Mass flow rate enhancement inside a solar chimney power plant

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Abstract

The Solar chimney power plant is a system that converts solar energy to mechanical energy and then to electrical energy. The present work aims to conduct numerical investigation on the influence of the radius ratio Rt* = Rtout/Rtinlet and the height of the tower-chimney, on the flow behavior inside the SCPP of Manzanares. A 2D axi-symetric turbulent model is adopted. The momentum and energy equations are solved using the finite volume method and the simple algorithm. Results show that velocity and mass flow rate inside the SCPP are affected by the radius ratio Rt*, the height of tower-chimney Ht* and intensity radiation Q. We obtain an enhancement of mass flow rate by about 58.23% for the divergence of the tower-chimney.

Keywords: Solar chimney, Radius ratio, height of tower-chimney, simulation, thermo-hydrodynamic behavior.

1. Introduction

Solar chimney is a solar installation that produces electrical power using solar radiation to increase internal air flowing in the system and then transforms solar energy to kinetic energy. This later is converted into electricity using a group of adequate aero-generators. The SCPP concept was originally examined in 1903 by Cabanyes [1]. In 1931, Gunther [2] presented a description of a solar chimney power plant. In 1970s Schlaich achieved the basic study on the solar chimney. In 1981, his research team began the construction Manzanares prototype in, Spain [3-4]. In order to improve the performance of SCPP, extensive research has been carried out in this field. Pastohr et al. [5] conducted CFD simulation of SCPP. They consider the geometrical dimension of Mazanares SCPP in order to carry out a more detailed analysis of both the operating mode and the efficiency of the system. Maia et al. [6] carried out a theoretical and numerical study of the effect of geometric parameters on the performance of solar chimney. Lebbi et al. [7-8] analyzed numerically the meteorological and geometrical parameters effects on the thermo-hydrodynamic flow control in the solar chimney. The obtained results indicate that the tower chimney dimensions affect significantly the flow behaviour in such systems. Kebabsa et al. [9-10] conducted a series of numerical investigation on the sloped collector entrance SCPP. They found that the new collector entrance design improve considerably the SCPP performance. Also, they proposed novel concept of tower solar chimney which consists of annular tower solar chimney. Daimallah et al. [11] studied the effect of the height and the radius of the collector on the flow behaviour in small solar chimney. They found that the mass flow rate is enhanced by about 27% for Rc = 12.5m and Hc = 0.25m. Recently, Ikhlef et al.[12] analyzed the effect of environmental factors on the performance of a large/small scale prototype of a solar chimney with a thermal storage system for five regions of Turkey corresponding to different meteorological data. They found that the best power production is for Antalya region according to the warmest and most irradiating site.

Thus, it emerges that geometrical parameters of the tower-chimney are a very important element of solar chimney power plant (SCPP). To improve the performance of SCCP, it is necessary to look for the optimal parameters of the tower-chimney.

The aim of this investigation is to study numerically the influence of the radius ratio Rt* = Rtout/Rtinlet and the height of the tower-chimney, on the flow behavior inside the SCPP of Manzanares.

2. Mathematical formulation

2.1. Physical model

Figure 1 shows the physical model geometry of the studied solar chimney. This design has a collector radius (Rc =120m), collector height entrance (Hc = 1.7m), tower chimney height (Ht = 195m) and tower chimney radius (Rt = 5m).

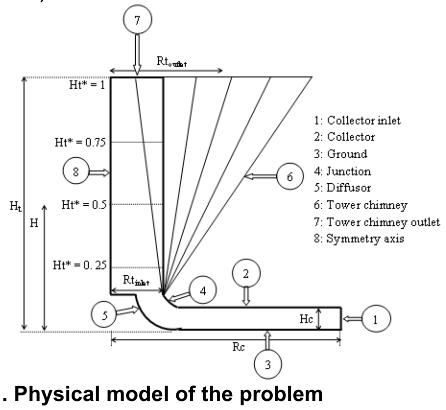

Fig. 1. Physical model of the problem

Table 1. Different configurations of the SCPP

	H(m)	Ht*= H/Ht	Rt*=Rt_{outlet}/Rt_{inlet}
Case 1	195	1	0.5-0.75-1-1.5-2-2.5-3-3.5-4-4.5-5
Case 2	146.25	0. 75	0.5-0.75-1-1.5-2-2.5-3-3.5-4-4.5-5
Case 3	97.5	0. 5	0.5-0.75-1-1.5-2-2.5-3-3.5-4-4.5-5
Case 4	49.25	0.25	0.5-0.75-1-1.5-2-2.5-3-3.5-4-4.5-5

