Original Article: Numerical Simulation and Geometrical Optimization of a Solar Chimney Power Plant

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ABSTRACT

Nowadays energy and electricity production is one of the major concern of governments. Electricity generation by solar systems is considered as one of the alternative for fossil fuels. There is a surge in the use of the solar chimney power plant in the recent years which accomplishes the task of converting solar energy into kinetic energy. In this study a numerical simulation and geometrical parameters optimization of the solar chimney is discussed. In this paper, solar chimney prototype in Manzanares, Spain, as a practical example is used. To explore the geometric modifications on the system performance (output power and efficiency), effect of chimney height, collector radius and collector height is studied. A numerical simulation in this paper were used 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. In order to validate the present work, upwind velocity in the solar chimney was compared with an experimental model.

Introduction

The production of energy and electricity is one the major concern of today's life. For last several decades, production of electricity was mainly dependent on fossil fuels. But limited resources and pollution effects has raised considerable concerns among world leaders. Today's electricity generation by solar energy is one of the important alternatives.Solar chimney (fig. 1) is one of the choices which have been available for electricity generation for many years. It was first proposed in 1978 and attracted many attentions on different aspects of its application.

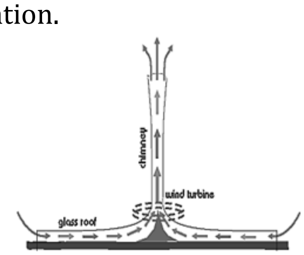

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Fig. 1. Schematic diagram of solar chimney power generating system [1]

Solarchimney'smechanism is based on anatural phenomenon. In the collector, solar radiation is used to heat an absorber (ordinarily soil or water bags) on the ground, and then a large body of air, heated by the absorber, rises up the chimney, due to the density difference of air between the chimney base and the surroundings. The rising air drives large turbines which installed at the chimney base to generate electricity [1].

In the recent years more researchers have shown interest in studying of solar power generating for its application all over the world [3-6]. Several analytical solutions and numerical simulations had been done to investigate solar chimneys [7-14].

In the present study, effect of geometrical parameters on the performance of Manzanares power plant (real model of solar chimney in Spain) is investigated. Therefore effects of chimney height, collector height from the ground and collector radius on the output power and the efficiency of the system is studied.

Materials and Methods

The Navier–Stokes equations, the continuity equation, the equation for the energy and k-ε equations describethe movement of the flow generally [1].

Continuity equation

$$\frac{\partial p}{\partial t}+\frac{\partial}{r\partial z}(r\rho u)+\frac{\partial}{\partial z}(\rho v)=0$$

Navier–Stokes equations

$$\rho\frac{du}{dt}=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial r}\left[2\mu\frac{\partial u}{\partial r}+\mu div(\vec{v})\right]+\frac{\partial p}{\partial z}\left[\mu(\frac{\partial u}{\partial z}+\frac{\partial v}{\partial r})\right]+\frac{2\mu}{r}(\frac{\partial u}{\partial r}-\frac{v}{r})$$

$$\rho\frac{dv}{dt}=-\frac{\partial p}{\partial z}+\rho g_z+\frac{\partial}{\partial z}\left[2\mu\frac{\partial v}{\partial z}+\mu div(\vec{v})\right]+\frac{\partial}{r\partial r}\left[r\mu(\frac{\partial u}{\partial z}+\frac{\partial v}{\partial r})\right]$$

Energy equation

$$\rho c_p\left[\frac{\partial T}{\rho t}+\frac{1}{r}\frac{\partial}{\partial r}(rTu)+\frac{\partial}{\partial z}(Tv)\right]=\frac{1}{r}\frac{\partial}{\partial r}(r\lambda\frac{\partial T}{\partial z})+\frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z})+\frac{\partial p}{\partial t}+\frac{\partial}{r\partial r}(rpu)+\frac{\partial}{\partial z}(pv)$$

K-ε equations

$$\rho\left(\frac{1}{r}\frac{\partial}{\partial r}(rku)+\frac{\partial}{\partial r}(kv)\right)=\frac{\partial}{\partial z}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right)+\frac{\partial}{r\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right)+G_k+\beta g_z\frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial T}{\partial z}-\rho\varepsilon$$

$$\rho\left(\frac{1}{r}\frac{\partial}{\partial r}(r\varepsilon u)+\frac{\partial}{\partial r}(\varepsilon v)\right)=\frac{\partial}{\partial z}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial z}\right)+\frac{\partial}{r\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial \varepsilon}{\partial r}\right)+C_{1\varepsilon}G_k\frac{\varepsilon}{k}-C_{2\varepsilon}\frac{\varepsilon^2}{k}$$

The variables r and z stand for the radial coordinate, direction in the collector and axial coordinate, in the chimney axial respectively. In the above equations C_p, g, p, T, u, v and μ are specific heat capacity, gravitational acceleration, pressure, temperature, velocity in the radial direction, velocity in the axial direction, viscosity respectively.

