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Numerical analysis of seawater desalination based on a solar chimney power plant

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HIGHLIGHTS

- Seawater droplets are sprayed for evaporation at the chimney inlet.
- 3D model was developed for the air cooling and condensation inside the chimney.
- The condensation level can be greatly reduced by the humidification.
- The humidification is conductive to improving the system desalination efficiency.

ARTICLE INFO

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ABSTRACT

In this paper, the desalination performance of a plant variant with the same size as the Manzanares pilot model was numerically investigated. A three-dimensional compressible flow and heat transfer model has been developed, describing the air cooling process along the chimney and the associated condensation. In this plant variant, instead of installing the turbine, water droplets were sprayed for evaporation at the bottom of the chimney, and thus airflow was subjected to humidification. Results show that with increased mass fraction of water in the air, the influence of the microclimate on the local environment will also increase. The evaporation of the droplets improves the relative humidity of the air within the chimney, and the condensation level can thus be greatly reduced. Moreover, the freshwater output increases with increasing amount of water sprayed, which is beneficial for the improvement of the desalination efficiency of the system.

1. Introduction

1.1. Background

The solar chimney power plant system (SCPPS) is a solar thermal application system to achieve output power, which has been verified and rapidly developed in recent years. In general, the system consists of four main components: a chimney, a collector, a thermal storage layer, and power conversion units (e.g. turbine generators). The main role of the collector is to harvest solar radiation to heat the air below. When the air density within the system is less than that of the ambient air at the same height, the system will produce a natural convection caused by buoyancy. Both the potential energy of the air and its thermal energy are converted into kinetic energy. The accumulated buoyancy causes a large pressure difference between the system and the ambient air. Because the chimney is erected in the middle of the collector, the heated air can rise through the chimney at a high speed. Turbine generators are located either at the bottom of the chimney or at the outlet of the collector (where there is a large pressure drop), thus converting the kinetic energy into electrical energy. The thermal storage layer enables electricity production after sunset.

1.2. Literature review

The idea of utilizing solar chimney technology to generate electricity was introduced by Professor Jörg Schlaich in the 1970s. In 1982, he built the world's first solar chimney pilot plant in Manzanares, Spain. The chimney had a height of 194.6 m, a diameter of 10.8 m, and a collector radius of 122 m. During the seven-year operation of the plant, it ran more than 95% of the expected time [1,2]. However, in 1986–1988 the annual

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Nomenclature

Ra	Rayleigh number
c_p	specific heat capacity [J/(K kg)]
L	characteristic length [m]
T	temperature [K]
u	velocity [m/s]
g	gravitational acceleration, 9.8 [m/s^2]
t	time [s]
S_m	mass source term [kg/(s m^3)]
S_F	momentum source term [N/m^3]
$coeff$	condensation coefficient
R_g	ideal gas constant [J/(kg K)]
R_s	water vapor gas constant [J/(kg K)]
Q_d	the amount of spray droplets [kg/s]
Q_{cons}	the condensed water [kg/s]
η_{cons}	condensation efficiency
p	pressure [Pa]
E	instantaneous energy inside the control volume [J]
k_{eff}	the effective conductivity [W/(m K)]
J	the diffusion flux of species
S_h	the heat of chemical reaction or any other volumetric heat sources [W/m^3]
h	sensible enthalpy [m/s^2]
Y	mass fraction of species
k	turbulence kinetic energy [J/kg]
G_k	the generation of turbulence kinetic energy due to mean velocity gradients [J]
G_b	the generation of turbulence kinetic energy due to buoyancy [J]
$C_{1\varepsilon}$, $C_{2\varepsilon}$, $C_{3\varepsilon}$	constants for turbulent model
S_{ct}	turbulent Schmidt number
S_{H2O}	water vapor added to or removed from the air [kg/(s m^2)]
D_{H2O}	diffusion coefficient of water vapor into air [m^2/s]
v	local air velocity [m/s]
q	the amount of injected water [kg/s]
h	convective heat transfer coefficient [W/(m^2 K)]
RH	relative humidity [%]

