Sciences & Technology Vol 3 – N°1, June 2018, pp. 17-20

3D NUMERICAL STUDY OF FLOW IN A SOLAR CHIMNEY POWER PLANT SYSTEM

Submited on 12/03/2014 – Accepted on 04/12/2014

Abstract

Heat transfer process and fluid flow in a Solar Chimney Power Plant System (SCPPS) are investigated numerically. As simulation object we use the Spanish prototype plant. The calculative model and boundary conditions in calculation are introduced. Boussinesq model was chosen in the natural convection processus, Discrete Ordinate radiation model was employed for radiation. The principal factors that influence on the performance of the Solar Chimney have been analysed. The effects on the flow of the Solar Chimney which caused by solar radiation intensity have been simulated. The calculated results are compared and are approximately equivalent to the relative experimental data of the Manzanares prototype. It can be concluded that the temperature difference between the inlet and outlet of collector, as well as the air velocity in the collector of the system, is increase with the increase of solar radiation intensity and the pressure throughout system is negative value.

Keywords: *Terms—Solarchimney power plant, Numerical simulation, solar radiation intensity, Flow characteristics.*

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I. INTRODUCTION

The Solar Chimney Power Plant System (SCPPS) is a natural driving power generating system. It can convert solar energy first into thermal energy then into kinetic energy finally into electrical power. The concept was first suggested by Günther in 1931 and again by Schlaich [1] in 1978. Subsequently a prototype of a solar chimney with a height of 194.6m and collector area of radius 122 m was constructed at Manzanares, (Spain) and data of actual working of the solar chimney was collected [1]. Schlaich reported the nominal electric power output at Manzanares to be 50 KW.

As the solar chimney, power plant systems could make significant contributions to the energy supplies of those countries where there is plenty of desert land, which is not being utilized, and sunlight available in Africa, Asia and Oceania, researchers have made many reports on this technology in the recent few decades.

Haaf et al. [2] provided fundamental investigations for the Spanish prototype system in which the energy balance, design criteria, and cost analysis were discussed. The next year, the same authors reported preliminary test results of the solar chimney power plant [3].

Zhou Xinping [4] presented experiment and simulation results of a solar chimney thermal power generating equipmentin China, and based on the simulation and the specific construction costs at a specific site, the optimum combination of chimney and collector dimensions was selected for the required electric power output. Ming et al. [5] presented a thermodynamic analysis of the solar chimney power plant and advanced energy utilization degree to analyze the performance of the system, which can produce electricity day and night. Ming et al. [6] developed a comprehensive model to evaluate the performance of a solar chimney power plant system in which the effects of various parameters on the relative static pressure, driving force, power output and efficiency have been further investigated. The authors supposed the existing models are insufficient to accurately describe all the phenomena occurring in solar chimney power plant. Using the solar chimney prototype of Manzanares, as a practical example, 3D turbulent flow numerical simulation studies were performed to explore the geometrical modifications on the system performance. Results showed a good agreement with the analytical model. The control of the SCPP analytical tools such as dynamic simulation of these systems is essential. Ming et al. [7] to analyze the characteristics of heat transfer and airflow in the solar chimney power plant system with energy storage layer. Different mathematical models for the collector, the chimney and the energy storage layer were established, and the effect of solar radiation on the heat storage characteristic of the energy storage layer was analyzed. Numerical simulation results show that the heat storage decreases firstly and then increases with the increase of the solar radiation from 200W/m2 to 800W/m2. The static pressure decreases while the velocity increases significantly inside the system with the increase of solar radiation; the average temperature at the outlet of the chimney and the one of the energy storage layer may increase too significantly with the increase in solar radiation. In addition, the temperature gradient of the storage medium may increase and this results in an increase of energy loss from the bottom of the energy storage layer. Pastohr et al. [8] used the FLUENT software for modeling a solar chimney power plant, geometrically similar to that of Mansaranes, with the aim of carrying out an analysis and reporting details on the operating mode and the system efficiency. They confirmed that the pressure drop in the turbine and the mass flow rate, decisive elements on the system effectiveness, cannot be only given by coupling all the parts of a SCPP. Numerical results given by FLUENT software are in good agreement with the results given by a simple model proposed by the authors, which led to the conclusion that it is much easier to use it for parametric studies. Chergui et al. [9,10] simulated a thermohydrodynamicbehaviour analysis of the airflow through an axisymmetric system, such as chimneys, with defined boundary conditions.

