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A two-dimensional simulation method of the solar chimney power plant with a new radiation model for the collector

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ABSTRACT

A two-dimensional axisymmetric CFD method is proposed for the solar chimney power plant (SCPP), which includes a solar radiation model within the collector, an energy storage model, an air flow and heat transfer model, and a turbine model. Numerical simulation is conducted for the Manzanares pilot plant. Different solar radiation modes in the collector and simulation methods are compared and discussed. Results show that the present two-dimensional method obtains consistent results with the three-dimensional method in the literature and experiment data, validating the feasibility of the proposed two-parallel-plate model for the radiation heat transfer within the collector.

1. Introduction

A solar chimney power plant (SCPP) mainly consists of a solar collector, a chimney and a turbine as shown in Fig. 1. The world's first SCPP was built in Manzanares, Spain, in 1981 and ran successfully seven years. The SCPP has no pollution to the environment and operates without auxiliary energy. These advantages have been drawing an ever increasing research attention, especially in recent years in the context of energy crisis and environment deterioration.

Since Haaf et al. [1,2] presented the principle and constructing of the pilot plant in Manzanares and later described the preliminary test results in 1984, a large amount of studies, including experimental, analytical and numerical have been reported. Some experimental prototypes have been presented in [3–8]. Experimental model study can provide test data which are useful for further understanding the physical process and can be used for validation of numerical models. However, in some sense it is prohibited because of the large consumptions in human resource, money and time. Early in the nineties of the last century, a thermal equilibrium method on the basis of the first law of thermodynamics was presented to analyze the performance of the SCPP, coupled with walls and thermal updraft air thermal equilibrium equations [9]. Since then several studies [10–14] developed different theoretical analyses and mathematical models to predict the efficiency, outlet air velocity and power output for the SCPP. Analytical method is simple and can provide a quick result such as system efficiency, but often is limited by its assumptions and cannot provide the details of physical process in the entire system. In the recent ten years, many studies used computational fluid dynamics (CFD) methods to simulate the flow and heat transfer in the SCPP and predict the output power on the basis of solving coupled mass, momentum and energy equations. Post-processing of simulation data can visually describe the flow and temperature of the SCPP in detail. Pastohr et al. [15] conducted a 2D steady numerical simulation for the Manzanares pilot plant by commercial software Fluent. After then, many papers proceeded to simulate the SCPP by adopting software Fluent.

The SCPP system is a multi-physics coupling system. The entire simulation model of the SCPP can be divided into four sub-models: the solar radiation model, the energy storage model, the air flow and heat transfer model, and the turbine model. In previous studies, solid model [15], porous model [16] and phase change model [17] have been proposed for the energy storage simulation. The air flow and heat transfer in a SCPP is a typical incompressible convective heat transfer induced by buoyancy force. This process can be simulated by many available commercial software, and Fluent is widely adopted. What's more Boussinesq approximation is always used to consider the change of air density with temperature [16,18,19,20,21], because temperature difference in the SCPP is small. For the turbine simulation, at present most papers adopt a pressure jump model in Fluent [19,21,22]. The major differences of the related papers adopted Fluent is the radiation model.

In the previous studies, there are three different modes taking solar radiation into consideration. The first mode sets the solar radiation as the boundary conditions, say, a heat source in a 0.1 mm-thickness ground surface, and a certain temperature or heat flux profile on the

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Nomenclature

A	area (m^2)
c_p	specific capacity ($J\ kg^{-1}\ K^{-1}$)
E	energy (J)
h	convection heat transfer ($W\ m^{-2}\ K^{-1}$)
I	solar radiation ($W\ m^{-2}$)
J	effective radiation ($W\ m^{-2}$)
m	mass flus ($kg\ s^{-1}$)
P	power (W)
P_{gage}	gage pressure (Pa)
Q	volumetric heat source ($W\ m^{-3}$)
Q_v	volume flow rate ($m^3\ s^{-1}$)
q	heat flux ($W\ m^{-2}$)
R	radius (m)
Ra	Rayleigh number (−)
T	temperature (K)
T_{sky}	equivalent temperature of the sky (K)

Greek symbols

α	absorptivity (−)
ε	emissivity (−)
λ	wave length
ρ	density ($kg\ m^{-3}$)
σ	Stefan-Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
μ	dynamic viscosity ($N\ s\ m^{-2}$)
τ	transmittance (−)
Δ	difference (−)
δ	thickness (m)

