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Performance analysis of conventional and sloped solar chimney power plants in China

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HIGHLIGHTS

► The optimum collector angle for maximum power generation is 60° in Lanzhou.
► Main parameters influencing performances are the system height and air property.
► Ground loss, reflected loss and outlet kinetic loss are the main energy losses.
► The sloped styles are suitable for Northwest China.
► The conventional styles are suitable for Southeast and East China.

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ABSTRACT

The solar chimney power plant (SCPP) has been accepted as one of the most promising approaches for future large-scale solar energy applications. This paper reports on a heat transfer model that is used to compare the performance of a conventional solar chimney power plant (CSCPP) and two sloped solar chimney power plants (SSCPPs) with the collector oriented at 30° and 60°, respectively. The power generation from SCPPs at different latitudes in China is also analyzed. Results indicate that the larger solar collector angle leads to improved performance in winter but results in lower performance in summer. It is found that the optimal collector angle to achieve the maximum power in Lanzhou, China, is around 60°. Main factors that influence the performance of SCPPs also include the system height and the air thermophysical characteristics. The ground energy loss, reflected solar radiation, and kinetic loss at the chimney outlet are the main energy losses in SCPPs. The studies also show SSCPPs are more suitable for high latitude regions in Northwest China, but CSCPPs are suggested to be built in southeastern and eastern parts of China with the combination to the local agriculture.

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1. Introduction

The solar chimney power plant (SCPP) is composed of three components: a solar collector, a chimney situated in the center of the collector and a power conversion unit (PCU). A schematic of the SCPP is shown in Fig. 1. Sunlight transmits through the transparent solar collector cover and heats the ground below. Ambient cold air enters the collectors from the periphery of the collectors and is heated as it flows along the collector toward the center. Due to the pressure created by the density difference between the warm airflow and ambient cold air, the airflow enters the chimney, and with the PCU, the kinetic energy of the airflow is converted into the electric power.

1.1. Theoretical study of SCPPs

The concept of SCPP was originally proposed in 1903 by Isidoro Cabanyes [1] and then presented in a publication by Günther [2]. A systemic research on the SCPP was first performed by Schlaich. In 1981, with the financial support from the German Ministry of Research and Technology, Schlaich began the construction of a pilot SCPP with the peak power about 50 kW in Manzanares, Spain [3,4]. This is the most systematic study of the solar chimney power technology in practice until now and successfully verifies the feasibility of SCPPs.

Since then, extensive research has been carried out on the huge-potential of the SCPP over the world. Haaf et al. carried out a basic research about the energy balance on the ground surface, energy loss in the chimney and turbine of the Manzanares pilot power plant

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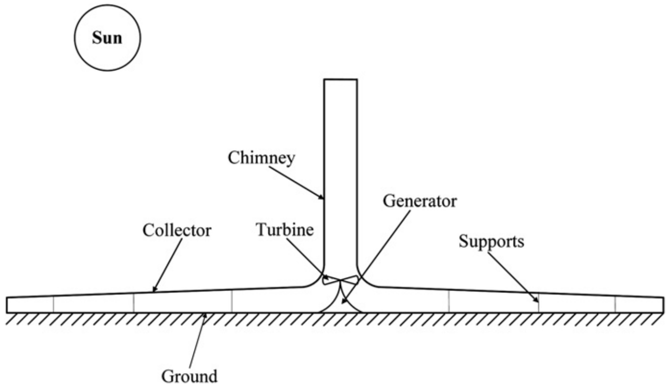

Fig. 1. Schematic of a solar chimney power plant.

[3]. von Backstrom et al. analyzed the pressure drop in solar chimneys [5], the turbine characteristics [6], and performances of the PCU [7]. Bernardes et al. analyzed some available heat transfer coefficients applicable to SCPP collectors [8], and evaluated some operational control strategies [9]. Pretorius et al. made a sensitivity analysis of the operating and technical specifications of SCPPs [10], and made a critical evaluation on the solar collector and heat storage layer [11]. Zhou et al. analyzed the influence of chimney height on SCPPs [12], and made preliminary research on the special climate around a commercial SCPP [13]. Schlaich et al. reported the design results of commercial SCPPs [14]. Yan et al. investigated the influence of the working fluid and chimney temperature [15]. Pasumarthi and Sherif built a complete mathematical model and analyzed the performances of SCPPs against the experimental research [16].