II. MODELING

a. Geometric Mode

The three-dimensional geometric model of the SCPPS was built in GAMBIT, which is a pre-processor of FLUENT. The grid was also generated in GAMBIT [11]. The collector is 240m in diameter, and the distance between its covering and ground surface is 1.7m, the chimney is 200m in height and 10m in diameter.

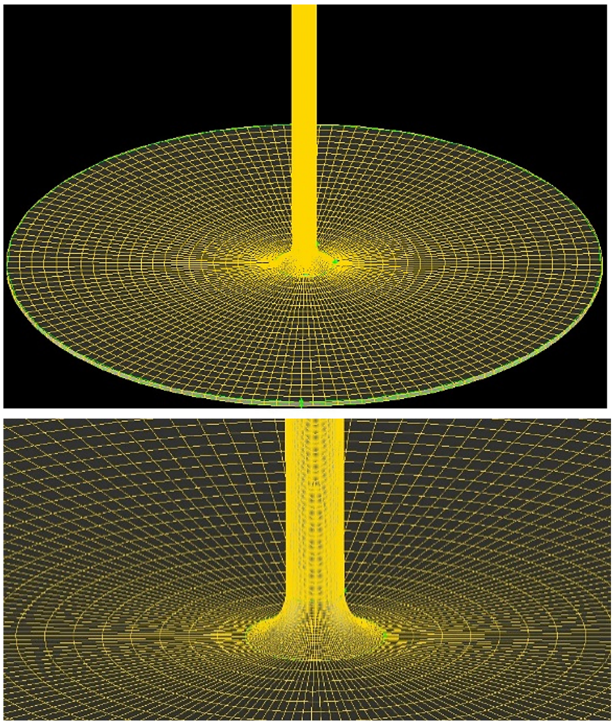

Fig.1 Grid model of the whole system

III. MATHEMATICAL MODEL

Based on the geometrical dimensions of the prototype Manzanares,a physical model for a solar chimney power plant was built. The basic equations including the models were numerically solved with the help of the commercial simulation program FLUENT [12]. The control equations including the continuity equation, momentum equation, energy equation, and turbulence equation (the standard k–ε equations) in the collector and chimney regions can be written as follows:

Continuity equation

$$\frac{\partial \rho}{\partial t}+\frac{\partial(\rho u)}{\partial x}+\frac{\partial(\rho v)}{\partial y}+\frac{\partial(\rho w)}{\partial z}=0 \qquad (1)$$

Navier-Stokes equation

$$\frac{\partial(\rho u)}{\partial t}+\frac{\partial(\rho uu)}{\partial x}+\frac{\partial(\rho uv)}{\partial y}+\frac{\partial(\rho uw)}{\partial z}=-\frac{\partial p}{\partial x}+\mu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}+\frac{\partial^2 u}{\partial z^2}\right) \qquad (2)$$

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho vu)}{\partial x}+\frac{\partial(\rho vv)}{\partial y}+\frac{\partial(\rho vw)}{\partial z}=-\frac{\partial p}{\partial y}+\mu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}+\frac{\partial^2 v}{\partial z^2}\right) \qquad (3)$$

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho wu)}{\partial x}+\frac{\partial(\rho wv)}{\partial y}+\frac{\partial(\rho ww)}{\partial z}=-\frac{\partial p}{\partial z}+\mu\left(\frac{\partial^2 w}{\partial x^2}+\frac{\partial^2 w}{\partial y^2}+\frac{\partial^2 w}{\partial z^2}\right)+\rho g\beta(T-T_0) \qquad (4)$$

Energy equation

$$\frac{\partial(\rho cT)}{\partial t}+\frac{\partial(\rho cuT)}{\partial x}+\frac{\partial(\rho cvT)}{\partial y}+\frac{\partial(\rho cwT)}{\partial z}=\lambda\left(\frac{\partial^2 T}{\partial x^2}+\frac{\partial^2 T}{\partial y^2}+\frac{\partial^2 T}{\partial z^2}\right) \qquad (5)$$

k–ε equations

$$\frac{\partial(\rho k)}{\partial t}+\frac{\partial(\rho ku)}{\partial x}+\frac{\partial(\rho kv)}{\partial y}+\frac{\partial(\rho kw)}{\partial z}=\frac{\partial}{\partial x}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right)+\frac{\partial}{\partial y}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial y}\right)+\frac{\partial}{\partial z}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right)+G_k+G_b-\rho\varepsilon+S_k \qquad (6)$$

$$\frac{\partial(\rho \varepsilon)}{\partial t}+\frac{\partial(\rho \varepsilon u)}{\partial x}+\frac{\partial(\rho \varepsilon v)}{\partial y}+\frac{\partial(\rho \varepsilon w)}{\partial z}=\frac{\partial}{\partial x}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x}\right)+\frac{\partial}{\partial y}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial y}\right)+\frac{\partial}{\partial z}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial z}\right)+C_{1\varepsilon}G_k+C_{1\varepsilon}C_{3\varepsilon}G_b-C_{2\varepsilon}\frac{\rho\varepsilon^2}{k}+S_\varepsilon \qquad (7)$$

G_k : represents the generation of turbulence kinetic energy due to the mean velocity gradients;

G_b : is the generation of turbulence kinetic energy due to buoyancy.

