Energy 112 (2016) 200–207

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Development of analytical model for solar chimney power plant with and without water storage system

Young Jae Choi, Dong Hoon Kam, Yoon Won Park, Yong Hoon Jeong*

Department of Nuclear and Quantum Eng., Korea Advanced Institute of Science and Technology, 291 Daehak-ro, Yuseong-gu, Daejeon, 305-701, Republic of Korea

ARTICLE INFO

Article history:
Received 4 April 2016
Received in revised form
3 June 2016
Accepted 5 June 2016

Keywords:
Solar chimney
Large-scale analysis
Water storage system

ABSTRACT

In a solar chimney power plant (SCPP) system, heated air under the collector rises up through the updraft tower and produces electricity in the turbine generator. An analytical model for a solar chimney was developed to estimate the power output and temperature configuration of the collector. The analytical model was validated using experimental data from a prototype plant in Manzanares, Spain. A water storage system was established under the collector to conserve heat energy during the night. The power of a large-scale SCPP was evaluated according to parameters such as the chimney height, collector radius, chimney diameter and solar irradiation, among others. The power of the large-scale SCPP with and without the water storage system was assessed. The power variation throughout a 24-h period was analyzed according to the depth of the water storage system.

1. Introduction

The use of fossil fuels in coal-fired plants has caused significant climate changes such as global warming over the past several decades. As a result, glaciers have melted, and the sea water level has risen. To solve these problems, renewable energy sources such as wind energy and solar energy are currently emphasized. A solar chimney power plant using solar energy is considered as a promising alternative among various renewable energy sources. A solar chimney power plant is an electricity generation system that uses updraft air flow heated by solar energy. The solar chimney is composed of three components, i.e., the solar collector, updraft tower and power generators. A schematic diagram of a solar chimney is shown in Fig. 1. In this system, air under a transparent collector is heated, and the density difference of the air induces updraft air flow in the tower located at the center of the collector. When heated air under the collector rises up through the solar chimney, the turbine generator produces electricity at the bottom of the chimney. The SCPP would be an effective system in areas with considerable amounts of solar energy and in largely unused areas such as desert regions. Compared to conventional solar power generation, the SCPP system has several advantages, such as a very simple structure and low maintenance cost.

The first solar chimney design was developed by J. Schlaich, and a pilot plant prototype was built in Manzanares, Spain, in 1981. The 50-kW prototype operated and produced electricity for 8 years, showing the feasibility of a solar chimney power plant. An experimental evaluation of the prototype and the preliminary test results of the prototype plant were reported by Haff et al. [1,2]. These authors presented the basic principles of solar chimney power plants, such as the construction cost and large-scale plants. Bernardes et al. [3] developed an analytical and numerical model for a solar chimney power plant, and heat transfer under the collector was investigated using thermal analysis. A water storage system was established under the collector. Additionally, simulation calculations was compared with experimental results from the pilot plant in Manzanares. Pretorius et al. [4–6] evaluated a numerical model for the performance of a large-scale solar chimney power plant. A computer simulation program was used to solve the governing equation and heat transfer equation. A comprehensive analysis of the solar chimney was conducted under various situations. A preliminary study examining the influence of several factors was conducted using a mathematical model. Two comprehensive studies from the Pretorious and Bernardes papers on heat transfer in the collector were summarized by Bernardes et al. [7]. Their paper compared the comprehensive governing equation for the collector and chimney. Additionally, the

* Corresponding author.
E-mail addresses: youngjaechoi@kaist.ac.kr (Y.J. Choi), jeongyh@kaist.ac.kr (Y.H. Jeong).

http://dx.doi.org/10.1016/j.energy.2016.06.023
0360-5442/

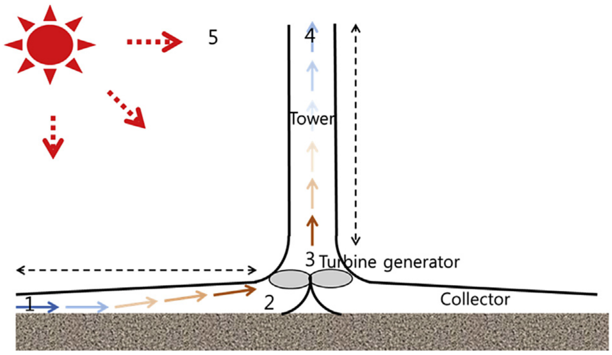

Fig. 1. Schematic diagram of an SCPP.

assumptions pertaining to the governing equations were compared with respect to continuity, momentum and the energy equation. The convective heat transfer schemes in the collector were compared under several situations. Zhou et al. [8] conducted a comprehensive review of solar chimney power plants, providing information on the description, physical process, experimental and theoretical study status, among others. The methods to improve the power output of an SCPP included the intermediate secondary roof and thermal storage system in the collecter and other components. Koonsrisuk et al. [9] developed a mathematical model of a solar chimney power plant and validated the result with an actual physical plant. They predicted the performance of a large-scale commercial solar chimney and found the optimum design for high power output. Guo et al. [10] predicted the annual performance of an SCPP in Sinkiang, China. The effect of the collector and chimney radii on the power output was estimated, and the potential annual power requirement of SCPPs in the Hami region was presented.

