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Computational Fluid Dynamics Analysis and Geometric Optimization of Solar Chimney Power Plants by Using of Genetic Algorithm

Amir Karami, Davood Toghraie*

Department of Mechanical Engineering, Khomeinishahr Branch, Islamic Azad University, Isfahan, 84175-119, Iran

**Corresponding Author: Toghraee@iaukhsh.ac.ir*

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Abstract

In this paper, a multi-objective optimization method is implemented by using of genetic algorithm techniques in order to determine optimum configuration of solar chimney power plant. The objective function which is simultaneously considered in the analysis is output power of the plant. Output power of the system is maximized. Design parameters of the considered plant include collector radius (R_c), collector height (H_c), chimney height (H_t), chimney radius (R_t) and heat flux (q''). The multi-objective optimization results show that there are a strong positive correlation between the chimney height and the output power, as well as a negative correlation between the solar collector radius and the output power. Also, it was concluded that, output power of the plant could be considerably increased with increasing solar chimney height while increasing collector radius could slightly reduce output power This study may be useful for the preliminary estimation of power plant performance and the power-regulating strategy option for solar chimney turbines.

Keywords: Solar Chimney, Geometric Optimization, Genetic algorithm, Output Power, Collector, Heat Flux.

1- Introduction

With the ongoing decrease in fossil fuel resources and the increase in worldwide pollution, environment-friendly renewable energy sources are highly demanded. The increasing demand for electricity has motivated considerable research interest in a wide range of engineering applications aimed at providing a sustainable solution for the energy security problem. Among various types of renewable energy sources, solar energy takes a large proportion. The solar chimney power plant is a renewable energy device which has advantages of simple technology, low operation cost and continuous generation over other solar power plants. A typical solar chimney power plant is generally composed of a circular solar collector, a chimney at the center of the collector, turbine generators at the bottom of the chimney, and the heat storage layer. During the day, solar radiation penetrates the transparent collector to warm the heat storage layer. Some heat energy is stored in the heat storage layer, while the other heat energy is transferred to the airflow on the heat storage layer surface by convection. The warm airflow accelerates along the solar collector to the bottom of the chimney, drives the turbine generators to generate electricity, and finally leaves the system from the top of the chimney. At the same time, the ambient air continuously enters the system from the edge of the solar collector, thereby forms the continuous air current. At night or on cloudy days, the heat energy is released from the heat storage layer, which makes the system continuously produce electricity. The idea of the solar chimney was proposed initially by two German engineers, Jörg Schlaich and Rudolf Bergermann in 1976 [1]. In 1979, they developed the first prototype with a designed peak output of 50kW in Manzanares-Spain. Mullett [2] presented an analysis for evaluating the overall plant efficiency. He inferred that solar chimney power plants have low efficiency, making large scale plants the only economically feasible option. Von BackstrÖm and Gannon presented a one-dimensional compressible flow approach for the calculation of the flow variables as a function of chimney height, wall friction, additional losses, internal drag and area change [3]. Pretorius and Krögerevaluated investigated the effect of convective heat transfer equation, more accurate turbine inlet loss coefficient, quality collector roof glass and various types of soil on the performance of a large scale solar chimney power plant [4]. Ming et al. [5] presented a mathematical model to evaluate the relative static pressure and driving force of the solar chimney power plant system and verified the model with numerical simulations. Computational fluid dynamics (CFD) methodology was employed to obtain results that are used to prove the similarity of the proposed dimensionless variables. Pastohr et al. [6] presented a numerical simulation result in which the storage layer was regarded as solid. Zhou et al. [7] have performed a study in a solar chimney power plant. A pilot solar chimney power setup consisting of an air collector of 10 m in diameter and an 8 m height chimney was built. They noted that the temperature difference between the collector outlet temperature and the ambient temperature usually might reach as much as 24.18°C, which generates the driving force of the air flow in the setup. Their data analysis showed an air temperature inversion in the latter chimney after sunrise which is due to the increase of the solar radiation. Koonsrisuk et al. [8] described the constructal theory search for the geometry of a solar chimney. Patel et al. [9] found that the collector inlet opening, the collector outlet height, the collector outlet diameter, the chimney inlet diameter, and the divergence angle of the chimney, significantly influence the overall performance of SCPPs. It was shown that plant power production is a function of the collector roof shape and inlet height. Dehghani and Mohammadi [10] simultaneously took the output power and capital cost as the objective functions to optimize the configuration of SCPPs. Gholamalizadeh and Kim [11] developed a triple-objective method for SCPPs to simultaneously optimize the expenditure, the total efficiency and the power generation. They showed that a collector with an inclined roof improves the system performance, other factors such as cleaning, maintenance, and safety must also be considered in the collector design. Ideally, the best places to build an SCPP are in sunny, desert regions, which happen to be also dusty and dry. Hence, periodic cleaning is required; otherwise the collector efficiency decreases significantly because of the problem of dust accumulation on the collector roof.

