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Parametric Study of the Effective parameters on the Performance of Solar Chimney Power Plant

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Abstract –*The solar chimney power plant (SCPP) is an effective option for electrical energy production from solar energy. In this paper, a numerical model to predict the SCPP performance is developed. The effects of collector angle and solar radiation are investigated on the parameters of air as the velocity and temperature. The study shows that when the collector angle is 20°, the velocity maximum is 1.8 m/s at the chimney base and the maximum temperature is 332.1k. in addition, increased solar radiation produces an increase in temperature (from 400 w/m² to 900 w/m²) and air velocity (from 22.25 m/s to 2.75 m/s) in the solar energy tower*

***Keywords**: Velocity, Solar chimney power plant, energy tower, solar energy, electrical energy.*
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I. Introduction

Solar chimney power plant is a renewable energy center with the potential to generate important quantities of electrical energy [1], which are a thermal system that creates electrical energy using both the effect of buoyancy of hot air and effect of chimney [2]. A solar chimney power plant is made up of three main elements: the solar collector, the solar tower and the turbine. The collector angle is one of principal parameters in the enhancement of electricity production [3]. The solar chimney power plant is used in hot areas with high intensity of solar radiation. Its operating principle is based on the fact that hot air, being lighter than cold air, rises. The hot air is produced by the greenhouse effect in the collector which can spread horizontally for several tens of meters on the surface of the ground. The tower (chimney) converts the heat flow captured by the collector into kinetic energy (convection current) and potential energy (pressure drop in the turbine), Thus the difference in air density caused by the temperature rise in the collector acts as a driving force. The movement of air allows turbines at the base of the chimney to generate electricity through generators coupled to them [4-5].

3D numerical model was developed to analyze the flow parameters such as temperature, velocity of solar updraft tour (SUT) and pressure also the influence of geometrical parameters such as chimney height and the roof collector. It was observed that when the collector roof angle increased, air velocity also increased whereas the air temperature decreased slightly [6]. In another work, 3D numerical model developed to analyze the influence of solar flux, the divergence angle of the chimney and turbine efficiency on the performance of SUT plant [7]. The influences of roughness shape of collector were investigated on the performance of SCPP. In their study, curved, the roughness shape of triangular and square grooves were studied and compared with the smooth case. In the authors erected a SCPP inside the University campus, with 1m collector radius, 0.2 m chimney diameter while the height was varied from 2 m to 4 m. The results revealed that the chimney height of 4 m and the collector inlet height of 0.04 m produced the optimal configuration [8].

Based on the buoyancy phenomenon, the power production from the gas of the power plant's chimney using the combination of the power plant's hot output with ambient air was investigated and modeled at temperatures and different discharge rates of the power plant's hot output on a pilot scale [9]. The authors proposed in a new chimney design of hyperbolic shape [10]. The design of chimney is enhanced by examining the effect of the divergence radius of the chimney on the performance of SCPP using a 2D CFD model. In another work [11], a novel collector design with double-pass counter flow mode was proposed to enhance further the SCPP efficiency and reduce the large plant area. The authors compared three collector models including double-pass collector with parallel flow, double-pass collector with counter flow and conventional collector by using CFD model.

Small-scale prototype of SCPP was designed and built at the University of Ouargla, Algeria [12]. In the study of a small-scale prototype of SCPP was designed and built at the University of Ouargla, Algeria. It was found that the velocities of air at the chimney base are in a good accord with those estimated from the CFD method. The maximum air velocity in the chimney achieved was 1.6 m/s and the predicted generated power reached 104 kW. A novel concept consists of a horizontal solar chimney power plant with an adapted collector entrance, named sloped collector entrance SCESCPP. The results indicate that the new collector entrance design affects significantly the system performance [13].

In this paper, a numerical model was presented to simulate the solar chimney for the Iranian plant and the SCPP performance is studied. The effect of collector angle and heat flux on the air temperature and velocity of air was investigated.

II. Methodology

In the solar chimney, the incident solar radiation will heat the air flowing inside the collector of the solar chimney by convection, causing the air temperature to rise by the phenomenon of the greenhouse effect under the transparent roof which acts mainly on the flow of heat absorbed not to leave the structure of the collector. And due to the temperature differences between the temperature at the base of the solar chimney and the temperature of the atmosphere, air is continuously drawn in through the periphery of the open collector in the chimney due to the buoyancy effect. A turbine is placed at the base of the chimney through which the hot air passes to convert part of the useful energy of the circulating air into electricity [14].

