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Fluid Flow and Heat Transfer Inside a Solar Chimney Power Plant

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Abstract: The flow and heat transfer characteristics inside a solar chimney power plant system are analyzed in this article. 3-D model with the k-ε turbulence closure was developed. In this model, to solve the radiative transfer equation the discrete ordinates radiation model was implemented, using a two-band radiation model. To simulate radiation effects from the sun's rays, the solar ray tracing algorithm was coupled to the calculation via a source term in the energy equation. Simulations were carried out for a system with the geometry parameters of the Manzanares power plant. Based on the numerical results, the velocity and temperature distributions were illustrated and the results were validated by comparing with experimental data of the Manzanares prototype power plant. Moreover, temperature profile of the ground surface of the system was illustrated.

1. Introduction

Solar thermal power systems utilize the heat generated by a solar collector to convert the solar energy into electrical power. A solar chimney power plant (SCPP) converts solar energy into electrical energy by a combination of four main parts, the collector, the chimney, wind turbine and energy storage media. The air inside the collector is heated by the greenhouse effect. Therefore, a continuous updraft in the chimney is produced by the upward buoyancy force. The airflow at the base of the chimney runs a pressure-staged wind turbine. Finally, mechanical energy is converted into electrical energy by using a conventional generator. A schematic of the SCPP is shown in Fig. 1.

The basic principles and reported preliminary test results for a prototype SCPP built in Manzanares, Spain, were presented in Refs. [1-3]. By introducing the SCPP concept, several studies including fluid dynamic and thermal models to simulate the SCPP have been done increasingly.(1-3) In Refs. [4-10], various one-dimensional mathematical models based on thermal equilibrium to analyze the

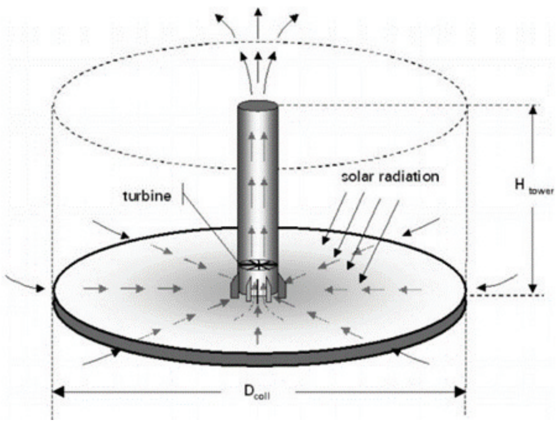

Fig. 1 A schematic of the SCPP

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performance of the SCPP were presented. (4-10) In general, one-dimensional mathematical models cannot provide detailed distributions of the velocity, temperature and pressure inside the whole system. Hence, several numerical simulations to solve a coupled set of conservation equations of mass, momentum and energy based on computational fluid dynamics (CFD) solution have been carried out. Bernardes et al.(11) presented a CFD solution for NaviereStokes and energy equations in an SCPP for the natural laminar convection in steady state using finite volumes method. Pastohr et al.(12) carried out a two-dimensional steady state numerical analysis on the whole solar chimney systems including the collector, chimney, energy storage layer, and turbine using CFD. The conservation equations for mass, momentum and energy were solved in a small-scale SCPP using the finite volume method by Koonsrisuk and Chitsomboon(13). Ming et al.(14) presented numerical simulations of the airflow and the characteristics of heat transfer in the SCPP with an energy storage layer including the effect of solar radiation on heat storage on the ground. Ming et al.(15) performed steady state numerical simulations on the SCPP coupled with turbine using the Manzanares prototype plant as a practical example. Chergui et al.(16) solved the mathematical model represented by the Navier-Stokes equations in steady state, continuity and energy equations for a natural laminar convective heat transfer, through an axis symmetric system in a dimensionless form. Numerical simulations were performed by Xu et al.(17) to analyze the influences of solar radiation and pressure drop across the turbine on the steady state flow and heat transfer, power output and energy loss of an SCPP similar to the Manzanares prototype plant.

The objective of this study is to accurately analyze the SCPP system. For this purpose, a three-dimensional unsteady CFD model is developed. It is based on the solution of the Navier-Stokes equation for turbulent flow using the RNG k-ε model. The convective and radiative transfer equations are simultaneously solved. The discrete ordinates (DO) radiation model is used, in which the non-gray radiation model is implemented using a two-band radiation for visible and infrared bands. Solar radiation reaches on the semitransparent collector cover as an irradiation beam from outside the computational domain that is simulated using the solar ray tracing algorithm. Based on the numerical results, velocity and temperature distributions of an SCPP by the geometry parameters of the Manzanares power plant are considered. In addition, temperature profile of the ground surface of the Manzanares prototype is calculated.

Fig. 2 Manzanares SCPP

2. Physical model

In order to analyze the buoyancy-driven flow and heat transfer in an SCPP, a system by the geometry parameters of the Manzanares power plant is considered.