Moreover, several other cost models were also presented to evaluate and optimize the configurations of SCPPs [12–17]. Okoye et al. [18] propose an effective approach to simultaneously determine the optimal dimensions of the solar chimney power plant and the economic feasibility of the proposed plant. The proposed approach is applied on a study in Potiskum, Nigeria, which reveals that building a plant with a collector diameter of 1128 m and chimney height of 715 m to Potiskum would be profitable for investors at an annual rate of return of 3% and would provide electrification to about 7500 people with a high level of reliability. Li et al. [19] derived an unsteady comprehensive mechanism model and a streamlined unsteady mechanism model of SCPPs to analyze the energy conversion and transmission of the solar chimney power plant. The coupling optimization results showed that there are a strong positive correlation between the chimney height and the power quality factor, as well as a negative correlation between the solar collector radius and the power quality factor. Sangi et al [20] conducted a more detailed numerical analysis of a solar chimney power plant. A mathematical model based on the Navier–Stokes, continuity and energy equations was developed to describe the solar chimney power plant mechanism in detail. Reasonably good quantitative agreement was obtained between the experimental data of the Manzanares prototype and both the numerical results. Guo et al. [21] investigated the optimal ratio of the turbine pressure drop to the available total pressure difference in a solar chimney system. Their results showed that the optimal ratios obtained from the theoretical model are close to those from the numerical simulation with a maximum relative difference. Cao et al [22] built a program based on TRNSYS is to simulate the performance of SCPPs. They found that the SCPP power generation is more relevant to the local solar irradiation than to the ambient temperature. Guo et al [23] investigated the optimal turbine pressure drop ratio for a solar chimney power plant by using of an analytical approach and 3D numerical simulations. Their results indicated that the solar radiation and ambient temperature have obvious influences to the optimal turbine pressure drop ratio and an improved performance of the SCPP system leads to a high pressure drop ratio. Gholamalizadeh and Kim [24] presented a computational fluid dynamics study on a solar-chimney power plant with an inclined collector roof. Their results showed that changes in the collector-roof inclination affect the convection pattern through the collector, which results in an increase in the mass flow rate of the system. Shabahang Nia and Ghazikhani [25] numerically investigated potential improvements in flow field and heat transfer characteristics of a prototype solar chimney power plant through passive flow control approaches. Evaluation of velocity magnitudes at the entrance of the chimney revealed that improvements in collector's heat transfer characteristics results in higher air velocity rates as expected. Mehrpooya et al. [26] solved a three-dimensional (3D) model of solar chimney power plant (SCPP) by componential fluid dynamic (CFD) method for Tehran climate data. Their results from the sensitivity analysis shows that, by variation of the solar radiation, the output electrical power changes from 180 Win the winter nights to 64.0 kW in the summer noon. In this case, the energy and exergy efficiencies changes from 3.50% to 93.3% and 2.00%-29.0%, respectively. In the present study, firstly we modeled a 3D solar chimney power plant which includes the parts of the ground, collector and chimney together and investigate the effect of geometric parameter on solar chimney output power. Next, a multi-objective optimization was performed by simultaneously considering the objective functions of output power. And, optimum dimension of geometric parameters were investigated. This study may be useful for the preliminary estimation of power plant performance and the power-regulating strategy option for solar chimney turbines. Design parameters of the considered solar chimney power plant included collector radius (R_c),collector height (H_c), chimney height (H_t), chimney radius (R_t) and heat flux (q'') (Fig 1).

