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Experimental study of geometrical and climate effects on the performance of a small solar chimney

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ABSTRACT

Nowadays, referring to the increasing rate of environmental pollution and limitation on fossil fuel resources, the use of sustainable energies seems to be inevitable and an absolute necessity for the world. Renewable energies are known as the best alternative for solving the energy shortage and CO_2 emission problems. Among the renewable sources, solar energy plays a significant role in aspects of accessibility of resource and diversity of energy conversion means. Solar chimney is a power plant that uses solar radiation to produce electricity by the created wind at the entrance of chimney. A solar chimney pilot power plant with 3 m collector diameter and 2 m chimney height was designed and constructed in University of Tehran, Iran. The temperature distributions and air velocity were measured and evaluated. The temperature difference between the chimney inlet and ambient reached to 26.3 °C. The output data for different collector inlet heights were obtained and the report shows that reducing the inlet size has a positive effect on the solar chimney power production performance. The air inversion at the latter of the chimney was not observed and it was found that this phenomenon directly associated with the geometry. The maximum air velocity of 1.3 m/s was recorded inside the chimney, while the collector entrance velocity was around zero.

Contents

1. Introduction

The concept of solar chimney power technology was first introduced in 1931 by Hanns Gunther and the first pilot of the solar chimney power plant was constructed in Manzanares, Spain in the early 1980s. After that, Haaf et al. and Schlaich presented the overall performance of the solar chimney. They also evaluated the results for the prototype power plant in Manzanares in 1982 [1–3]. Then, Mullet presented a simple treatment of the thermodynamics of the solar chimneys and the governing equations for efficiency as a function of design parameters [4].

As solar chimney systems can make significant role in energy supplies of those countries where there is abundant sunlight and plenty of wasteland, researchers have carried out many studies on this technology. In the recent few decades, more and more researchers have shown strong interest in studying solar thermal power production technology for its huge potential of applications all over the world. Gannon and Von Backström proposed a mathematical model of a single rotor layout for a large-scale solar chimney. The results showed that the inlet guide vanes improve the overall efficiency [5] and also in

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another study, evaluated various radial sections along the blades in the turbine model with different number of rotor [6]. A thermal and technical analysis for the solar chimney power system can be found in Bernardes et al. [7].

Pretorius and Kröger analyzed the effects of different kinds of soil and quality collector roof glass on the efficiency of a large scale solar chimney power plant [8]. Von Backström and Gannon proposed analytical equations of turbine flow, load coefficient, and degree of reaction. In that work, they evaluated the influence of each coefficient on turbine efficiency [9]. A mathematical model was developed based on monthly average meteorological data and thermodynamic cycle at high latitudes by Bilgen and Rheault. The results showed the annual electric energy production in higher latitudes may be reached as high as 85% of the same plants in southern locations [10]. Zhou et al. carried out a simulation study of power outputs in steady state of the solar chimney power plant for different global solar radiation intensities, collector areas and chimney heights [11]. Kashiwa proposed a kind of solar chimney device called the Solar Cyclone that is introduced for the condensation and separation of water from atmosphere [12].

The feasibility study of solar chimney power plants in the Mediterranean region was analyzed by Nizetic et al. and it was shown that the cost of the produced electric energy by solar chimney power plant in Mediterranean region is higher than the other power sources [13]. Sakonidou et al. proposed a mathematical model to determine the optimum tilt that maximizes the natural air flow inside a solar chimney. The results show that the optimum tilt for chimney with height up to 12 m varies in a rather narrow range between 65° and 76° whereas for maximum irradiation it varies between 12° and 44° [14]. Ming et al. carried out numerical simulations to analyze the characteristics of heat transfer and air flow in a solar chimney power plant system with an energy storage layer [15]. Akbarzadeh et al. proposed a chimney system that is combined with a salinity gradient solar pond to produce power in salt affected areas [16].

