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Power generation quality analysis and geometric optimization for solar chimney power plants

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ABSTRACT

Solar chimney power plant (SCPP) is one of the promising power generation approaches for future applications of solar energy. An unsteady comprehensive mechanism model and a streamlined unsteady mechanism model of SCPPs are derived to analyze the energy conversion and transmission of the system in this paper. The streamlined unsteady mechanism model with concise expressions clearly indicates the correlations among the power output and geometric parameters. Both of the two models are verified by the experimental data from the Spain Manzanares demonstration plant. Moreover, a power quality factor is defined to evaluate the power generation quality of SCPPs both from the points of generation efficiency and power stability. The suitability of the geometric optimization of SCPPs based on the streamlined unsteady mechanism model is finally verified by an example. The coupling optimization results show that there are a strong positive correlation between the chimney height and the power quality factor, as well as a negative correlation between the solar collector radius and the power quality factor. Furthermore, the optimal solar collector height is a quadratic function relation with the chimney diameter, while the optimal thickness of the heat storage layer is little associated with other geometric parameters.

1. Introduction

The solar chimney power plant (SCPP) is a renewable energy device which has advantages of simple technology, low operation cost and continuous generation over other solar power plants (Zhou and Xu, 2016). A typical SCPP is generally composed of a circular solar collector, a chimney at the center of the collector, turbine generators at the bottom of the chimney, and the heat storage layer, as shown in Fig. 1.

During the day, solar radiation penetrates the transparent collector to warm the heat storage layer. Some heat energy is stored in the heat storage layer, while the other heat energy is transferred to the airflow on the heat storage layer surface by convection. The warm airflow accelerates along the solar collector to the bottom of the chimney, drives the turbine generators to generate electricity, and finally leaves the system from the top of the chimney. At the same time, the ambient air continuously enters the system from the edge of the solar collector, thereby forms the continuous air current. At night or on cloudy days, the heat energy is released from the heat storage layer, which makes the system continuously produce electricity.

The power generation principle and manufacturing technology of SCPPs were proposed by Schlaich (Pasumarthi and Sherif, 1998a, 1998b). The first SCPP prototype plant was built in Manzanares, Spain, and operated between 1982 and 1989 with approximately 50 kW of electrical power output, which demonstrated the technology feasibility of SCPPs (Haaf et al., 1983; Haaf, 1984; Schlaich, 1995). However, due to the huge investement, large occupied area, and poor efficiency, SCPPs has not yet been commercialized until now (Zhou and Xu, 2016).

In recent years, numerous researches have been conducted to study the performance of SCPPs. It was found that the turbine pressure drop ratio, the air velocity at chimney inlet, the chimney friction, as well as meteorological conditions, including solar irradiation, the sunlight zenith angle, the ambient temperature, the temperature lapse rate, the nocturnal temperature inversion, the ambient crosswind and so on, affect the power output of the plant (Gannon and von Backström, 2000; Bernardes et al., 2003; Pretorius and Kröger, 2006a, 2006b, 2009; Nizetic and Klarin, 2010; Ming et al., 2012; Guo et al., 2013, 2015; Hamdan, 2013; Dehghani and Mohammadi, 2014).

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Nomenclature

Abbreviation

A	area (m^2)
c	specific heat capacity (J kg^{-1} K^{-1})
D	diameter (m)
f	friction factor
F	power generation fluctuation
Fo	Fourier coefficients
G	solar radiation intensity (W m^{-2})
h	heat transfer coefficient (W m^{-1} K^{-1})
H	height (m)
k	turbine pressure ratio
m	mass flow rate (kg s^{-1})
P	power output (kW)
Pr	Prandtl number
p	Pressure (Pa)
q	heat transfer intensity (W m^{-2})
QF	power quality factor
R	radius (m)
T	temperature (K)
v	velocity (m s^{-1})

Acronym

SCPP	solar chimney power plant
SUMM	streamlined unsteady mechanism model
UCMM	unsteady comprehensive mechanism model

Greek symbols

α	absorption rate
δ	thickness (m)
ε	emissivity
η	efficiency
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
γ	reflectivity
σ	Boltzmann constant
τ	transmissivity
ν	kinematic viscosity (N s m^{-2})
Δ	difference

Subscript

a	air
am	ambient air
ch	chimney
col	solar collector
dew	dew point
f	friction
in	inlet
out	outlet
s	heat storage layer
sf	suction force
t	time
te	turbine electricity generation performance
tm	turbine machinery performance

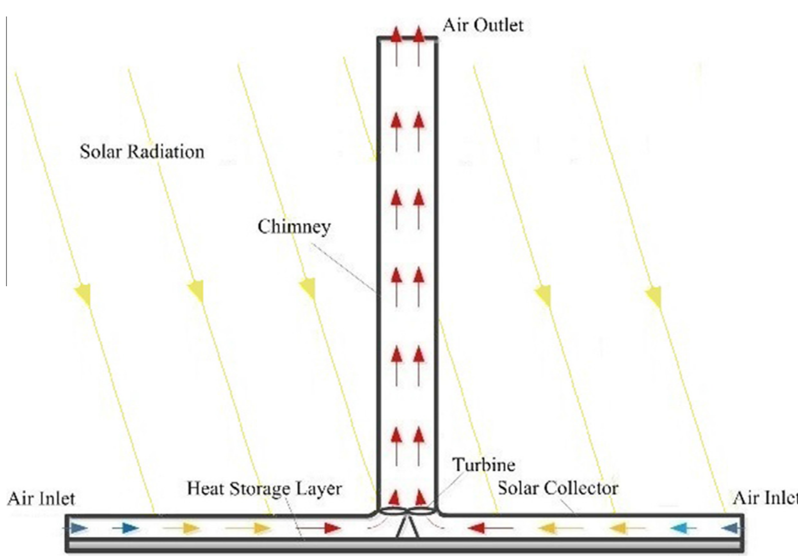

Fig. 1. Schematic overview of a typical solar chimney power plant.

Moreover, it has been verified that geometric parameters significantly impact the performance of SCPPs. Generally, the power output and efficiency increase with its dimension and the energy production cost reduces (Mullett, 1987; Schlaich et al., 2005). And the height and diameter of the chimney, the collector radius are the essential variables for solar chimney design (Zhou et al., 2007, 2009; Maia et al., 2009; Hamdan, 2013). Koonsrisuk et al. (2010) evaluated the ratio of height to radius for the maximum mass flow rate of the plant. In the meanwhile, collector roof shape also impacts the power output of SCPPs and the proper collector roof shape can maximize the power output (Pretorius and Kröger, 2007; Bernardes, 2010; Cottam et al., 2016). Patel et al. (2014) found that the collector inlet opening, the collector outlet height, the collector outlet diameter, the chimney inlet diameter, and the divergence angle of the chimney, significantly influence the overall performance of SCPPs. It was shown that plant power production is a function of the collector roof shape and inlet height (Pretorius and Kröger, 2006b). The SCPP with proper sloping