Greek symbols

Δ	difference or increase
α	thermal diffusivity [m^2/s]
β	thermal expansion coefficient [1/K]
ρ	air density [kg/m^3]
γ	latent heat of condensation [J/kg]
ε	turbulence kinetic energy dissipation rate [W/kg]
μ	dynamic viscosity [kg/(m s)]
μ_t	turbulent dynamic viscosity coefficient [kg/(m s)]
ν	kinematic viscosity [m^2/s]
σ_k	turbulent Prandtl number for k
σ_ε	turbulent Prandtl number for ε
τ	stress tensor [N/m^2]
Γ	diffusion coefficient
ϕ	scalar

Subscripts

i,j	any directions of x, y and z

average crude oil prices were nearly $15 nominal ($32 inflation adjusted price), as compared to $37 ($109 inflation adjusted) of the prices in 1980 [3], which resulted in reduced funding for research on solar energy and lack of maintenance of the guyed chimney, which collapsed in 1989 during a strong storm. Since then, the theoretical study of solar chimneys has attracted worldwide attention among researchers. Haaf et al. [1,2] provided experimental results and a scientific description of a solar chimney pilot plant. Zhou et al. [4,5] made a comprehensive overview of the scientific literature on solar chimney test power plants.

However, an unavoidable problem is that the overall efficiency of the SCPPS is relatively low, with nearly 3% in theory per 1 km height of chimney due to the Carnot cycle efficiency, but more or less only 1% can be achieved in reality due to frictions losses and components efficiency [6]. The overall efficiency of the SCPPS is affected by sunlight energy collection efficiency of the greenhouse, the ascending airflow efficiency of the chimney, the thermo-mechanical efficiency of the turbine, and the mechanical power of the generator [7]. Furthermore, the chimney plays an important role in improving the overall efficiency of the SCPPS: the higher the chimney, the higher the overall efficiency. The construction of the world's first large-scale SCPPS of up to 1000 m was planned to start in Mildura, Australia in 2002, with the support and significant attention of the federal government; the chief architect of this project was Professor Schlaich [8]. Pretorius and Backström [9,10] proposed the idea of building a SCPPS with a chimney height of 1500 m, and they also provided detailed calculations and structural designs. However, for the construction of such a high chimney, the economic costs and technical problems are formidable.

Encouragingly, researchers found the output performance of the SCPPS to be closely related to the ambient and operation conditions and structural dimensions, thus some optimization measures can help to increase the overall output power of the system.

Based on the establishment of a comprehensive mathematical model, a research group led by Prof. Sherif [11,12] analyzed the effects of parameters such as environmental conditions and structural dimensions on the temperature and output power of SCPPS. In addition, they built three different types of pilot plants in Florida, taking into account the chimney shape, the collector structure, and the performance of the thermal storage layer. Ming et al. [13] evaluated the performance of SCPPS via theoretical analysis and numerical validation. They used numerical models to study the effects of strong ambient crosswind [14] and chimney shape [15] on the heat transfer, air flow, and output power of SCPPS. Bernardes et al. [16] evaluated the effects of various environmental conditions and structural dimensions on the output power of SCPPS by establishing a numerical model. The results showed that the chimney height, the pressure drop factor of the turbine, the diameter of the chimney, and the optical properties of the collector were all important parameters that need to be considered for designing the SCPPS. Nizetic et al. [17] developed an analytical approach based on a simplified thermodynamic analysis of the overall SCPPS cycle, the optimum factors of the turbine pressure drop, which are important for the output power of SCPPS were investigated. Kratzig et al. [18] simulated the physical process of the SCPPS, demonstrated the efficiency of the system, and demonstrated its applicability in arid regions through two SCPPS optimization cases. Furthermore, they built a mathematical model to analyze the thermal-fluid mechanical processes within a SCPPS and evaluated the performance of the power generation system using output power as the indicator [7]. Shirvan et al. [19] investigated the effects of various parameters on the maximum potential power output of the SCPPS numerically, and their results indicated that the potential maximum power output increases with both chimney diameter and height, and decreases with increasing entrance gap of the collector. Patel et al. [20] studied the effect of geometric parameters on optimizing the structure of SCPPS. Maia et al. [21,22] established a numerical model of the internal turbulence of a solar chimney to assess the effect of geometric parameters and manipulated variables on fluid flow. The results showed that the height and diameter of the chimney

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