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Numerical investigation and optimization of the solar chimney collector performance and power density

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ABSTRACT

Solar energy is an important renewable energy resource for many Arabic countries. The solar chimney is considered as one of the feasible solar energy conversion techniques. The present work introduces a detailed numerical investigation and optimization of the solar chimney power density under different operating conditions. The finite volume CFD code ANSYS Fluent was implemented in the present work. The solar irradiance was modeled using the discrete ordinates (DO) radiation model. The present numerical simulation shows that the chimney collector has an optimum radius that strongly depends on the operating solar irradiance. Moreover, the turbine pressure drop significantly affects the collector performance. Increasing the turbine pressure drop increases the value of the optimum collector radius. Equations for estimating the optimum collector radius, efficiency, and power density were obtained and presented. The present investigation shows an optimum collector radius of 17 times the chimney radius at an irradiance of 500 W/m^2 using a turbine with a pressure drop of 160 Pa. An aero-economical optimization of the collector radius is recommended for future work.

1. Introduction

For many centuries, humans have had many attempts to use natural energy resources such as the wind and solar energy to take their advantage in their daily life. Global warming, pollution, and the limited amounts of the traditional energy resources have directed the scientists and researchers to search for new energy resources. These new resources should be renewable, eco-friendly, and convertible into other energy forms in order to be useful for the human life; such as the conversion of the solar energy into electricity or thermal energy. Solar chimney power plant (SCPP) is a system which produces electricity by heating and drafting the air through an air turbine mounted inside a chimney. It could be a feasible solution in the regions having high amounts of solar radiation like the Middle East. In 1903, Isidoro Cabanyes presented a description of the first SCPP model [1]. Through 1926, the French Academy of Sciences received a proposal offered by Prof. Bernard Dubos to construct an SCPP in North Africa [2]. However, the first small-scale experimental prototype of the solar chimney was designed and constructed in 1981 with a peak output of 50 kW in Manzanares, Ciudad Real, Spain [3].

Many researchers have experimentally and theoretically investigated the solar chimney performance. Kasaeian et al. [4] conducted an experimental investigation of the climatic effects on the efficiency of a pilot solar chimney power plant. Li et al. [5] introduced a simplified theoretical model that investigates the effect of the collector radius and chimney height on the power output of a solar chimney power plant. They reported that the variation of the output power was not significant for a collector radius greater than 400 m. Hu et al. [6] studied the effect of guide wall height and geometry on the power output of a solar chimney power plant using a small-scale experimental prototype. Nasirivatan et al. [7] conducted an experimental study to enhance the convective heat transfer coefficient of the solar chimney absorber.

Researchers have also implemented the numerical methods and Computational Fluid Dynamics (CFD) in the study of the solar chimney power plants. Guo et al. [8] presented a theoretical model to study the performance of a solar chimney power plant with and without heat storage. They also evaluated the output power using different types of soils. Chergui et al. [9] investigated the natural laminar convection heat transfer inside the solar chimney using the finite volume technique. Dos Santos Bernardes and von Backström [10] introduced a numerical simulation of two schemes for the control of the solar chimney output power. Hamdan [11] presented an analysis of a solar chimney power plant for the Arabian Gulf region. Hurtado et al. [12] evaluated the influence of the soil thermal inertia on the performance of a solar chimney power plant. Hamdan [13] presented a mathematical thermal

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Nomenclature

A	area (m^2)
C_p	specific heat at constant pressure (J/kg K)
CPD	collector power density (W/m^2)
$\dot{E}$	incident solar power (W)
g	gravitational acceleration (m/s^2)
H	chimney height (m)
h	convective heat transfer coefficient ($W/m^2{\cdot}K$)
k	thermal conductivity (W/m·K)
$\dot{m}$	mass flow rate (kg/s)
p	pressure (Pa)
$\dot{Q}_{con}$	convection heat transfer (W)
q_s''	solar irradiance (W/m^2)
r	radius (m)
R	collector radius (m)
T	temperature (K)
$\dot{V}$	volume flow rate (m^3/s)
v	velocity (m/s)
β	thermal expansion coefficient (1/K)
$\Delta\dot{E}$	power transferred to the air (W)
Δp_T	turbine pressure drop (Pa)
η	efficiency (%)
ρ	density (kg/m^3)

Subscripts

amb	ambient
ch	chimney
col	collector
in	chimney inlet
opt	optimum
out	chimney outlet
s	collector surface
T	turbine

