

Simulation of flow and heat transfer in 3D solar chimney power plants- numerical analysis

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Abstract: According to geographical situation of Iran in northern hemisphere of earth with good solar radiation; it is one of the capable zones to use solar energy. The solar chimney power plant is an interesting system to generate power from solar energy. In this paper we modeled a 3D solar chimney power plant. So we use a five degree model power plant to reduce computational effort, this is true because of a symmetry consideration. In this way, we consider steady turbulent flow so that RANS equations are used for modeling along with Realize k- ϵ model. Solar radiation is considered according to geographical place and time of day. We consider bousinesq approximation and ideal motion for turbine with Beetz power limit.

The basis for geometry is the prototype Manzanares. We use geographical data of Yazd, which is located in center of Iran where the solar radiation has a big value. Results are compared with previous literatures. The operation and efficiency of solar chimney power plants with five different dimensions have been compared. Also the operation of solar chimney with dimensions of Manzanares prototype has been modeled in different months of a year. So an unsteady simulation during a year is represented.

Keywords: Renewable Energy, Solar Radiation, Solar Chimney Power Plant, Buoyancy, Electricity Production

1. Introduction

The energy supply of earth will become a problem in future. This is conditional by shortage of the natural recourses, like coal, gas and oil, as well as an increase in the concentration of gaseous CO₂ in the atmosphere. Regenerative energy sources must be used more increasingly to safeguard the increasing energy consumption [1]. According to geographical situation of Iran in Northern Hemisphere of earth with good solar radiation, it is one of the most capable zones to use solar energy.

The solar chimney power plant is an interesting system to generate power from solar energy. The main features of solar chimney power plants are a solar collector and a tall chimney. The collector consists of a circular transparent roof and the ground under the collector surface. Solar radiation heats the ground, which, in turn heats the air under the collector roof just like inside a greenhouse. In figure 1 a schematic of solar chimney power plant is shown. Flow in solar chimney power plant witch circulates turbine generators to generate electricity is driven by buoyancy resulting from the temperature which is higher than the surroundings at different heights.

Detailed theoretical preliminary research and a wide range of wind tunnel experiments led to the establishment of an experimental plant with a peak output of 50 kW on a site made in Manzanares (about 150 km south of Madrid) in 1981/82. The experimental plant in Manzanares operated for about 15,000 hours from 1982 onwards. In Australia a 200MW solar tower project is currently being developed [2, 3, and 4]. Pasumarthi and Sherif [5, 6] developed a mathematical model to study the effect of various environment conditions and

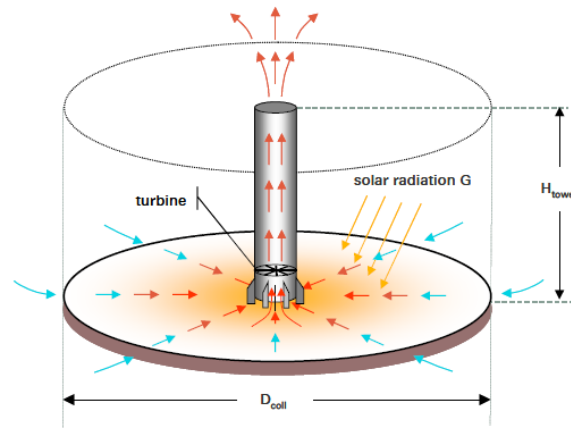


Fig. 1. Principle of solar chimney power plant

geometry on the flow and heat transfer characteristics and output of the solar chimney. They also developed three different models in Florida and reported the experimental data to assess the viability of the solar chimney concept. Pastohr et al. [7] carried out a numerical simulation to improve the description of the operation mode and efficiency by coupling all parts of the solar chimney power plant including the ground, collector, chimney, and turbine. Bilgen and Rheault [8] designed a solar chimney system for power production at high latitudes and evaluated its performance. Koonsrisuk and Chitsomboon [9] proposed dimensionless variables to guide the experimental study of flow in a small-scale solar chimney for generating electricity. The achievement of complete dynamic similarity between a prototype and its models imposed the use of different solar heat fluxes between them. These researchers in [10] showed that, to achieve the same-heat-flux condition, the roof radius between the prototype and its scaled models must be dissimilar, while all other remaining dimensions of the models are still similar to those of the prototype. In other words, the models are ‘partially’ geometrically similar to the prototype. The functional relationship that provides the condition for this partial similarity is proposed and its validity is proved by scaling the primitive numerical solutions of the flow. Tingzhen Ming et al. [11] performed numerical simulations to analyze the characteristics of heat transfer and air flow in the solar chimney power plant system with an energy storage layer. According to this paper as the material used for energy storage can be regarded as porous media, the Brinkman–Forchheimer Extended Darcy model is used to describe the flow and heat transfer characteristics in the convective porous layer. Ming Tingzhen et al. [12] advanced a 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. In present study we modeled a 3-D solar chimney power plant which includes the parts of the ground, collector, chimney and turbine together. The diagrams of electricity production and overall efficiency of plants with different dimensions and different conditions are presented.