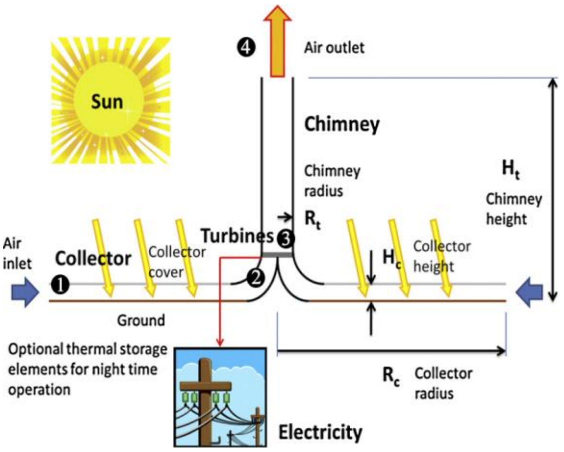


Fig 1. Schematic of solar chimney power plant.

2. Mathematical Modeling

The viscous effect was not included as the variables. The cited studies had concluded and proved that the flow in a solar tower, with low ratio of tower height to radius, could be approximated as viscous flow. Therefore, this study will investigate only inviscid flow. Turbine work also is not included since it is beyond the scope of this study because the amount of the air kinetic energy is the main aim. The numerical analysis of solar chimney treatment can be investigated by using of classical transport equations with thermophysical properties of the air. The Navier–Stokes equations, the continuity equation, the equation for the energy describe the movement of the flow generally. Accordingly, the axisymmetric mathematical model including the continuity equation, Navier-Stocks equation, energy equation used to describe the problem is as follows:

-Continuity equation:

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

-Momentum equations:

$$0=-\frac{\partial p}{\partial r}+\frac{\partial}{\partial r}\left[2\mu\frac{\partial u}{\partial r}+\mu' div(\vec{v})\right]+\frac{\partial}{\partial z}\left[\mu\left(\frac{\partial u}{\partial z}+\frac{\partial v}{\partial r}\right)\right]+\frac{2\mu}{r}\left(\frac{\partial u}{\partial r}-\frac{v}{r}\right) \quad (2)$$

$$0=-\frac{\partial p}{\partial z}+\rho g_z+\frac{\partial}{\partial z}\left[2\mu\frac{\partial v}{\partial z}+\mu' div(\vec{v})\right]+\frac{\partial}{r\partial r}\left[\mu r\left(\frac{\partial u}{\partial z}+\frac{\partial v}{\partial r}\right)\right] \quad (3)$$

-Energy equation:

$$\rho c_p\left[\frac{\partial}{r\partial r}(rTu)+\frac{\partial}{\partial z}(Tv)\right]=\frac{\partial}{r\partial r}\left(\lambda r\frac{\partial T}{\partial z}\right)+\frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right)+\frac{\partial p}{\partial t}+\frac{\partial}{r\partial r}(rpu)+\frac{\partial}{\partial z}(pv)+\varphi \quad (4)$$

Modeling turbulence:

The analysis shows that the flow through the solar chimney system is turbulent. In order to simulate the turbulent flow, the $\kappa-\varepsilon$ model is used. In this model, the turbulence kinetic energy, k, and its rate of dissipation, ε, are obtained from the following transport equations, respectively:

- $\kappa-\varepsilon$ equations:

$$\rho\left(\frac{\partial}{r\partial r}(rku)+\frac{\partial}{\partial z}(kv)\right)=\frac{\partial}{\partial z}\left(\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial z}\right) \quad (5)$$
$$+\frac{\partial}{r\partial r}\left(r\left(\mu+\frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial r}\right)+G_k+\beta g_z\frac{\mu_t}{pr_t}\frac{\partial T}{\partial z}-\rho\varepsilon$$

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

Where r, stands for the radial coordinate, and z, represents the axial coordinate. The pressure drop in solar chimney is defined by:

$$\Delta p=\frac{1}{2}\rho V^{2}_{t,\max} \quad (7)$$

Where $V_{ch,\max}$ is the maximum velocity of the air in the chimney without turbine. The output power is given by:

$$P_{tot}=\dot{m}gH\,\frac{\Delta T}{T_0} \quad (8)$$

Where $\dot{m}$ is the air mass flow rate, g is the acceleration of gravity, H is the chimney height, ΔT is the temperature difference and T_0 is the inlet temperature. The efficiency of the solar chimney calculated from"

$$\eta=\frac{\dot{m}gH\,\frac{\Delta T}{T_0}}{Q_{in}} \quad (9)$$

Where Q_{in} is the input thermal power.

3. Numerical solution

Solar energy is converted into heat energy when the solar insolation directly irradiates the surface of the energy storage layer through the transparent canopy. Thereby, the temperature of the surface of the energy storage layer rises significantly. On the other hand, convection heat transfer between the air inside the collector and the surface of the energy storage layer occurs, which can also make the air temperature increase notably. It should be noted that only a small part of the solar energy is transferred to the air inside the collector, with the rest entering the energy storage layer and being stored inside as heat energy.

A physical model for a solar chimney power plant was built based on the geometrical dimensions of the prototype Manzanares. The basic equations were simplified to axisymmetric and steady state equations. Because a turbulence model is necessary for the description of the turbulent flow conditions, the $k-\varepsilon$ standard model and standard wall mode were selected to describe the fluid flow inside the collector and the chimney. The governing equations for each model are discretized by finite volume method. For the convective and diffusive terms, a second order upwind method is employed and the SIMPLE algorithm was selected as the pressure-velocity coupling scheme.

The Body Force Weighted algorithm was selected as the discretization method for pressure term. Adaptive unstructured tetrahedral grid was adopted and the grid was refined adaptively near walls in the present study. In order to examine the accuracy of numerical results, different grids sizes are used. Finer grids are used near the wall and in the entrance of solar chimney. The number of grids was chosen to be 98730 after grid independency test. Table 1 summarizes the grid independency test results.

The plant is modeled as axis-symmetry, which the centerline of the tower is the axis of symmetry. The computational grid for calculations is shown in Fig.2.

Table1: Relative errors for power and efficiency at different grids against with Ref.[18].

Parameter	Grid1 (54960 elements)	Grid 2 (78842 elements)
Power	28%	12%
Efficiency	30%	14%
Parameter	Grid 3 (98730 elements)	Grid 4 (126314 elements)
Power	4.8%	4.6%
Efficiency	4.4%	4.3%

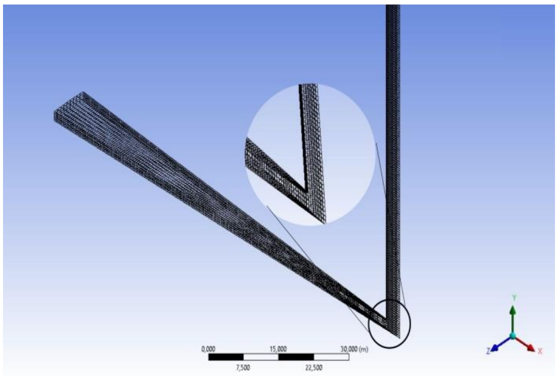


Fig 2. Computational grid for calculations

3.1 Boundary conditions

The governing equations for all the four models are subjected to the following boundary conditions:

-At the roof inlet, the total pressure and temperature are specified.