Superscript

*	normalized

model for the analysis of solar chimney power plant using Bernoulli's equation with buoyancy effect and ideal gas equation at steady state conditions. Koonsrisuk and Chitsomboon [14] implemented iterative techniques to find out a solution for the mathematical model of solar chimney power plant. Koonsrisuk [15] introduced a performance comparison between the conventional solar chimney power plants and the sloped solar chimney power plants using a second law analysis. Okoye and Atikol [16] studied the possibility and economic feasibility for setting up a solar chimney power plant in North Cyprus. They used a mathematical model to estimate the plant size, collector diameter, and chimney height. Ming et al. [17] introduced a one-dimensional compressible flow and heat transfer mathematical model for a solar chimney that is capable of producing power while extracting water from the air. Xu et al. [18] presented a numerical simulation and mathematical model of the airflow, heat transfer and power output characteristics of a solar chimney power plant. Sangi et al. [19] introduced a detailed modeling and numerical simulation of solar chimney power plants based on the Navier–Stokes and continuity equations. Koonsrisuk [20] developed a mathematical model for the performance prediction of sloped solar chimney power plants based on continuity, momentum, energy, and state equations. Koonsrisuk and Chitsomboon [21] investigated the changes in static pressure, mass flow rate and output power caused by the variations of flow area using CFD modeling. Cao et al. [22] utilized the TRNSYS software to identify the main meteorological parameters that affect the SCPP performance. Guo et al. [23] presented a theoretical analysis and three-dimensional numerical simulation to find out the optimal turbine pressure drop ratio in a solar chimney power plant. Guo et al. [24] conducted a three-dimensional numerical simulation of a solar chimney power plant that implements the radiation model provided by the commercial CFD code ANSYS Fluent. Gholamalizadeh and Kim [25] presented a three-dimensional CFD analysis for the simulation of the greenhouse effect in solar chimney power plants using a two-band radiation model and the RNG k-ε turbulence model. Patel et al. [26] conducted a geometry optimization of the major components of the solar chimney power plant with tower heights of 8 m and 10 m using CFD. Guo et al. [27] investigated the solar chimney optimum heat storage system design parameters like the thickness, specific heat capacity, and thermal conductivity. Nia and Ghazikhani [28] proposed a passive flow control to improve the flow field and heat transfer characteristics using a two-dimensional axisymmetric incompressible CFD. Guo et al. [29] presented a three-dimensional numerical model of a solar chimney which includes the radiation model, solar load model, and a real turbine. Guo et al. [30] introduced an analytical method and three-dimensional numerical simulations to find the optimal turbine pressure drop ratio. Lal et al. [31] implemented a mathematical and CFD model to calculate the energy and exergy efficiencies. Choi et al. [32] developed an analytical model for the solar chimney to determine the output power and temperature configuration of the collector with and without water heat storage system. Semai et al. [33] performed a numerical simulation to analyze the effect of the collector cover slope on the performance of solar chimney power plant using two types of storage systems. Mehrpooya et al. [34] presented a case study for a solar chimney power plant using the climate data of Tehran. Gholamalizadeh and Kim [35] performed a three-dimensional CFD simulation using the k-ε turbulence model and a non-gray radiation model to show the effect of collector height on the performance of the solar chimney. Shirvan et al. [36] conducted a two-dimensional axisymmetric numerical simulation and sensitivity analysis for a solar chimney in Zanjan, Iran. They also tested the effect of the entrance gap, chimney diameter, chimney height and inclination of collector roof to get the most effective design parameters.

Most of the previous investigations have not considered the power density of solar chimney power plants. Therefore, the objective of the present research work is to obtain the optimum collector radius that maximizes the power density of the solar chimney power plants under different geometric and operating conditions. This objective was achieved by firstly conducting an accurate axisymmetric numerical simulation of a typical solar chimney using a radiation model and taking the heat storage in the soil into considerations. After that, the collector radius and the chimney height were varied and the power density of the chimney was optimized. The collector shape also influences the energy conversion within the collector. The investigation and optimization of the collector shape will be considered in a future work.

2. Solar chimney system description

Solar chimneys have different types and sizes while having the same main components. These main components include a collector, air turbine, chimney, and an energy storage medium as shown in Fig. 1. The collector is a circular area located on the ground and roofed by a thin sheet of plastic or glass. The transparent cover transmits the shorter wavelength solar radiation and blocks the longer wavelength solar radiation that emitted from the ground. Accordingly, the ground under the collector is an important element in the solar chimney for two reasons. First, the short wavelength solar radiation heats the ground up and the heated ground transfers heat to the air inside the collector.