2D numerical solution of solar chimney power plant (SCPP) as shown in Figure 1, is developed according to the dimension of Iranian prototype (Table 1) [15]. SCPP is simulated by COMSOL Multiphysics, Simulations are used by solving RANS equations to predict the output of SCPP output.

Table 1. Geometric parameters of the SCPP

parameter	Value[m]
Collector opening height	0.15
Diameter of Chimney	0.25
Diameter of Collector	10
chimney height	12

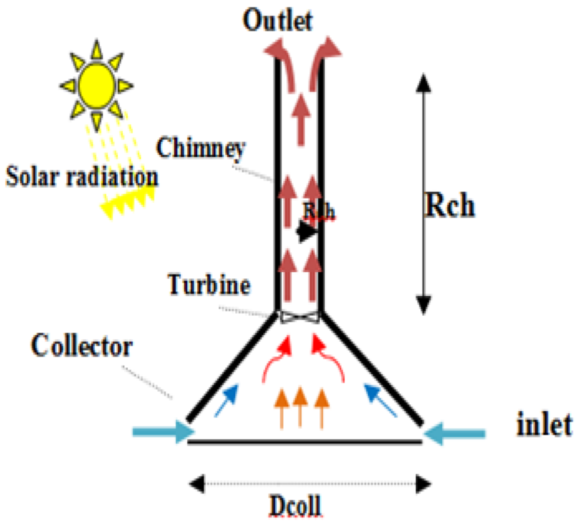

Figure 1. diagram Schematic of solar chimney power plant

II.1 Mesh creation

Domain grid is important phase in the CFD analysis. In this simulation, a triangular mesh in Figure 2 is created using the meshing tool COMSOL, it consist of 11477 elements with more concentrating element density on the inlet, outlet and junction regions.

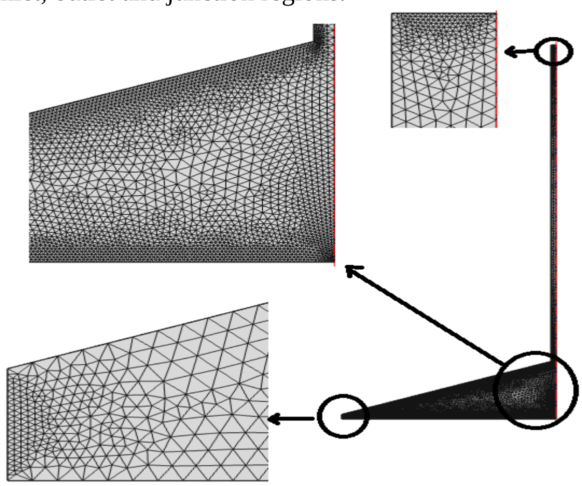

Figure 2. The meshing of the SCPP system

II.2 Governing equation

based on Rayleigh's number the air flow type is determined and it is evaluated as:

$$R_a = \frac{g\beta\Delta T H_{col}{}^{3}\rho}{\mu\alpha} \quad (1)$$

where H_{col}, ΔT, g, α and μ are collector height and difference of temperature in the system, gravity, thermal diffusivity and kinematic viscosity respectively.

Pr and Gr indicate Prandt number and Grashof number, respectively. Rayleigh number is more than 10^9, so air flow in the system is considered as turbulent.

The problem is governed by the conservation of momentum, energy and mass equations is given as follows:

Continuity Equation:

$$\frac{\partial\rho}{\partial t} + \nabla.(\rho\mu) = 0 \quad (2)$$

Momentum equation:

$$\rho\frac{\partial u}{\partial t} + \rho(u.\nabla) = \nabla.[-PI + (\mu+\mu_T)(\nabla\mu + (\nabla u)^T) - \frac{2}{3}(\mu+\mu_T)(\nabla.u)I - \frac{2}{3}\rho KI] + F \quad (3)$$

Energy equation:

$$\rho C_p\frac{\partial T}{\partial t} + \rho C_p u.\nabla T = \nabla.(K\nabla T) + Q + Q_{vh} + W_P \quad (4)$$

where F, u, P and ρ are volume forces, radial velocity, pressure and density respectively.