-At the chimney exit the 'outlet' condition with zero static pressure is prescribed.

-The 'symmetry' boundary conditions are applied at the two sides of the sector.

-The adiabatic free-slip conditions are prescribed to the remaining boundaries.

As specified above, that frictionless flow is being modeled, and the no-slip condition is applied to all walls.

3.2 Geometrical dimension

In table 2, the dimensions of the modeled power plant are shown.

Table 2: Dimensions of the modeled power plant

Parameter	Chimney Height	Chimney Radius	Collector Radius
Value	100m	4m	100m
Collector Height			
2m			

4- Numerical Results

In this part of the study, the numerical results of the solar chimney power plant are presented. The parameters investigated in this study were: chimney height, chimney radius, collector height, and collector radius and heat flux. The variation of flow power and efficiency with the plant geometric parameters in the chimney under different conditions is plotted in Figs. 3-6 while holding heat flux at $q''=800$ W/m^2 and $q''=600$ W/m^2. The variation of flow power and efficiency with the collector height H_c in the chimney under different conditions for heat flux are plotted in Fig.3. H_c was varied from 1m to 10m. In this figure, the dashed line represents $q''=600$ W/m^2 and the solid line denotes the $q''=800$ W/m^2 in the system.

The results show that increasing the outlet collector height from 1m to 10m causes a decrease in output power from 82.5kW to the 52.5kW at $q''=800$ W/m^2. Also, this trend has been seen for $q''=600$ W/m^2. With increase in collector height, the pressure increases and due to ideal gas law, the temperature decreases and with respect to the Eq. (8) the output power decreases. Efficiency curves for different heat flux have a similar behavior and decrease by increase the collector height. The variation of flow power and efficiency with the chimney radius R_t in the chimney under different conditions for heat flux is plotted in Fig. 4, where R_t was varied from 1m to 10 m. In this figure, the dashed line represents $q'' = 600$ W/m^2 and the solid line denotes the $q'' = 800$ W/m^2 in the system.

a

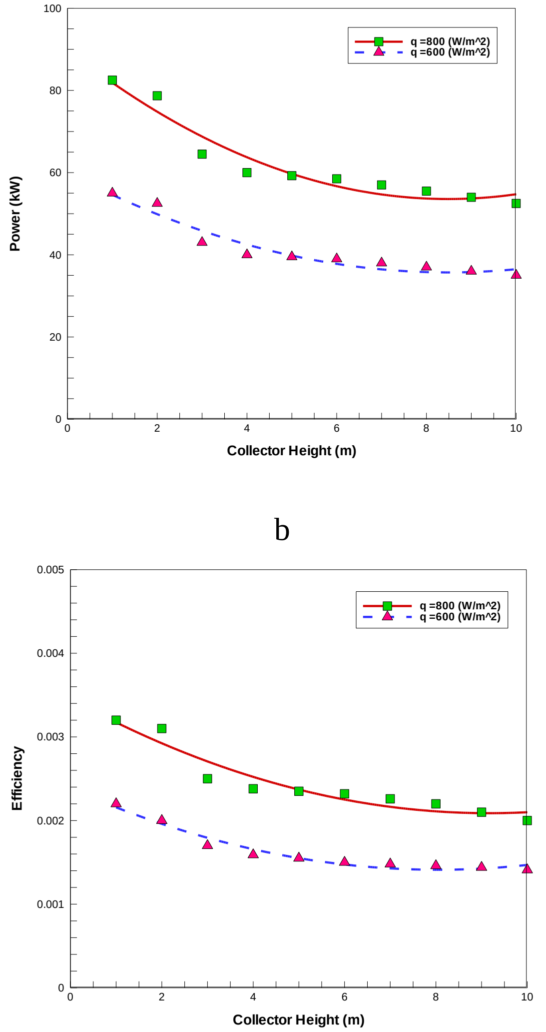


Fig 3. Effect of collector height on power and thermal efficiency of solar chimney plant.