2. Methodology

In this paper we want to model a 3-D solar chimney power plant. For this purpose we use a five degree model power plant to reduce computational effort, this is true because of a symmetric consideration. Koonsrisuk and Chitsomboon in [9, 10] used a 5-degree wedge out of the whole power plant geometry, before. In figure 2 the computational domain is shown. The basis for geometry is the Manzanares prototype. Figure 2-a shows the 2-D dimension model of power plant with structure and dimensions in [1], in figure 2-b the 2-D dimension

rotates for 5-degree and creates the 3-D model which we use here. In table 1 dimensions of modeled power plant are shown. The previous literature shows that a ground thickness of 2m is already sufficient, so for the investigated steady-state problem a thickness of 5m was assumed [1]. Pastohr in his 2-D study [1] assumed that the energy fluxes from radiation are small in comparison to the energy fluxes from convection and heat conduction. He considered a source term (W/m^2) in the ground instead of solar radiation. In figure 3 results for 2-D symmetric model is compared with Pastohr's results for temperature at collector in [1]. As you can see there is a good fitness between results in this figure.

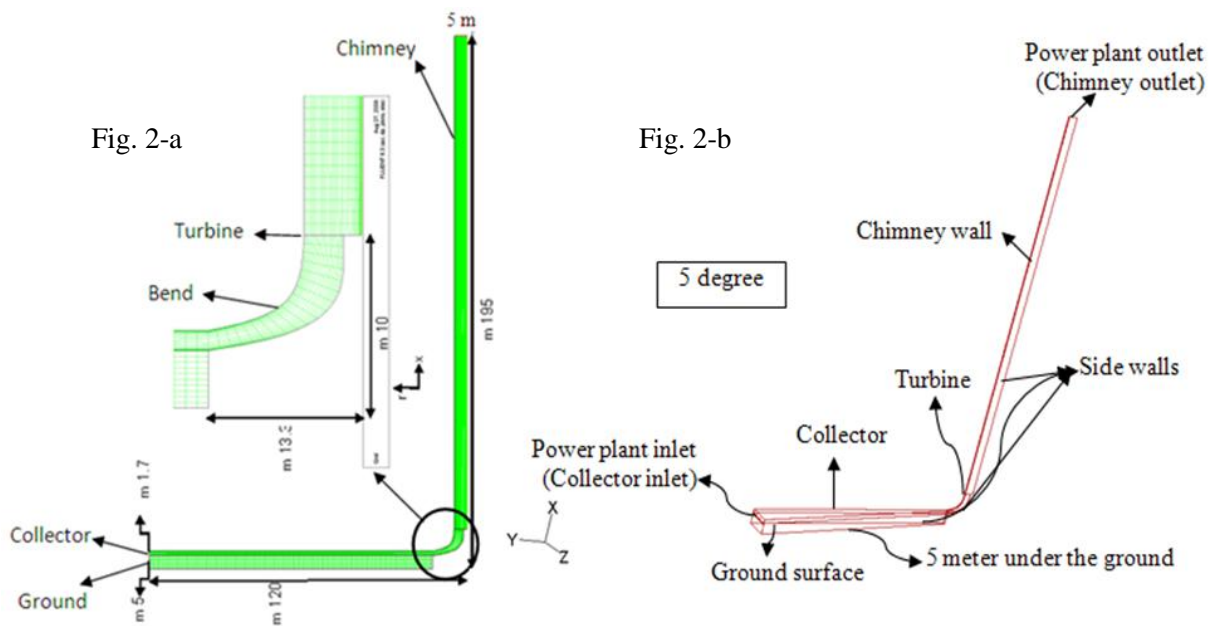


Fig. 2. Physical model: figure 2-a: 2-d dimension model, figure 2-b: 5degree 3-d model