The dissipation rate and kinetic turbulence energy are obtained as:

k equation:

$$\rho\frac{\partial k}{\partial t} + \rho(u.\nabla)k = \nabla.[(\mu + \frac{\mu_T}{\sigma_k})\nabla k] + P_k - \rho\varepsilon \quad (5)$$

ε Equation:

$$\rho\frac{\partial\varepsilon}{\partial t} + \rho(u.\nabla)\varepsilon = \nabla.[(\mu + \frac{\mu_T}{\sigma_\varepsilon})\nabla\varepsilon] + C_{\varepsilon 1}\frac{\varepsilon}{k}P_k - C_{\varepsilon 2}\rho\frac{\varepsilon^2}{k} \quad (6)$$

where $\varepsilon = C_\mu^{3/4}\frac{k^{3/2}}{L_T}$ is the energy dissipation and $\mu_T = \rho C_\mu\frac{k^2}{\varepsilon}$ is the turbulent viscosity.

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

P_k indicate to the generation of kinetic turbulent energy due by mean gradients of velocity, is calculated by:

$$P_k = \mu_T[\nabla u : (\nabla u + (\nabla u)^T) - \frac{2}{3}(\nabla.u)^2] - \frac{2}{3}\rho k\nabla.u \quad (7)$$

II.3 Boundary condition

The main boundary conditions for the studied SCPP are indicated in Table 2.

Table 2. Boundary conditions

Surface	Type	Value
Inlet Collector	Pressure Inlet	$P_{ci} = 101325$ pa, $T = T_{am} = 300K$
Outlet of Chimney	Pressure Outlet	P =101325 pa
Surface of Collector	Semi-transparent wall	Solar irradiation; h=10.45 W/m^2
Chimney wall	Adiabatic	q=0 W/m^2

III. Results and discussion

III.1 impact of solar radiation on temperature and air velocity

Figure 3 displays impact of angle of collector roof on the air velocity. It is found that the variation of collector angle from15°-30° has an considerable effect on the velocity of air, when the velocity air augment (from 1.5 m/s to 1.8 m/s) with the increasing of collector angle (from 15° to 20°), after this angle the air velocity decreases (1.8 m/s to 1.5 m/s) by increasing collector angle (from 20° to 30°).

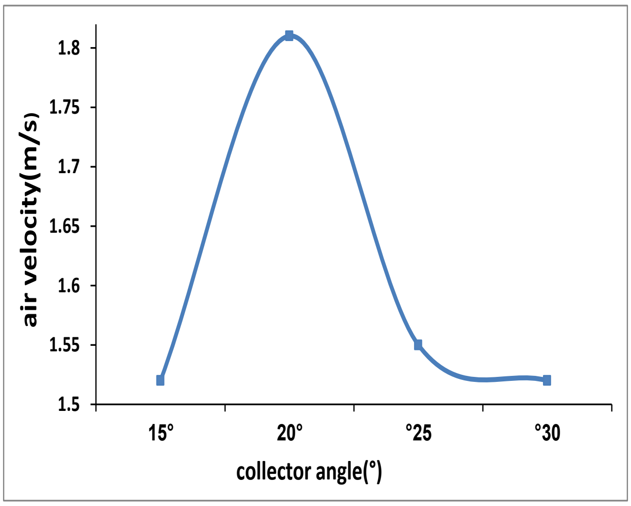

Figure 3. variation of air velocity for different collector angle

Figure 4 illustrates effect of angle collector roof on temperature of air. It is found that the air temperature augment significantly (from 324.7k to 332.1k) with higher collector angle (from 15° to 20°) and declines significantly after a certain point (from 20° to 30°). From these results, it can be concluded that the appropriate collector angle is 20°.

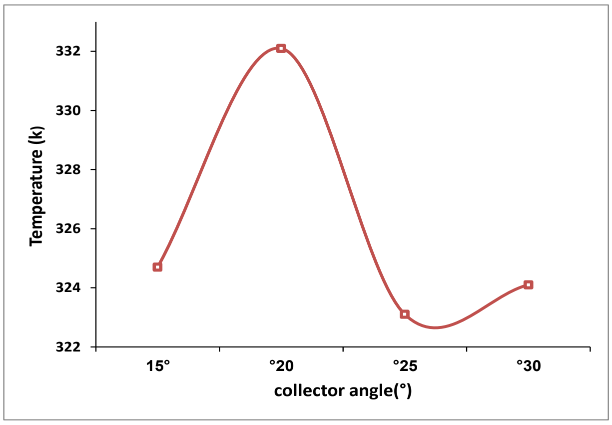

Figure 4. Variation of temperature of air for different collector angle

Figure 5 illustrate the distribution of velocity of air and temperature for appropriate collector angle is 20°, on the left figure we show that the minimum values of the temperature are located at the entrance of the collector then it increases progressively to maximum value in the collector center.