To consider effects of pressure drop in the collector and chimney, table 1 used.

Table 1, skin friction coefficient

$\frac{c_w}{2}=\frac{0.0592}{\mathrm{Re}^{(1/5)}}$	Laminar fully developed Re<2100, Bachr &Stephan (1996)
$c_w=\frac{0.072}{\mathrm{Re}_l^{(1/5)}}-\frac{1700}{\mathrm{Re}_l}$	Turbulent fully developed, 4000<Re<10^7
$\frac{1}{\sqrt{\tau}}=1.5635\ln(\mathrm{Re}/7)$	Turbulent, Roughness (10^{-6}< k_r/l <10^{-2})
$c_w=\left[1.89-1.62\log(\frac{k}{l})\right]^{-2.5}$	Schilikhting (1999)

With the Beetz [15] power limit, the pressure jump at the turbine is given by:

$$\delta p_T=-\frac{8\rho u^2}{27} \quad (1) \quad (6)$$

(2)

Maximumoutput power of the solar chimneyisdefinedas:

$$P_{\max}=\frac{\dot{m}\delta p}{\rho} \quad (3) \quad (7)$$

Where $\dot{m}$, Δp and ρ are mass flow rate, Maximum pressure difference and density at the base of the chimney respectively. (4)

Maximum efficiency of the solar chimney is obtained from the following equation where q Indicates solar heat:

$$\eta_{\max} = \frac{P_{\max}}{Q} = \frac{P_{\max}}{\pi R_{coll}^{2} q} \quad (8)$$

The geometry of the solar chimney system simulated in this study is as like as Manzanares real model in Spain. Radius of the collector (r_r), height of the collector from ground (h_r), height of the chimney (h_c) and radius of the chimney (r_c) is considered 122m, 2m, 195m and 5m respectively. Boundary conditions of the system is considered as shown in the table 2:

Table 2, Boundary conditions and model parameters

place	type	value
Collector's Inlet	Pressure inlet	S=0, T=298
chimney' s Outlet	Pressure outlet	S=0, T=298
Chimney' s Surface	wall	q=0
Collector's surface	wall	Solar heat

During the simulation, the conservation equations for mass, momentum and energy are selected, and natural convection and gravity effect are taken into consideration The CFD analysis consists of the following numerical models and methods:

- **Turbulent model**: standard k-ε model
- **Solver algorithm**: pressure based coupled algorithm
- **Spatial discretization**: Second order of upwind
- **Convection term discretization method**: high resolution 2nd order
- **Hexahedra mesh type**

Figure 2 shows upwind velocity distribution of the Spanish prototype [2]. Figure 3 shows the result of present study. There is a little difference in the result because it is supposed in this numerical model that the solar radiation is fully absorbed by the air inside the system. Figure 3 suggesting a strong agreement.

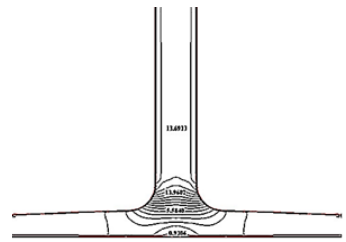

Fig 2. Velocity distribution in the solar chimney (m/s) [2].

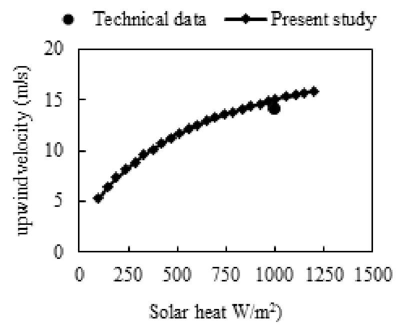

Fig. 3. Diagram of upwind velocity via solar heat

Results and discussion

In this paper effect of geometrical parameters on the output power and the efficiency of of the canazas power plant (real model of solar chimney in Spain) is investigated. Figures 4 and 5 show the effect of collector radius on the output power and the efficiency of the system. In the constant solar radiation, with the increase of the collector radius, the collector area and the air temperature in the system increases which results in the decrease of the air density. Thereby, the relative static pressure in the system and the output power increases accordingly. But results of study show that with the increase of the collector radius, the efficiency of the system decreased. It can be seen that finding an optimized point is necessary.