In this study, a new mathematical analysis model was developed considering realistic physical pressure drops throughout the whole SCPP system. This new analysis model was validated through comparison with the experimental data of a prototype plant in Manzanares, Spain. The pressure drop and mass flow rate were calculated through an iteration process using MATLAB. The final output power can be predicted from the pressure, density, temperate and pressure drop at each point. Additionally, the large-scale solar chimney was evaluated according to dimension such as the collector radius and chimney height, among others. To determine the electricity generated at night, an analysis of the water stored under the collected was conducted. The power output with the water storage system was predicted based on the change in depth under the collector.

2. Analytical model development

2.1. Assumptions

The analytical model is based on several assumptions: the ideal gas law, steady state, one-dimensional flow under the collector, and an adiabatic tower wall. Based on these assumptions, a thermal analysis of the collector was conducted. The heat source is solar irradiation during the day. The heated collector roof and the ground were assumed to transfer the heat to the air flow by convective heat transfer. The radiative heat emissions from the collector roof and the ground were also considered. The dimensions of the solar tower of the pilot plant in Manzanares, Spain, were used to validate our developed mathematical model in Table 1. The roof height of the collector was inclined toward the tower center. Thus, the inlet collector height was 1.2 m and the height increased linearly,

Table 1
Dimensions of the solar chimney power plant.

Tower height	194.6 m
Tower radius	5.08 m
Collector radius	122 m
Collector inlet height	1.2 m
Collector outlet height	2.5 m

resulting in an outlet collector height of 2.5 m.

Many researchers have analyzed the optimum values of pressure ratio. In calculation of turbine pressure drop, the ratio of the pressure drop across the turbine to the total driving pressure was assumed to 2/3. In this study, the pressure ratio across the turbine was optimized in large scaled power plant using our developed analytical model.

2.2. Thermal analysis of the collector

The collector consists of two parallel flat boards, upon which the roof is slightly inclined from the inlet to the chimney center. The temperature configuration of the collector was analyzed using a thermal equilibrium equation for each node of the roof, air and ground in specific controlled volume. We assumed that the ambient velocity over collector is 1 m/s to make convective heat transfer from roof to sky. The mass flow rate of the whole system was generally constant. The temperature increase of the air flowing through the collector was calculated by considering the heat transfer of the collector system. Thermal analysis with and without the water storage system was conducted.

2.2.1. Thermal analysis without water storage

The schematic diagram of heat transfer in the collector without the water storage system is shown in Fig. 2. The solar irradiation heats the collector roof and ground, and the heated roof and ground then transfer the heat to the air flowing in the collector. The heat transfer equation is as follows:

$$Roof: I_r + h_{R,g\to r}(T_g - T_r) = h_{C,r\to s}(T_r - T_s) + h_{C,r\to f}\left(T_r - T_f\right) + h_{R,r\to s}(T_r - T_s) \quad (1)$$

$$Air: \ h_{C,r\to f}\left(T_r - T_f\right) + h_{C,g\to f}\left(T_g - T_f\right) = \frac{\dot{m}c_p}{2\pi r}\frac{\Delta T_f}{\Delta r} \quad (2)$$

$$Ground: I_g = h_{C,g\to f}\left(T_g - T_f\right) + h_{Cd,g\to so}(T_g - T_{so}) + h_{R,g\to r}(T_g - T_r) \quad (3)$$

The left side of the equation refers to incoming heat from the surroundings, and the right side of the equation refers to heat been emitted to the surroundings. Equations (1)–(3) refer to the thermal

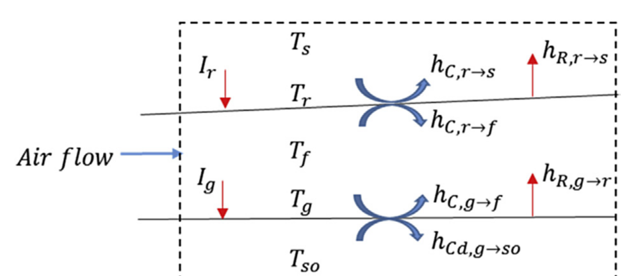

Fig. 2. Thermal analysis of the collector without water storage.