Sustainable Energy Technologies and Assessments 30 (2018) 59–67

Contents lists available at ScienceDirect

Sustainable Energy Technologies and Assessments

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

Original article

Mathematical evaluation of solar chimney power plant collector, integrated with external heat source for non-interrupted power generation

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ARTICLE INFO

Keywords:
Energy recovery
Hybrid energy system
Integrated solar collector
Solar chimney power plant
Thermal enhancement channels

ABSTRACT

One of the largest challenges in the use of solar energy for power generation is the interruption at night and during cloudy weather. This study proposed a new technique of integrating the solar chimney power plant with an external heat source. The integration can be achieved by installing “Thermal Enhancing Channels” inside the collector region between the canopy and the ground to enhance the kinetic energy of the air inside the collector, eventually allowing the plant to operate at night. The thermo-fluid dynamics of the proposed hybrid system were modeled mathematically to evaluate the performance of the proposed model. The analysis gave a good propaedeutic overview of solar chimney power plant integrated with an external heat source. The results showed that the temperature of the air inside the collector could be increased by the addition of thermal enhancing channels within the collector of the solar chimney. The increasing percentage of the temperature for the air inside the collector reached to 5.88% and for power generation 23.1% when the wall temperature of thermal enhancing channels is100°C and solar intensity 1000 W/m^2.

Introduction

The solar chimney power plant (SCPP) system presents an interesting option for the large-scale use of solar energy. This plant has three main components: collector (greenhouse), chimney and turbine. The system is capable of converting solar energy into thermal energy by the solar collector and this energy is converted to kinetic energy in the air. The increasing of kinetic energy for the air inside the collector is utilized to operate wind turbine inside the chimney which drives a generator to produce the electric power and that is the working principle of the SCPP. The (SCPP) has no influence on the environment and has low maintenance costs. This technique is efficient for generating electricity in a vast desert. In 1970, Professor Schlaich from Germany proposed the concept of the solar chimney. After that, the construction of a pilot plant began in Manzanares, Spain, which ran from 1982 to 1989. The system was simple and reliable, also the operations and maintenance costs were not high [1].

Many researchers analyzed the flow characteristics of the system and also some of them tried to improve and enhance the power generation or efficiency of plant, by proposed a mathematical model, numerical simulation or experimental research work. Most of the researchers employed mathematical model to study the parts of the plant or study the effect of any enhancement on the efficiency of the plant. In line with this, Ming et al. [2] established a mathematical model for the collector, chimney, and the energy storage layer, etc. They analyzed the air flow and the characteristics of heat transfer by performing a numerical simulation for SCPP.

Li et al. [3] proposed a comprehensive theoretical model to evaluate the performance of SCPP and verified the model with experimental data. They studied the effect of collector radius and chimney height on the plant's power and told that no limitation exists for chimney height except the construction and there was a limitation in collector radius for the attainable power. Guoliang et al. [4] established a mathematical model of flow and heat transfer for SCPP. The researchers analyzed the flow, power and energy losses of the plant; also they achieved numerical simulation to study the characteristics of the airflow, heat transfer with heat storage layer and power output. They showed in this study, the influence of solar irradiation and pressure drop across the turbine on the performance of the Manzanares plant. The results showed that energy losses increased with canopy collector area and mass flow rate through the chimney. Nizetic and Klarin [5] evaluated the pressure drop turbine factor by using a simplified analytical approach in SCPP. The researchers used Manzanares model as a case study and found that the optimal pressure drop ratio across the SCPP turbine varies from 0.8 to 0.9. Pretorius and Kroger [6] employed a theoretical model developed by Pretorius to make an evaluation of the performance of SCPP

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https://doi.org/10.1016/j.seta.2018.06.012
Received 29 December 2016; Received in revised form 26 September 2017; Accepted 28 June 2018

Nomenclature

A_c, A_g, $A_{channel}$	area of transparent cover, ground and flue channels respectively (m^2)
C_p	specific heat of air (J/kg K)
EHS	External heat source
g	gravitational constant
H_{ch}	height of the chimney (m)
$h_{con,c-air}$	coefficient of convective heat transfer from canopy to collector air ($W/m^2 K$)
$h_{con,g-air}$	coefficient of convective heat transfer from ground to collector air ($W/m^2 K$)
$h_{r,g-c}$	radiated heat transfer coefficient from the absorber plate to cover ($W/m^2 K$)
I	intensity of solar radiation (W/m^2)
k	Thermal conductivity (W/m.K)
$\dot{m}$	air mass flow rate (kg/s)
POE	Percentage of enhancement
TECh	Thermal Enhancing Channels
T_g, T_{air} and T_c	mean temperature of the ground, air and canopy, respectively (K)
T_{amb}	ambient temperature (K)
u_w	wind speed (m/s)
$V_{o,coll}$	Velocity of air at the exit of the collector (m/s)