Table 1. Dimensions of modeled power plant

different part of power plant	dimensions (m)
chimney height	195
chimney radius	5
collector radius	120
collector height	1.7
height of turbine location	10
depth of ground	5

In this study, the parts including ground, collector, chimney and turbine are modeled together numerically. In this way, we consider steady turbulent flow so that RANS equations are used for modeling along with Realize k- ϵ model. Solar radiation is considered according to geographical place and time of day. We consider Bousinesq approximation to account for the air density variation. Ideal motion is applied to turbine with Beetz power limit.

The basic equations are as follows

$$\text{Mass conversion equation: } \frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i} (\rho u_i) = 0 \quad (1)$$

Reynolds average Navier Stokes equation

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left[\mu \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \frac{\partial u_k}{\partial x_k} \right) \right] + \frac{\partial}{\partial x_j} (-\rho \overline{u'_i u'_j}) \quad (2)$$

Realize k-ε model equations

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_j}(\rho k u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_k} \right) \frac{\partial k}{\partial x_j} \right] + G_k + G_b - \rho \epsilon - Y_M + S_k \quad (3)$$

$$\frac{\partial}{\partial t}(\rho \epsilon) + \frac{\partial}{\partial x_j}(\rho \epsilon u_j) = \frac{\partial}{\partial x_j} \left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon} \right) \frac{\partial \epsilon}{\partial x_j} \right] + \rho C_1 S_\epsilon - \rho C_2 \frac{\epsilon^2}{k + \sqrt{\nu \epsilon}} + C_{1\epsilon} \frac{\epsilon}{k} C_{3\epsilon} G_b + S_\epsilon \quad (4)$$

$$C_1 = \max \left[0.43, \frac{\eta}{\eta + 5} \right], \eta = S \frac{k}{\epsilon}, S = \sqrt{2 S_{ij} S_{ij}}$$

Bousinesq approximation: $-\rho \overline{u'_i u'_j}$

$$= \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \left(\rho k + \mu_t \frac{\partial u_k}{\partial x_k} \right) \delta_{ij} \quad (5)$$

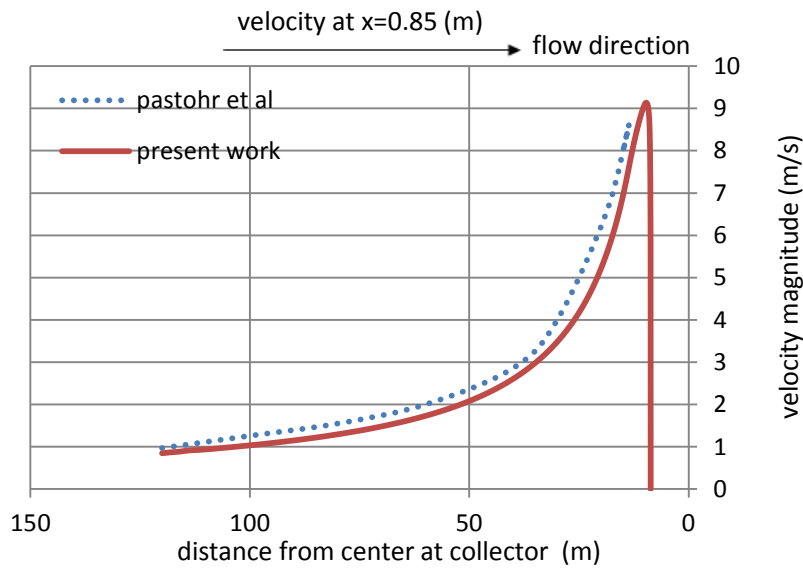


Fig. 3. Comparison between present works and reference number 1

The basis for all sections is a numerical CFD program. This program solves the basis equations of the thermal fluid dynamics. The grids performed by software are tetrahedral grids. We use hanging node adaption along with boundary adaption, volume adaption and y+ adaption during solving procedure. The geographical data of Yazd is used, which is located in center of Iran where the solar radiation has a big value. The boundary conditions which used in reference condition are shown in table 2.