The constants have the following values [13]:

$C_{1\varepsilon}=1.44, C_{2\varepsilon}=1.92, C_\mu=0.09, \quad \sigma_k=1, \sigma_\varepsilon=1.3.$

a. Boundary Conditions:

Settings of boundary conditions are shown in TABLE I. Pressure boundary condition was used to simulate the natural convection flow in the actual system. DO radiant model and convection heat transfer boundaries were used in this study (considering that air, has the heat transfer medium in the system, as thin optical thickness). The ground under collector covering roof that absorbs solar energy can be seen as a local heat source ($q_0 = G.\tau.\alpha$ W/m^2). Ambient temperature T_0 is set at 293 K, the ground absorptivity is $\alpha = 0.9$ and the glass roof transmissivity is $\tau = 0.9$. Solar radiation intensity Ghas been changed.

TABLE I:The main boundary conditions

Place	Type	Value
The ground	Wall	$q_0 = G.\tau.\alpha$ (inner heat source)
Surface of the chimney	Wall	$q = 0$ W/m^2
Glass roof	Wall	h=8W/(m^{2}K), $T_0 = 293K$
Collector inlet	Pressure inlet	$T_0 = 293K, \Delta P = 0$ Pa
Chimney outlet	Pressure outlet	$\Delta P = 0$ Pa

IV. RESULTS AND DISCUSSION

All numerical calculations had to be performed with the solver with double precision. The iteration error was at least 10^{-4} for all calculations, and was at least 10^{-6} for the energy equation. The solution converged in less than 600 iterations.

Figures 2–4 illustrate the temperature, velocity and pressure distributions in the solar collector of the solar chimney power plant at three different solar radiations.

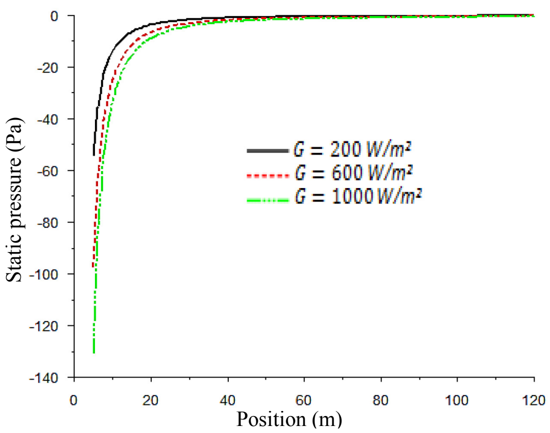

Fig.2 Static pressure profile of the fluid flowing through the collector.

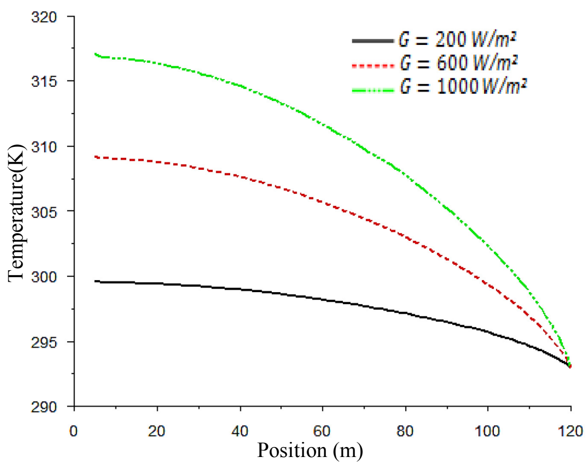

Fig.3 Temperature profile of the fluid flowing throughthe collector.