On the right figure we show that the velocity magnitude is very weak at the entrance of the collector then increases gradually to outlet of the collector; it then reaches its maximum value in the chimney base.

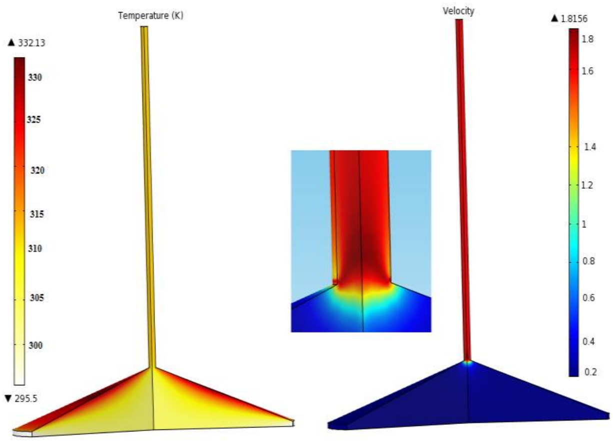

Figure 5. Velocity and temperature contours at collector angle is 20°

III.2 Effect of solar radiation on temperature air and velocity

The roof angle is 20° and the same temperature conditions and varies solar radiation such as 400w/m² to 900 w/m².

Figure 6 and 7 show the effect of solar radiation on temperature of air and velocity. As the solar radiation augment at 900 w/m² both the temperature and the velocity rise reaches a maximum value of 325 k and 2.7 m/s respectively. From these results, it is clear that the solar radiation has significant effect on both air velocity and temperature.

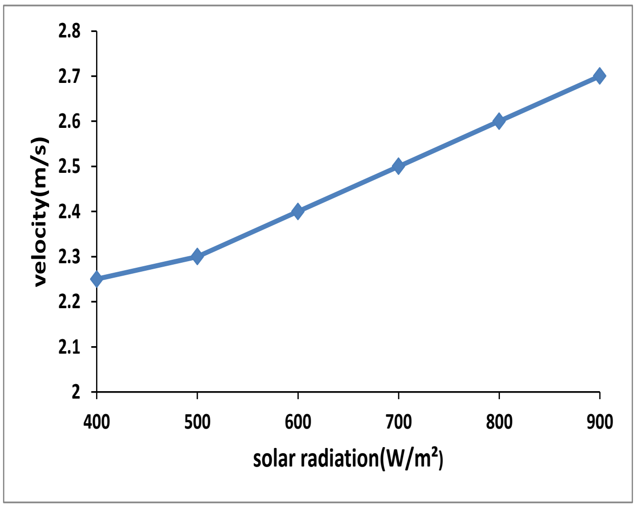

Figure 6. Effect of solar radiation on air velocity

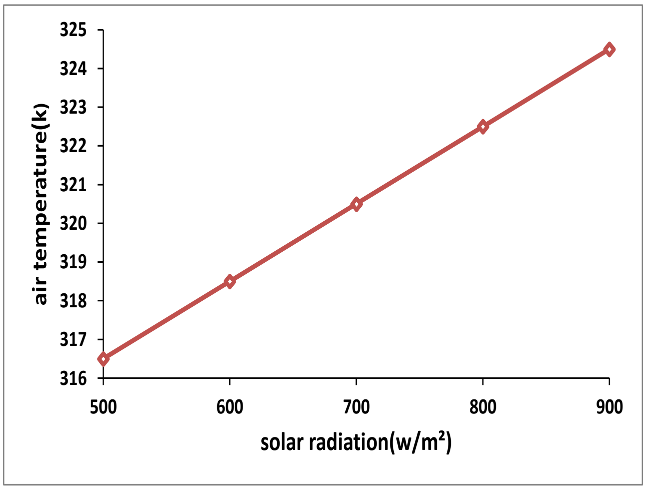

Figure 7. Effect of solar radiation on temperature

IV. Conclusion

Numerical modeling on the performance of SCPP using two-dimensional (2D) energy and Navier-Stokes equation was presented. The airflow is turbulent and simulated with k-epsilon model, using COMSOL Multiphysics.

According to simulations, we can conclude the following:

- The angle of the collector roof has a considerable effect on both the velocity distribution and temperature in the SCPP when collector angle is 20°, while the maximum velocity is 1.81 m/s and the maximum temperature is 332.1 k.
- The increasing of the solar radiation increases the air temperature (from 315 k to 224.5 k) and velocity in the solar chimney (from 2.25 m/s to 2.75 m/s).

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