ANSYS FLUENT by solving a series of governing equations consisting of the continuity equation, the