Greek letters

ν	kinematic viscosity
α_{-c}	Absorptivity of the canopy
τ_{-c}	transitivity of the canopy
α_{-g}	absorptivity of the ground
σ	Stephan–Boltzmann constant
ε	emissivity of the canopy
μ	viscosity
β	Volume coefficient of expansion
ρ	density

and solved this model numerically. They studied the effect of three types of soil (Limestone, Sandstone soil and Granite-based model) on the performance of a large scale SCPP. Zhing et al. [7] developed a mathematical model to describe the flow and heat transfer of the air inside the collector and the chimney, to study the storage layer, and to describe the influence of the different storage layers on the power output with different solar radiation. Vieira et al. [8] presented a numerical simulation for solar chimney power plant to study the effect of geometric parameters on the power generation of solar chimney power plant (SCPP) by means of Constructional Design. The researchers used three degree of freedom to study as parameters by using the ratios for the plant main parts: collector, turbine, and chimney. In this study, the researchers noticed that there was a large and sensitive effect of the ground temperature over the available power and geometric effects.

Also, in the same line, many researchers focused on the solar chimney power plant main parts enhancement or modification by using different ways and proposed many models to improve the plant efficiency. The Solar Collector (SC) is considered as the major component of the plant because of being responsible for collection and heating of the air by absorbing solar radiation [9]. The improvement and enhancement of the collector is in two main parts, canopy and the ground. Bernardes reported that 50% of heat losses happened in the collector of SCPP [10]. These losses are thermal or heat losses at canopy, friction flow, and conduction ground losses. New collector concept with ribs containing their branching's introduces by Bonnelle [11] to reduce the turbulent friction losses of the air flow inside the collector. The proposed collector design contained a flow guide which forced the flow toward the chimney center instead of the circulation in the convention collector; these guides reduced the friction flow losses and heat losses inside the collector. Karimi et al. [12] investigated numerically different heat storage materials as alternative of the soil in SCPP. The researcher mentioned that use of water-stone storage media gave better stabilization of power generation in the plant and more efficient than the soil and water bags as a heat storage media. Huang et al. [13] studied and described details of the experimental process on the hybrid thermal storage material in the solar collector. In this study, two experimental modifications were tried on the thermal storage material in the collector, i.e. pebbles along with water tubes having a black surface. The results showed that the temperature difference between the inlet and outlet of the collector which changed gradually but collector efficiency was increased at first instance then reduced slightly as the volume flow rate increase using both the liquid and solid thermal storage materials to enhance the solar collector performance.

Some researchers reported that the power output of the SCPP is heavily dependent on the scale of the system and the chimney height [14]. Schlaich [15] investigated the chimney height and found that the increase in chimney diameter reduces the friction losses and the chimney height represent a major determinant of the chimney efficiency. The chimney shape and materials type also investigated by many researchers [16–18].

On the other hand, some researchers used an external heat source to enhance the collector and improve its efficiency. Azeemuddin et al. [19] proposed twenty-four-hour operation of SCPP model by using flue gases as an external heat source to enhance the Manzanares plant, the model has been simulated numerically by using ANSYS code and the results give a significant increase in the overall performance of the plant. Al-Kayiem et al. [20] studied the effect of flue gases of the thermal power plant to enhance the performance of the SCPP. He observed that the flue gases contain more than 50% of the fuel thermal energy. Chikere et al. [21] suggested a model enhanced heat transfer and the performance of the SCPP by using flue gas waste heat. The new model contains flue gas channels, absorber plates, flue gas exit chimney, and a main air exit chimney. All the above researchers and many others used different ways and models to enhance the (SCPP).

Remains the biggest challenge in using this type of plants is low-lying efficiency and low processing power sudden at night and on rainy or cloudy days.

The main objective of this research study is divided into two parts; first, introduce a proposed novel system to improve the performance of SCPP and to ensure the continuity of its work for 24 h a day. Second, this study establishes a mathematical model which is able to simulate the thermo-hydrodynamic effect of solar chimney power plant collector enhanced by an external heat source (EHS). It is proposed in this work, that EHS is a flue gas passing through metal channels. The channels have the collector cross-section area for the gas flow and an outside configuration spans the plane between the ground and the canopy. The mathematical model is established for the system collector using the conservation equations of mass and heat; it was converted to a computer program and solved in MATLAB environment by matrix inversion technique.

Method of proposed hybrid SCPP

In case of no sun due to the cloud or at night, the SCPP is not producing any power; therefore its efficiency is almost zero. To overcome this problem, hybrid solar chimney power plant is proposed (Fig. 1) and this model could be a solution for power generation for long time because it would not only increase the power plant efficiency during the day, rather it would provide power even during no sun or at night. The technique in this model utilizes the flue gases or exhaust