The results show that increasing the chimney radius from 1m to 5 m causes an increase in output power and has a maximum value equal to 85.5kW for q''=800W/m^2

In Fig. 4 (a) it is clear that the output power increases with increasing chimney radius from 1m to 5 m and has a maximum value equal to 85.5kW for q''=800W/m^2. The possible reason for this can be increase in mass flow inlet due to decrease in the chimney pressure. Then by increase chimney radius from 5 to 10 m the output power decreases 28%. Also, this trend has been seen in output power curve for q''=600 W/m^2.

a

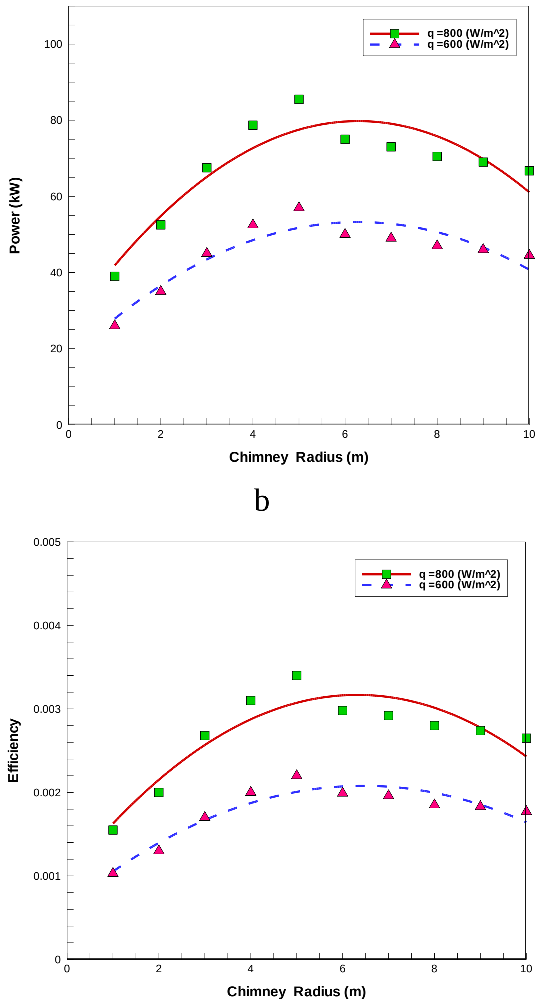


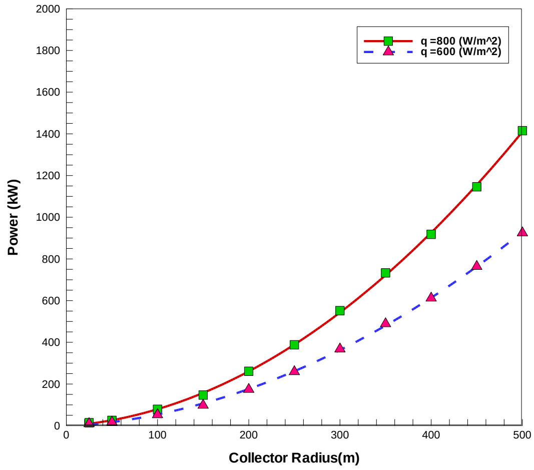
Fig 4.Effect of chimney radius on power and thermal efficiency of solar chimney plant

It can be seen from the Fig. 4 (b) that in chimney radius equal to 5 m the maximum efficiency is 0.00334 but at chimney radius equal to 10 m the efficiency decrease 28% for q''=800 W/m^2.

The variation of flow power and efficiency with the R_c in the chimney under different conditions for heat flux is plotted in Fig. 5. In this figure, the dashed line represents $q'' = 600$ W/m^2 and the solid line denotes the $q'' = 800$ W/m^2 in the system.