A new method of heat and moisture extraction from seawater under the collector of the solar chimney for both power production and seawater desalination can be found in Zhou et al. [17]. The results show that temperature and velocity of the air inside the chimney in the combined plant are less than in the conventional plant. Also Zhou et al. proposed and designed a solar chimney power technology to be built in Qinghai-Tibet Plateau where there is abundant solar radiation. The obtained results showed that the solar chimney in plateau can produce twice more power than the same latitude of other regions [18]. In another work, Zhou et al. carried out economic analysis of power generation from floating solar chimney technology by analyzing cash flows during the whole service period of a 100 MW plant [19]. The most important factor of turbine in solar chimney power plants (pressure drop) was evaluated by Nizetic and Klarin. In their study, it was reported that the turbine pressure drop factors were in the range of 0.8–0.9 for solar chimney power plants [20]. Modeling of temperature changes for solar chimney power plant with chimney height of 8 m was carried out by Kasaeian and Heidari [21], and in another work by Kasaeian et al., the mathematical model and the temperature distribution of the collector were obtained and then compared with the experimental results for different states of the fluid inlet flow [22]. Kasaeian et al. carried out numerical study of solar chimney power plant to optimize the geometric configurations of experimental setup [23].

Chergui investigated the heat transfer models, airflow fields, and a natural laminar convective heat transfer problem in solar chimney [24]. Panse et al. proposed a new structure for solar chimney power plant which has an inclined chimney. This structure was constructed along the face of a high rising mountain [25]. Cao et al. designed a solar chimney power plant with 5 MW output power of which the collector radius and chimney height were 607.2 m and 252.2 m, respectively [26]. Also in another study by Cao et al. [27], they proposed a heat transfer method and compared the performance of a conventional solar chimney power plant with sloped solar chimney. Li et al. [28] presented a mathematical model for the performance evaluation of a solar chimney power plant and the results were verified by the experimental data of the Manzanares prototype. Larbi et al. presented the performance analysis of a solar chimney power plant in Algerian southwestern region. Their results showed that the solar chimney power plant can produce from 140 to 200 kW of electricity in their site during the year [29]. Zhou et al. constructed a pilot experimental solar chimney consisted of an air collector 10 m in diameter and an 8 m tall chimney. In their setup temperature difference between the collector outlet and the ambient can reach 24.1 °C [30].

Asnaghi and Ladjevardi investigated the performance of a solar chimney power plant in Iran. The results showed that the solar chimney with the same dimension of Manzanares pilot is capable of producing from 10 to 28 MW h/month of electrical power [31]. The effects of various ambient conditions and structural dimensions on the solar chimney in Iran were evaluated [32]. It was shown, from their results, that the solar chimney power plant with 350 m chimney height and 1000 m collector diameter can produce a monthly average of 1–2 MW electric power. A thermal method for steady state airflow inside a solar chimney power plant consisted of Bernoulli equations with a buoyancy effect can be found in Hamdan [33]. Park et al. carried out the energy and exergy analyses of typical renewable energy systems and Maia et al. presented the exergy analyses of airflow inside the solar chimney power plant using experimental data [34,35].

There are several research based on review on renewable energy especially solar chimney. Zhou et al. provided a comprehensive picture of research and development of solar chimney power plant in the past few decades [36]. Zhai et al. presented the review of main configurations and the integrated renewable energy systems based on solar chimneys. The results showed that solar chimney technology has been regarded as an effective and economical design method in low carbon buildings [37]. Shi and Chew presented a review of designing renewable energy systems specifically a solar-based energy system [38]. Kapoor et al. reviewed the solar energy potential in India for better planning and management in the field of solar energy [39]. Banos et al. presented a review of the current state of the art in computational optimization methods applied to renewable and sustainable energy [40].

2. Solar chimney set-up

For performing the experimental works and temperature measuring, the solar chimney in pilot scale was constructed in University of Tehran, Iran, in 2012. The chimney has the capability of having variable height between 1 and 2 m and the collector has 3 m diameter. The simulation studies on the collector slope angle for both Zanjan and this set-up were done before by the authors, and the results represent that zero angle of collector is the most appropriate option for the small-scale solar chimney power plants [41]. So, zero angle for collector is chosen. Tehran town has the geographical length and width of 51.4° and 35.7°, respectively [42]. Because of two main reasons including the resistance to heat transfer and transparency for detecting fluid flow with smoke, a 2 m polycarbonate pipe with diameter of 20 cm and thickness of 4 mm was utilized for making the chimney. This chimney is intrinsically the natural thermal engine and has an optimal surface–volume ratio which causes chimney become pressure tube with low friction loss. Polycarbonate sheets have a balance of