Table 2. Boundary condition

surface	type	value
power plant inlet	pressure inlet	$\Delta p=0$ (pa) & $T=300$ (k)
power plant outlet	pressure outlet	$\Delta p=0$ (pa) & $T=300$ (k)
chimney wall	opaque wall	$q=0$ (w/m ²)
bend	opaque wall	$q=0$ (w/m ²)
collector	semi-transparent wall	solar load model
ground surface	opaque wall	coupled
5 meter under the ground	opaque wall	$T=300$ (k)
Two side walls	symmetry	-----
turbine	Pressure jump	Beetz power limit

3. Results for Power Plant with Different Dimensions

The operation and efficiency of solar chimney power plants with five different dimensions have been compared. In this way we consider four below options. In each case other dimensions and conditions are equal to reference case.

High chimney: chimney height=400(m)

Big collector: collector radius=240(m)

Short chimney: chimney height=100(m)

Small collector: collector radius=60(m)

To calculate different quantities we use area-weighted averages. The area-weighted average of a quantity is computed by dividing the summation of the product of the selected field variable and facet area by the total area of the surface as below [20]:

$$\frac{1}{A} \int \phi dA = \frac{1}{A} \sum_{i=1}^n \phi_i |A_i| \quad (6)$$

Results show that by increasing chimney's height or collector radius, the power plant will operate better. With a bigger collector, we have observed the most electricity production. In figure 6 the results for output power in solar chimney power plants with different dimensions are shown. To produce figure 6, the power was calculated from

$$P = \eta \Delta P_{tt} V \quad (7)$$

Where ΔP_{tt} is the total pressure drop over the turbine section, V is the average volume flow in the turbine section and η is the conversion efficiency from fluid power to electrical power. η has been assumed to be constant at 80% [14, 15, 16, 17, 18, 19].

However, the highest efficiency will occur in power plant with higher chimney. It must be noticed that in each case we defined the overall efficiency of solar chimney power plant as the ratio of the useful electric power output and the insolation over the area of the collector, so with bigger collector area the overall efficiency will reduce. The smallest amount of electricity production belongs to power plant with shortest chimney. And also, the worst

amount of efficiency belongs to power plant with shortest chimney. In figure 6 the results for overall efficiency in solar chimney power plants with different dimensions are shown.

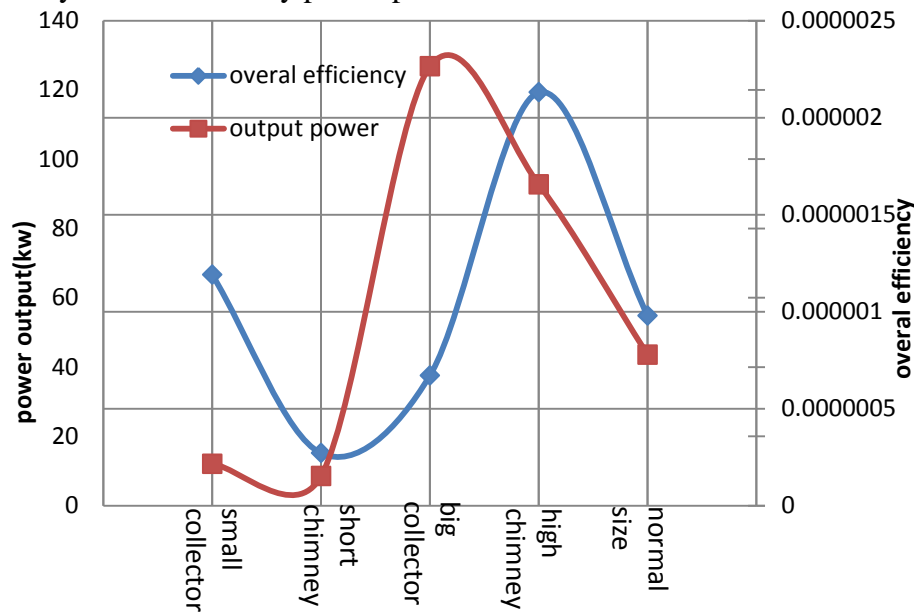


Figure 4 :Results for output power and overall efficiency in power plants with different dimensions

4. Results for Power Plant in Several Months of a Year

The operation of solar chimney with dimensions of Manzanares prototype has been modeled in different months of a year. We did the simulation for five different months (first, forth, sixth, eighth and eleventh month of a year) during a year and then results were interpolated and also extrapolated to have curves during a year. So an unsteady simulation during a year is represented. In next picture the number 1 in horizontal axis stands for first month in Persian calendar "Farvardin" and the number 12 stands for twelfth month in Persian calendar "Esfand". In each month the results are for twenty sixth day of month. In Persian calendar spring starts with "Farvardin", the first month of the year and summer starts with "Tir", the fourth month of the year. Fall starts with "Mehr" the seventh month of the year and finally winter starts with "Dey" the tenth month of the year.