In Fig. 5, the values of R_c were varied from 25m to 200 m. The results show that the flow power increases with R_c while the opposite is generally true for the efficiency. According to the fig. 5, for q''=800W/m^2 and at the collector radius 25m, the output power and efficiency are 14.25 kW and 0.003 respectively. By increasing the chimney radius to 500 m output power and efficiency have a different behavior.

a



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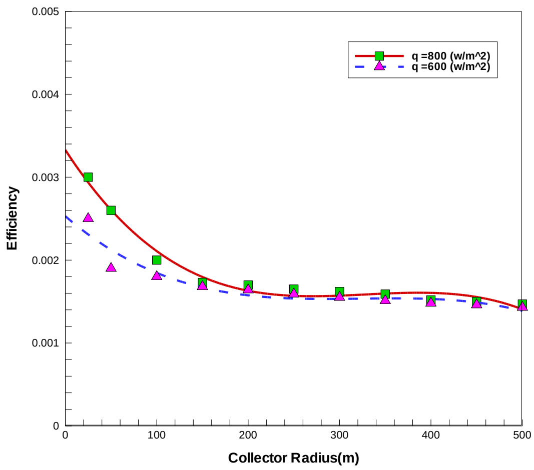
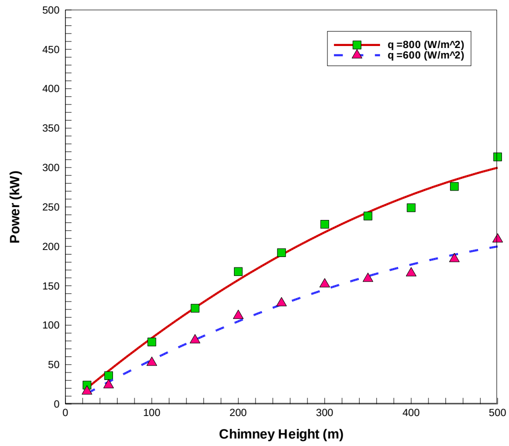


Fig 5.Effect of collector radius on power and thermal efficiency of solar chimney plant

The output power increases to 1415kW and the efficiency decreases to 0.00195. The main reason of augmentation in output power can be reduction in pressure due to collector radius increase which causes increment in mass flow rate and temperature of the air. But by increasing the collector radius, the area of heat transfer increases and with respect to the constant heat flux and Eq. (9) the efficiency decreases.

Now, we consider the effects of the chimney height, H_t. The values of H_t were varied from 25m to 500 m. Not surprisingly, an increase of H_t results in increases of power and efficiency, as shown in Fig. 6. In this figure, the dashed line represents $q'' = 600$ W/m^2 and the solid line denotes the $q'' = 800$ W/m^2 in the system.

a



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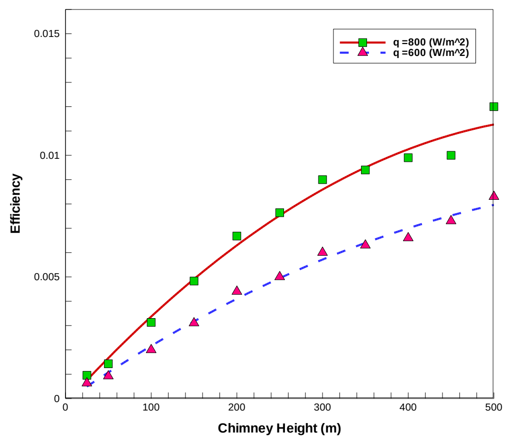

Fig 6. Effect of chimney height on power and thermal efficiency of solar chimney plant

According to Fig. 6 (a), the solar chimney output power variation versus chimney height for different heat fluxes are plotted.

It can be seen that, for q''=800 W/m^2 , the output power increases from 24 kW for chimney height 25m to 313.5 kW for chimney height 500 m. Also, for q''=600 W/m^2 the output power are 16 kW and 209 kW for chimney height 25m and 500 m respectively. It should be noted that, by increasing the chimney height, the air pressure decreases and the velocity and mass flow rate increases. Augmentation in mass flow rate causes increment in output power. In fig. 6 (b) the efficiency of the solar chimney for $q''=600$ W/m^2 and $q''=800$ W/m^2 are shown. Similar to output power variation, efficiency increases from 0.00063m at 25 m to 0.0083m at 500 m chimney height.