The chimney of this prototype power plant has a height and diameter of 195 m and 10 m,

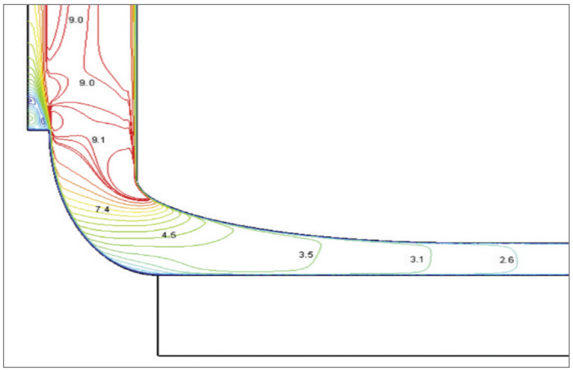

Fig. 3 Distribution of the velocity (m/s)

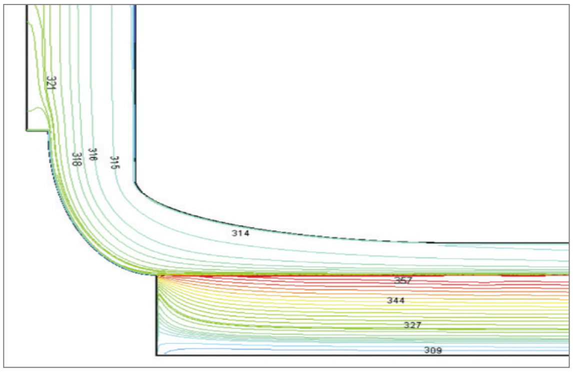

Fig. 4 Distribution of the temperature (K)

respectively. The radius of the collector is 122 m and its average height is 1.85 m. The turbine is installed on a framework 9 m above ground level. The collector height rises adjacent to the chimney base up to 6 m. The Manzanares prototype SCPP is shown in Fig. 2.

3. Results

3.1 The velocity and temperature distributions

The velocity distribution through the system in the solar insolation of 850 W/m^2 is illustrated in Fig. 3. It is seen that the velocity at the base of the chimney reaches its maximum value.

The temperature distribution through the system in the solar insolation of 850 W/m^2 is also illustrated in Fig. 4. The mean air velocity at the chimney inlet is 9.1 m/s (Fig. 3) and the mean air temperature rise through the collector of about 18 K (Fig. 4) is predicted. In the Manzanares prototype, the air velocity at the chimney inlet of 8.8 (m/s) and the air temperature rise through the collector of 17.5 K were reported(2) and therefore, there are good agreements between the predicted values and the experimental data.

A comparison of the numerical results of temperature profile of the ground surface at solar insolation of 800 W/m^2 among the energy equivalent method(4), the Pastohr method(12) and the Ming method(14) was considered in Ref. [14]. Fig. 5 compares the results of the mentioned simulations with the results of the present model. Data measured in Manzanares solar chimney power plant shows that the maximum temperature of the ground surface at the middle of the collector is 348 K when the solar insolation is about 800 W/m^2. As shown in Fig. 5, the present model predicts temperature of the ground surface at the middle of the collector 352 K. the large variation of the temperature profile of the ground surface shows that the previous methods are unable to correctly model the heat transfer in the system. The main reasons are as follows: 1) the solar radiation used in the previous models is regarded as a heat source and therefore, it is different from real energy transfer process. 2) the greenhouse effect in solar collector has not been considered. 3) the nature of the energy storage layer of the solar chimney system is unsteady.

4. Conclusions

The goal of this paper was to analyze the flow field and heat transfer inside the solar chimney power plant. In this study, a 3-D unsteady CFD model to analyze the solar chimney power plant

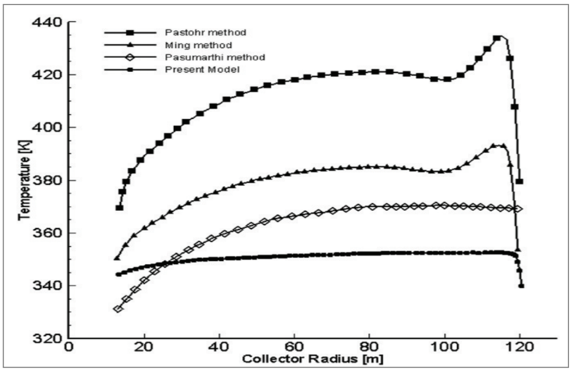

Fig. 5 Temperature (K) profile of the ground surface

system was developed. The model provided good agreement with experimental measurements of the Manzanares power plant. Based on the results, the distributions of the velocity and temperature were illustrated, using geometry parameters of the Manzanares power plant. Furthermore, temperature profile of the ground surface of the system was illustrated.

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