2.2. Governing equations

The airflow through the solar chimney power plant is prescribed by two-dimensional turbulent natural convection in cylindrical coordinates. The fluid is incompressible and satisfies the Boussinesq approximation, which implies that the density variation with temperature is negligible except in the motion equation for the buoyancy term. The governing equations that describe the flow are given by,

Continuity equation

$$\frac{\partial(\rho u)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho v)}{\partial r}=0 \quad (1)$$

Momentum equations

$$\frac{\partial(\rho uu)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho uv)}{\partial r}=-\frac{\partial p}{\partial x}+2\frac{\partial}{\partial x}\left[(\mu+\mu_t)\frac{\partial u}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[(\mu+\mu_t)r\left(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial r}\right)\right]+(\rho-\rho_0)g \quad (2)$$

$$\frac{\partial(\rho uv)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho vv)}{\partial r}=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial x}\left[(\mu+\mu_t)\left(\frac{\partial v}{\partial x}+\frac{\partial u}{\partial r}\right)\right]+2\frac{1}{r}\frac{\partial}{\partial r}\left[(\mu+\mu_t)r\frac{\partial v}{\partial r}\right]-\frac{2(\mu+\mu_t)v}{r^2} \quad (3)$$

Energy equation

$$\frac{\partial(\rho uT)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho vT)}{\partial r}=-\frac{\partial}{\partial x}\left[\left(\frac{\mu}{\Pr}+\frac{\mu_t}{\sigma_t}\right)\frac{\partial T}{\partial x}\right]+\frac{1}{r}\frac{\partial}{\partial r}\left[\left(\frac{\mu}{\Pr}+\frac{\mu_t}{\sigma_t}\right)r\frac{\partial T}{\partial r}\right] \quad (4)$$

Turbulent kinetic energy equation

$$\frac{\partial(\rho ku)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho kv)}{\partial r}=\frac{\partial}{\partial x}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right)+G_k+\beta g\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial x}-\rho\varepsilon \quad (5)$$

Dissipation of kinetic energy equation

$$\frac{\partial(\rho\varepsilon u)}{\partial x}+\frac{1}{r}\frac{\partial(r\rho\varepsilon v)}{\partial r}=\frac{\partial}{\partial x}\left(\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial x}\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_\varepsilon}\right)\frac{\partial\varepsilon}{\partial r}\right)+G_kC_{1\varepsilon}\left(\frac{\varepsilon}{k}\right)-C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad (6)$$

Where: $\beta g\frac{\mu_t}{\sigma_t}\frac{\partial T}{\partial x}$ represents the effect of buoyancy;

μ_t is the eddy viscosity, expressed by: $\mu_t=\frac{\rho C_\mu k^2}{\varepsilon}$

G_k is the turbulence kinetic energy generation.

ρ_0 is the density of ambient air (kg/m3).

- Boundary conditions
- The boundary conditions for the computational domain are summarized in Table 2

Table 2.Boundary conditions

Place	Type	Description
Centreline	Axis	Symmetry
Ground	wall	250 W/m^2 ≤ Q ≤ 1000 W/m^2
Collector	wall	T= 300 K
Tower	wall	Q = 0 W/m^2
Collector inlet	Pressure inlet	Gauge total pressure=0 Pa Turbulent intensity= 5% T = T_0=300K
Chimney Outlet	Pressure outlet	Gauge pressure=0 Pa Turbulent intensity= 5% Backflow turbulent viscosity ratio=4 Backflow temperature T=T_0 =300K

3. Numerical computation

The finite volume method and the SIMPLE algorithm have been used to solve the flow governing equations (1)-(6). The second order upwind scheme is used to discretize the convective terms. We adopt a structured non uniform grid of (48 X400) cells throughout the calculation domain. We consider the prototype of Mazanares as a model and we adopt the same working conditions of Pastohr et al. [5] in order to validate the numerical model.

4. Results and discussion

4.1. Effect of the tower-chimney divergence on the velocity contours for Ht*=1

Figure 5 illustrates the velocity contours for various values of Rt*. We note that velocity increases versus the radius ratio of the towers. The obtained results indicate that air enters in the collector at low velocity and then increases to reach a high value at the entrance of the chimney tower.