As we can see from figure 10, power output and overall efficiency, at the first six month of the year are higher than second six month. The maximum power will occur between "Mordad" (5) to "shahrivar" (6), the maximum efficiency will occur between "Tir" (4) to "Mordad" (5) and the minimum power and efficiency will occur between "Aban" (8) to "Azar"(9).

5. Conclusion

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

In this paper a 3-D solar chimney power plant is modeled. The operation and efficiency of solar chimney power plants with five different dimensions have been compared. Results show that by increasing chimney's height or collector radius, the power plant will operate better.

With a bigger collector, we have observed the most electricity production. However, the highest efficiency will occur in power plant with higher chimney. Also the operation of solar chimney with dimensions of Manzanares prototype has been modeled in different months of a year. So an unsteady simulation during a year is represented. Power output and overall efficiency, at the first six month of the year are higher than second six month. The maximum power will occur between fifth to sixth months of a year, the maximum efficiency will occur between forth to fifth month of a year and the minimum power and efficiency will occur between eighth to ninth months of a year.

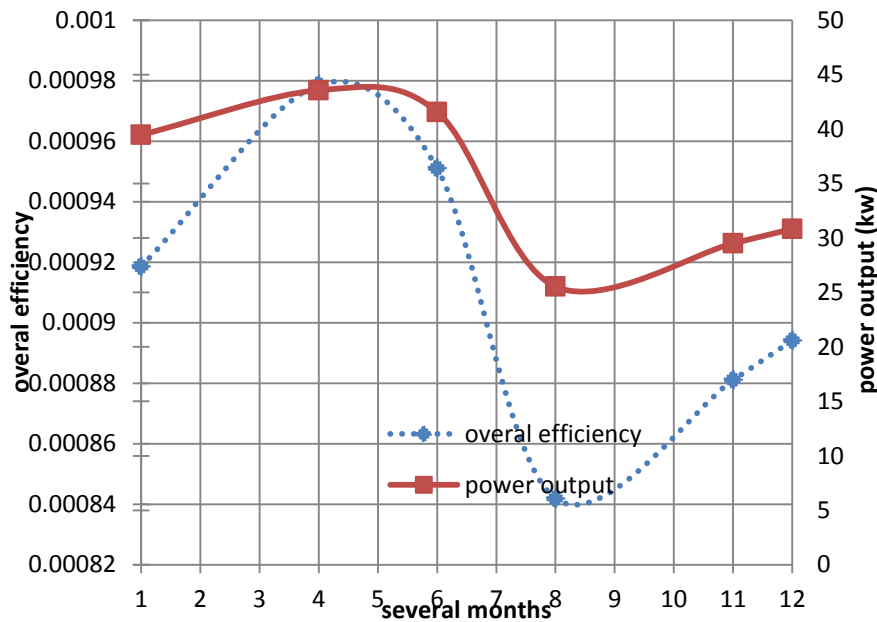


Figure 5: Power output and overall efficiency for power plant at several months

According to results of simulation of power plant with dimension of Manzanares plant, with solar insolation on collector equal to 996 (w/m²), power output is 43.57 (kw). From [2] power output of Manzanares power plant with the same value of solar insolation is equal to 43.69 (KW). The small difference can be from some idealization and software errors. So there is good fitness between present results with Manzanares experimental results.

The assumption of a steady solution does not take into account the heat storage of the ground and the fluid, so time-dependent calculations are of special interest in the future. Even more exact results can be obtained with improved physical models for the turbine. More efficient computers allow calculating even larger dimensions or full 360 degree model. In front of the importance of this subject in the future, taking into account the increasing energy needs, we hope that it will be used as a basis for other more detailed studies. These studies will take into account other parameters which influence the performances of solar chimneys power plants.

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