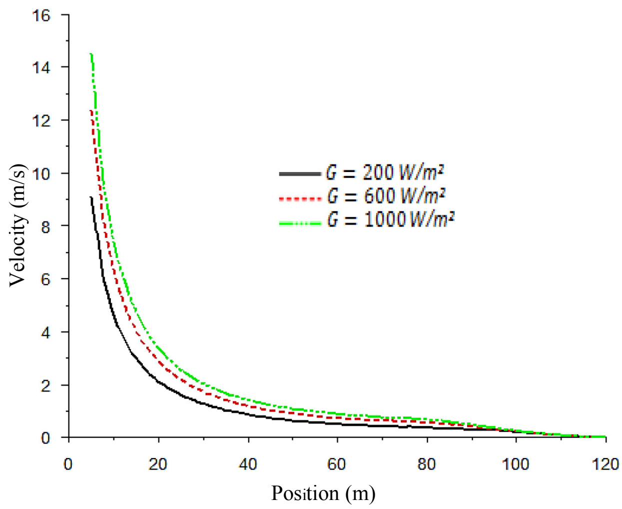

Fig.4 Velocity profile of the fluid flowing through the collector.

Figure 2 shows the static pressure profile, which decreases through the collector and drops dramatically near the chimney base. It also demonstrates that when the collector radius is constantthe increasing in solar radiation results in a decrease in the static pressure.

Figure 3 illustrates that, when the solar radiation intensity increases, the air temperature increases for the same collector radius and when the solar radiation is constant, the temperature of fluid increases by decreasing the radius.

The velocity increases through the collector by decreasing the radius, but it increases more sharply by reaching the chimney base. When the collector radius is constant, an increase of solar radiation causes an increase of the air velocity, but the effect is not very significant (see Fig.4).

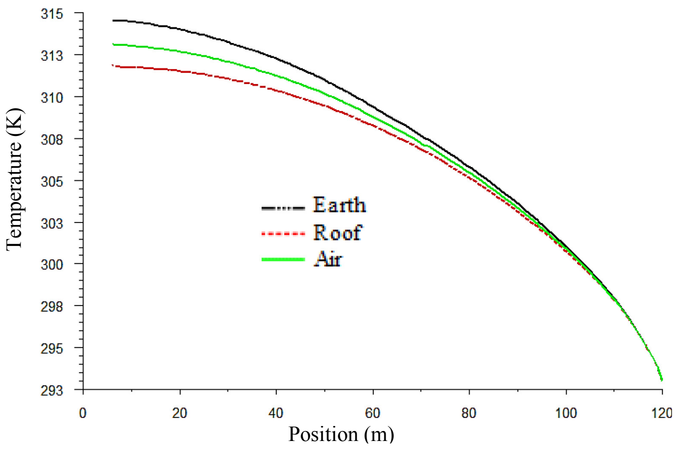

Fig.5 Temperature profiles of the earth, roof and air through the collector for *G=800* W/m^2.

Figure5 illustrates the earth, roof and air temperature profiles through the collector. As shown in Figure 5, by decreasing the collector radius, all the temperatures increase, but the earth temperature increases more steeply.

TABLE II. Results of calculations for different solar radiations.

Solar radiation *G* (W/m^2)	Temperature difference between the inlet and outlet of collector (K)	Air velocity at outlet of collector (m/s)	Pressure difference between the inlet and outlet of collector (Pa)
200	6.62	9.10	54.343
400	11.77	10.97	77.86
600	16.25	12.37	97.58
800	20.31	13.52	115.04
1000	24.07	14.61	130.89

Simulative results (See Table II) show the relations between solar radiation intensity and three main parameters, including the differential pressure of collector, the air velocity of chimney base and the temperature difference between the inlet and outlet of collector. These three main parameters increase with the increasing solar radiation intensity. It's the reason that the SCPPS is always built in the countries or areas of which much more in annual mean sunshine.

To validate the numerical results, the temperature increase in the collector was compared with the experimental data of the Spanish prototype for 1000 w/m^2 [2]. As is shown in TABLE III, an acceptable quantitative agreement was obtained between the experimental data of the Manzanares prototype and both of the numerical results.

TABLE III. Comparison between the numerical results and the experimental data.

Results	Temperature increase	Air velocity at outlet of collector
Experimental data from Manzanares	20K	15 m/s
Our work	24.07K	14.61 m/s

V. CONCLUSION

A numerical simulation was performed with the help of FLUENT to analyze the characteristics of the flow for the geometry of the prototype in Manzanares, Spain, and both results are consistent with the experimental data of the Manzanares prototype. Numerical profiles for the temperature, velocity and pressure in the collector of the solar chimney power plant were shown for different solar radiations. It can be concluded that the pressure throughout system is negative value. The temperature difference between the inlet and outlet of collector is increase with the increase of solar radiation intensity, and increases by decreasing the radius. The velocity increases through the collector by decreasing the radius, and also an increase of solar radiation causes an increase of the air velocity. The calculated results are approximately equivalent to the relative experimental data of the Spanish prototype.

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