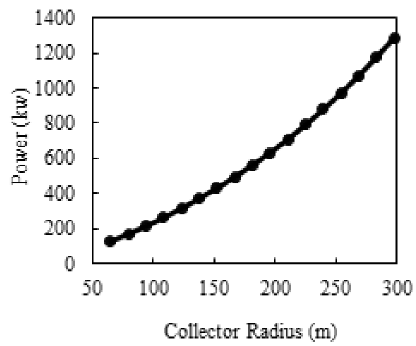

Fig. 4. Output power histories via collector radius

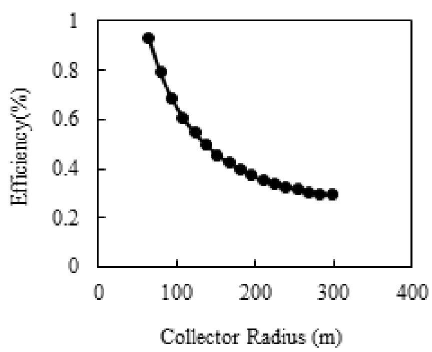

Fig. 5. Output power histories via collector radius

Figures 6 and 7 show the output power and the efficiency of the solar chimney system via collector height from the ground. As it is shown, with increase of the collector height from the ground, the temperature of the inletair will be decreased. Thereby, the relative static pressure in the system and the output power decrease accordingly.

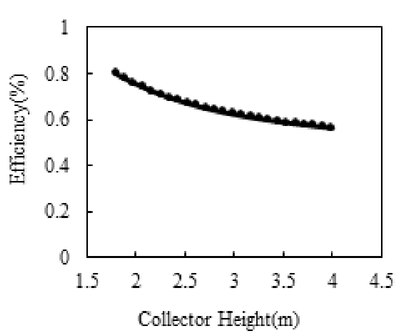

Fig. 6. Output power histories via collector height

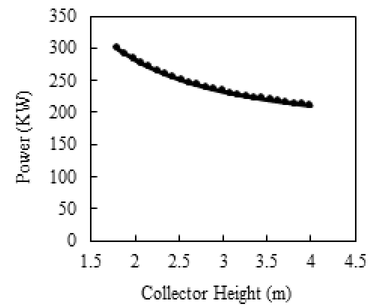

Fig. 7. Efficiency histories via collector height

Figures 8 and 9 show the effect of chimney height on the output power and the efficiency of the solar chimney system. When the solar radiation is constant, an increase of the chimney height causes an increase of the mass flow rate and the pressure difference across the turbine. Therefore, the chimney height has a strong effect on the power output of the system.

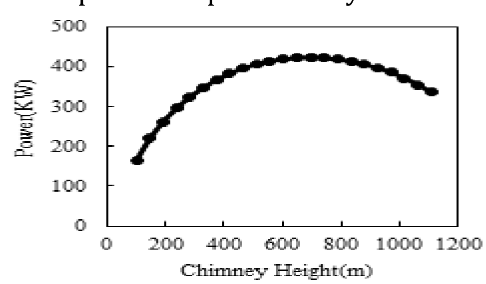

Fig. 8. Output power histories via chimney height

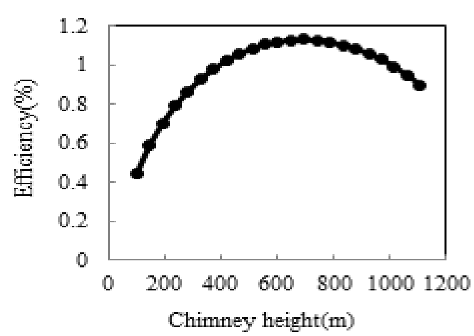

Fig. 9. Efficiency histories via chimney height

Conclusion

There is a surge in the use of the solar chimney power plant in the recent years which accomplishes the task of converting solar energy into kinetic energy. As the existing models are insufficient to accurately describe the mechanism. A numerical simulation in this paper were used 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. In order to validate the present work, upwind velocity in the solar chimney was compared with an experimental model. Results of this paper show that increase and decrease of geometrical parameters have a strong effect on the output power and the efficiency of the solar system. Thereby according to the required power, geometrical optimization will reduce costs electricity generation considerably.

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