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Research Paper

Experimental study on an indoor scale solar chimney setup in an artificial environment simulation laboratory

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HIGHLIGHTS

- An artificial environment simulation laboratory was built.
- An indoor scale solar chimney setup was constructed in the AESL.
- The upper limitations of collector radius and chimney height were discussed.
- Collector efficiency increases non-linearly with solar radiation intensity.

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ABSTRACT

An artificial environment simulation laboratory (AESL) was built and successfully applied to the experimental study of a solar chimney setup for the first time. A solar simulator and a temperature control system are included in the laboratory to achieve active control of environmental parameters. An indoor scale solar chimney setup with a collector diameter of 1.22 m and chimney height of 1 m was constructed in the testing area of the AESL. The airflow temperature and updraft velocity were measured for the solar chimney setup with varying radiation intensities and chimney heights. The measured data were used to validate a thermal model for the collector. The thermal characteristics of the solar collector were investigated through the temperature field in the collector. The upper limitations on the collector radius and chimney height were discussed based on experimental results. The experimental work on the basic solar chimney setup performance helped in understanding the thermodynamic characteristics of the solar chimney power plant (SCPP), thereby serving as the basis for the design of large-scale commercial SCPPs.

1. Introduction

Several problems, such as depletion of fossil fuel reserves, climate change and other environmental concerns, are associated with continued use of fossil fuels. An environmentally friendly renewable energy resource is the solution to growing energy challenges [1]. A solar chimney power plant (SCPP) is an attractive renewable technology concept for large-scale utilization of solar energy. Fig. 1 shows that the solar collector comprises a translucent cover to admit short wavelength solar radiation and retain long wavelength radiation that is emitted by the heated ground. Buoyancy-driven flow that is generated in the chimney is used to drive pressure-staged turbines installed at the chimney base for electric power generation. The SCPP system does not depend on cooling water, thereby making it a promising development in vast desert regions that lack water resources but are abundant in solar energy. Many studies worldwide have reported valuable feasibility analysis on the SCPP because of its considerable potential applications [2,3]. For example, Guo et al. [4] made an annual performance analysis for a 100 MW SCPP system in Sinkiang, China. The results showed that a peak power generation of 72.16 TJ was achieved in June, and the annual total power generation is about 522.0 TJ.

A 50 kW prototype with an approximately 200 m high solar chimney was jointly constructed and operated in Manzanares, Spain, by the German government and a Spanish utility company in 1982 [5]. Haaf [6] and Schlaich et al. [7] reported the measured data of the Spanish prototype, which have been used to validate mathematical models [8–10]. The Spanish prototype operated for seven years and conclusively proved the feasibility and reliability of the SCPP technology. Several solar chimney pilots have been constructed and tested around the world after the construction of the Spanish prototype. Pasumarthi and Sherif [11] built a

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Nomenclature

$C_{p,a}$	specific heat capacity (J kg^{-1} K^{-1})
g	gravitational acceleration (m s^{-2})
h	heat transfer coefficient (W m^{-2} K^{-1})
H	height (m)
I	radiation intensity (W m^{-2})
$\dot{m}$	mass flow rate (kg s^{-1})
q	heat flux (W m^{-2})
r	radius (m)
S	absorbed solar radiation (W m^{-2})
T	temperature (K)
z	level from the ground (m)

Greek symbols

β	thermal expansion coefficient (K^{-1})
Δp	pressure drop or loss (Pa)
ΔT	air temperature rise (K)
ρ	density of air (kg m^{-3})
η	efficiency

Subscripts

a	ambient
c	collector
ch	chimney
c, a	collector to ambient
c, s	collector to sky
f	airflow
f, c	airflow to collector
g	ground surface
g, c	ground surface to collector
g, f	ground surface to airflow
in	inside the chimney
out	chimney out
∞	ambient

demonstration model to assess the viability of the solar chimney concept. The experimental performances of three types of collectors were compared to examine their enhancement modifications on the collector. Zhou et al. [12] built a pilot experimental setup to examine the effect of time of day on temperature field and found that air temperature inversion appears in the latter chimney after sunrise. Motsamai et al. [13] constructed a solar chimney pilot in Botswana, in which a wind turbine was installed to rotate a small DC generator. Experimental results indicated that ambient wind velocity influences system performance by increasing updraft velocity in the chimney. Al-Dabbas [14] built the first solar chimney pilot in Jordan to evaluate such technology in the Mutah area. He found that ambient temperature plays a minor role in affecting power generation. A similar conclusion was mentioned in other numerical studies when discussing the unsteady simulation of SCPP [15,16]. Kasaeian et al. [17] built a solar chimney pilot to investigate climatic effects on system efficiency. Later, the same group built another experimental setup to investigate the effects of dimensions, heat storage materials, and collector design parameters on system performance [18,19]. Lal et al. [20] performed experimental studies on a laboratory-type solar chimney to investigate its thermal performance. The experimental data were compared with simulation results to validate the proposed numerical model. The main structural parameters of aforementioned small experimental SCPP setups are presented in Table 1.

The experimental studies were all conducted in a natural outdoor environment. The environmental factors, which are complicated and constantly changing, affected SCPP performance in vastly different ways. The outdoor experimental study on the solar chimney setup is usually time consuming because of the uncontrollability of environmental factors, such as solar radiation intensity, ambient temperature, and humidity. Moreover, the uncertainty of the ambient parameters makes accurately determining the effects of a single parameter on system performance difficult. One solution to this problem is the application of artificial environment simulation technology. One of the most famous

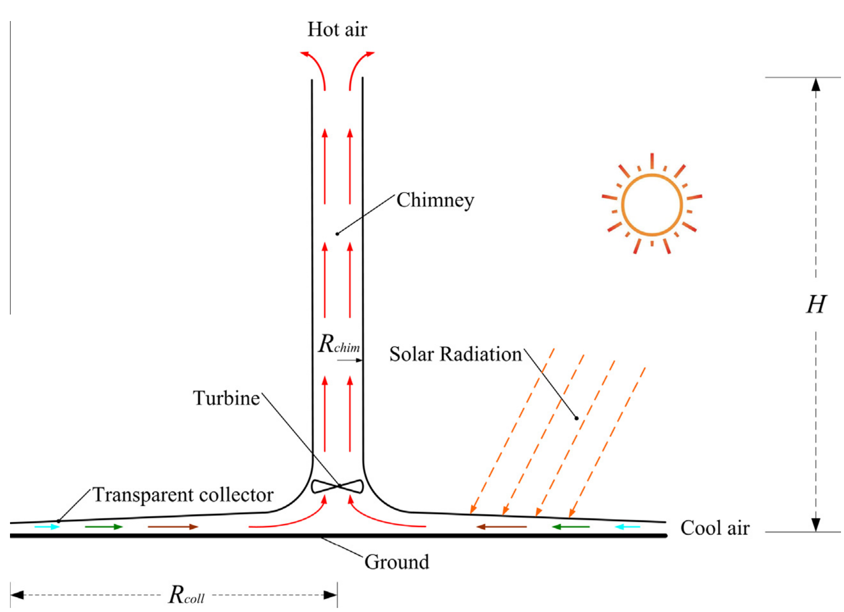

Fig. 1. Schematic diagram of solar chimney power plant.