Subscripts

a	ambient
b	the bottom of the collector
c	collector
t	the top of the collector/turbine

ground surface. There are two ways for implementing this mode. The first method of this mode [15,23,24] is the simplest which does not take the collector canopy into consideration and takes 0.1 mm thin layer of the ground surface absorbing all the solar radiation (Fig. 2a). The second method of this mode [18,25] simply considers the collector canopy absorption and transmission of solar short-wave radiation (named as τ-α model, Fig. 2b). It can be seen that the two methods do not consider the greenhouse effect of the collector. The 2nd mode was adopted in Koonsrisuk and Chitsomboon's study [26], where solar energy is treated as volume heat source of air within the airflow in the collector. It should be noted that according to heat transfer theory [27,28] air is a transparent medium and does not participate radiation heat transfer. Thus this mode might be simple but conceptually incorrect. The 3rd mode applies the solar ray tracing model and the DO radiation model in Fluent by Guo et al. [19] and Gholamlizadeh and Kim [22]. Their results both show a decline on the updraft velocity and the whole output power, and are closer to the measured data compared with relative previous studies. Compared with former two modes, Mode 3 is more reasonable and practical. Because Mode 3 considers the greenhouse effect in the collector resulted from the spectral radiative properties of the semi-transparent canopy and energy storage layers. Taking glass for example, a clear glass can transmit almost 90% radiation for $\lambda < 2.5\ \mu m$, but is nearly opaque for $\lambda > 2.5\ \mu m$. Solar radiation is substantially in the range of 0.29–2.5 μm, and radiation wave length emitted by the ground is mainly in the range of 3–120 μm

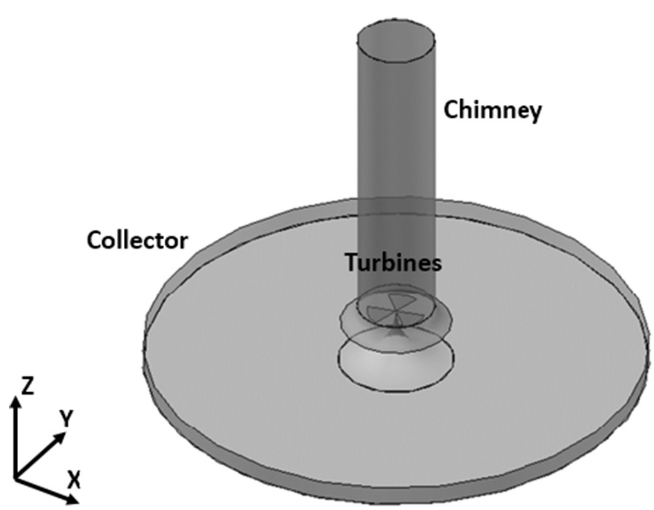

Fig. 1. Structure sketch of the SCPP.

[28]. So about 96% solar energy can arrive in the ground, and the ground radiation can barely transmit through the glass to the ambient. Thus in the radiation model taking the greenhouse effect into consideration is very important for appropriate simulation of the SCPP. Nevertheless, it must be pointed that in Fluent the solar ray tracing model is only available for 3D simulation, and even for the steady state simulation the 3D method is very time-consuming. Considering the fact that a real SCPP usually has huge geometric configuration, it is very attractive that if a 2D model can be established in which the radiative effects can also be taken into account with enough accuracy. In addition a 2D model will make the unsteady state simulation much less expensive than a 3D model.

In this paper, we propose an improved 2D model for SCPP simulation. The simulation model is consisted of four sub-models as indicated above. The major contribution of this paper is the improvement of the solar radiation model, which can take the spectral property of the collector into account and is named as Mode 4. This new radiation model is self-coded and combined with Fluent 14.0 in ANSYS as UDFs. This improved 2D method is used to simulate the Manzanares pilot plant, and good agreement between the measured and predicted results is obtained. The improved 2D method overcomes the overestimation for the SCPP performance of previous methods and has similar results to the 3D method with the solar ray tracing model and the DO radiation model with much less computational efforts.

2. Numerical methods

In order to simplify the calculation while still keep the major features of an SCPP, the following assumptions are made in simulations:

(1) The solar irradiation is constant and uniform.
(2) The soil temperature 5 m underneath the ground surface is set to be 300 K and is taken to be as the boundary condition.
(3) When the radiation heat transfer between collector top and bottom is considered the collector is treated as a two-parallel- plate system.
(4) Radiation surfaces are all diffuse-grey surfaces.
(5) The heat loss of the chimney wall is negligible.
(6) Boussinesq approximation is used to account for the change of air density.
(7) The environment is static.
(8) The process is in the steady state.

2.1. Mathematical models

In an SCPP, the strength of the buoyancy-induced flow is measured

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