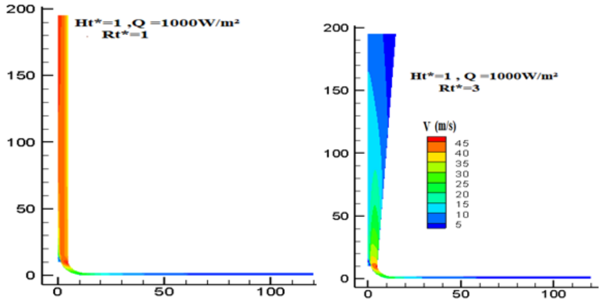

Fig.5. Development of velocity contours for various Rt* for Ht* = 1

4.2. Effect of the tower-chimney divergence on the velocity contours for Ht*=0.5

The velocity contours are shown on figure 6 for various radius ratio Rt*. We note that velocity is affected by the radius ratio Rt* and radiation intensity Q. Indeed, velocity increases from 13m/s for Q =500 W/m² to 16 m/s for Q = 1000 W/m².

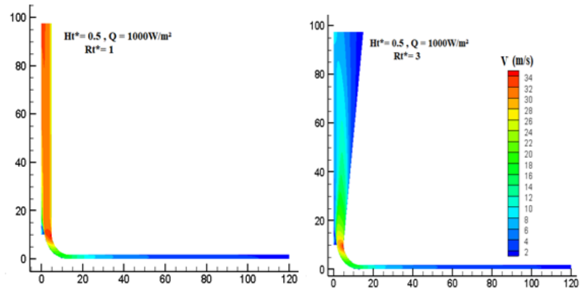

Fig. 6. Development of velocity contours for various Rt* for Ht* = 0.5

4.3. Effect geometrical parameters of the tower-chimney on mass flow rate

Figures 7 illustrates the evolution of mass flow rate versus radius ratio Rt* for various values of Q and Ht*.

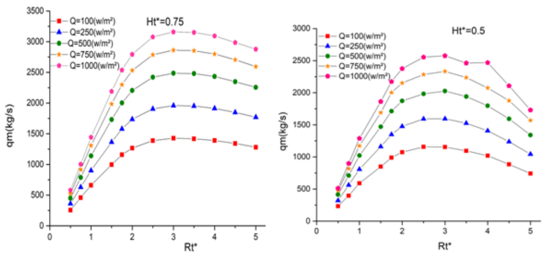

Fig.7. Evolution of mass flow rate versus Rt* for various Q and Ht*

We note that mass flow rate is affected by the variation of radius ratio Rt*. Indeed, mass flow rate increases versus Rt* until a maximal value and then decreases. This result is obtained for different values of Q and Ht*. For 0.75≤Ht*≤ 0.5, the maximal value of mass flow rate is obtained for Rt*=3.5 while for Ht* = 0.25, the maximal mass flow rate is reached for Rt* = 2.5. Also, there is a variation of mass flow rate versus the high of the tower-chimney Ht*. Indeed, mass flow rate decreases versus Ht*. Also, we note an increase of mass flow rate versus radiation intensity. The obtained results indicate that divergence of the tower-chimney conducts to an enhancement of mass flow rate by about 58.23%.

5. Conclusions

In this study, we conduct 2D-numerical investigations in order to analyze the influence of the radius ratio Rt*, the height of the tower-chimney Ht* and radiation intensity Q on the flow behavior in the SCPP of Manzanres. The obtained results indicate that velocity and mass flow rate inside the tower-chimney are affected by the Rt*, Ht* and Q. For 0.75≤Ht*≤ 0.5, the maximal value of mass flow rate is obtained for Rt* = 3.5 while for Ht* = 0.25, the maximal mass flow rate is reached for Rt* = 2.5. Also, we note an enhancement of mass flow rate by about 58.23% for the divergence of the tower-chimney.

Nomenclature

Rc	[m]	Collector radius
Hc	[m]	Collector height
Rt	[m]	Tower radius
R_{tinlet}	[m]	Inlet tower radius
$R_{toutlet}$	[m]	Outlet tower radius
Ht	[m]	Tower height
Rt*		Radius ratio
Ht*		Height ratio
u	[m/s]	The velocity in the axial direction
v	[m/s]	The velocity in the radial direction
k	[-]	Turbulent kinetic energy
Special characters		
ρ	[kg/m^3]	Air density
μ	[kg/m.s]	Dynamic viscosity
β	[K^{-1}]	Thermal expansion coefficient
ε	[-]	Dissipation of kinetic energy
μ_t	[-]	The eddy viscosity

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