In 2005, Bilgen and Rheault proposed a sloped solar chimney power plant (SSCPP), whose solar collector is laid along the hillside (see Fig. 2) [17]. They concluded that SSCPP has higher thermal efficiency at high latitudes. This kind of SCPP is suitable for high latitude and mountain areas. Serag-Eldin explored the feasibility of an SCPP with the chimney built over the steep side of the mountain [18]. Zhou and Yang reported a novel SSCPP with floating chimney and predicted its potential in China's Desert [19]. Wei et al. and Cao et al. analyzed the slope angle effect on receiving insolation and investigated on the optimal collector slope of the SSCPP [20,21]. The SSCPP is based on the SCPP principle and takes advantage of the local geographical features. So, we could recognize the SSCPP in Fig. 2 as the development of the horizontal solar chimney power plant in Fig. 1, which in this study is called the conventional solar chimney power plant (CSCPP).

1.2. Case study of SCPPs

There are some case studies of CSCPPs in literature. Mullet made detailed analysis about the efficiency of SCPP, and concluded the feasibility of building SCPPs in developing countries [22]. Zhou et al. investigated the performances of a 100 MW CSCPP in Qinghai-Tibet Plateau [23]. Nizetic et al. analyzed the feasibility of implementing SCPPs in the Mediterranean region [24]. Larbi et al. made a performance analysis of an SCPP in the southwestern region of Algeria [25]. Ketlogetswe et al. described a systematic experimental study on a mini-solar chimney system in Botswana [26]. Dai et al. explored the feasibility of SCPPs in three regions of Northwest China [27]. However, as for the SSCPP, to our knowledge the only case is that a simulation of SSCPP in Lanzhou, China was carried out by Cao et al. [28].

Because of significant meteorological and geographical differences and local economic differences, case studies of SCPPs for different countries or regions are of high value. The authors' previous study suggested that the SSCPP had better performances in spring and autumn days, whereas the CSCPP developed superiority in summer days [28]. For Northwest China, where local geographical resources are rich (over 30 mountain chains) and annually solar radiation is also strong (over 5852 MJ/(m^2 year)) [29], it is thus of high significance to analyze and compare the performances of CSCPPs and SSCPPs in such areas throughout the year.

By using a mathematical model based on the heat transfer, thermodynamics and fluid dynamics theories, a comparative study of the performances of a CSCPP and two SSCPPs in Lanzhou, China is performed. Main tasks of this study include:

1) To build a simplified mathematical model for SCPPs.
2) To compare the performances of the CSCPP and SSCPPs in Lanzhou.
3) To analyze the power generation of CSCPPs and SSCPPs at different latitudes in China.

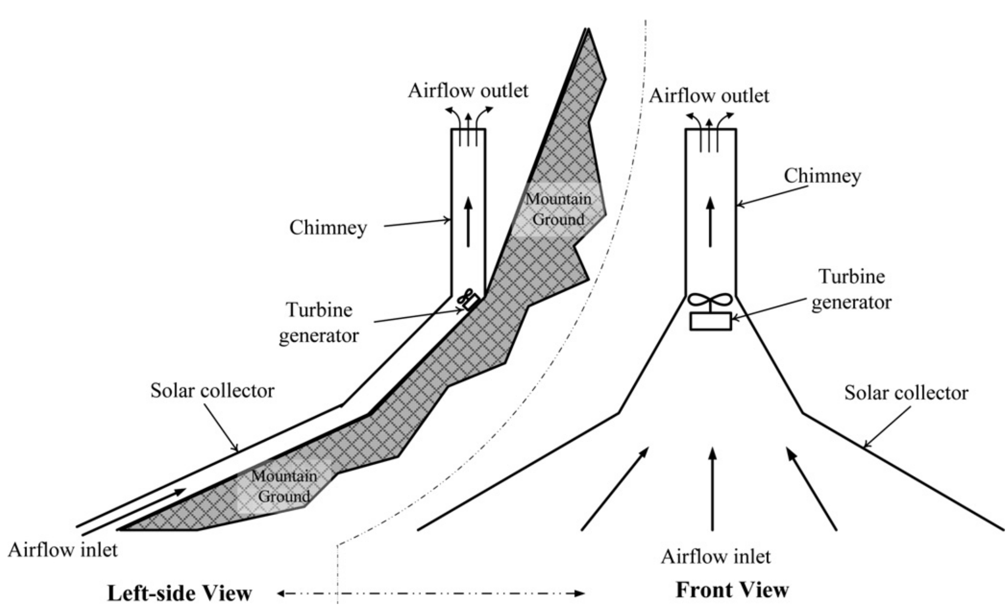

Fig. 2. Schematic of a sloped solar chimney power plant.

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