5. Optimization

5.1 Genetic algorithm

A multi-objective optimization problem requires simultaneous satisfaction of a number of different and often conflicting objectives. A multi-objective optimization method based on a genetic algorithm (GA) technique is employed to the solar chimney power plant system to determine the best geometric parameters of the plant. Genetic algorithm is an optimization technique based on natural genetics. GA was developed in an attempt to simulate growth and decay of living organisms in a natural environment. Even though, originally designed as simulators, GA proved to be a robust optimization technique. The basic steps for the application of a GA for an optimization problem are summarized in Fig. 7. A set of strings is created randomly. This set, which is transformed continuously in every step of the GA, is called population. This population, which is created randomly at the start, is called initial population. The size of this population may vary from several tens of strings to several thousands. The criterion applied in determining an upper bound for the size of the population is that further increase does not result in improvement of the near-optimal solution. This upper bound for each problem is determined after some test runs. Nevertheless, for most applications the best population size lies within the limits of 10 and 100 strings .The "optimality" of each string in the population is calculated. Then on the basis of this value an objective function value, or fitness, is assigned to each string. This fitness is usually set as the amount of "optimality" of each string in the population divided by the average population "optimality". An effort should be made to see that the fitness value is always a positive number. It is possible that a certain string does not reflect an allowable condition. For such a string there is no "optimality". In this case, the fitness of the string is penalized with a very low value, indicating in such a way to the GA that this is not a good string. Similarly, other constraints may be implemented in the GA. A set of "operators", a kind of population transformation device, is applied to the population. These operators will be discussed. As a result of these operators, a new population is created, that will hopefully consist of more optimal strings. The old population is replaced by the new one. A predefined stopping criterion, usually a maximum number of generations to be performed by the GA, is checked. If this criterion is not satisfied a new generation is started, otherwise the GA terminates. It is now evident that when the GA terminates, a set of points (final population) has been defined, and in this population more than one equivalently good (optimal) point may exist. As it was discussed, this advantage of the GAs permits the selection of the most appropriate solution for the optimization problem.

5.2Objective function definition

Objective function including output power (should be maximized) was taken into account for multi objective optimization problem. The selected decision variables including main geometric parameters of the SCPP were: collector radius (R_c), collector height (H_c), chimney height (H_t), chimney radius (R_t) and heat flux (q'').The decision variables might be varied in the optimization process; however, each variable is generally required to be within a reasonable range as follows:

$$\begin{aligned} &25m \le H_t \le 500m \\ &1m \le R_t \le 10m \\ &25m \le R_c \le 500m \\ &1m \le H_c \le 10m \\ &600\left(W/m^2\right) \le q'' \le 800\left(W/m^2\right) \end{aligned} \tag{10}$$

5.3Optimization results

In this study, multi-objective optimization was performed for investigating optimum dimension of geometric parameters in solar chimney power plant. The results are shown in the table 3.

Table 3: Results of optimization using genetic algorithm

q'' (W/m^2)	H_t (m)	R_t (m)	R_c (m)	H_c (m)	Power (kW)
800	100	4	100	2	53
800	100	5	100	2	60
600	200	4	150	2	110
800	100	4	100	1	58
600	150	4	100	2	180
600	100	4	300	2	402
800	500	4	100	2	250

The optimization results indicate that there is a strong positive correlation between H_t , R_t and the output power. But overall, the output power of solar chimney power plant improves with the increase of H_c and decrease with the R_c.

6. Conclusions

Steady-state numerical simulations of solar chimney power plants were presented in this paper. A mathematical model was developed to accurately describe the solar chimney power plant mechanism. A 3D domain with the k-ε turbulence closure was simulated. A parametric study was carried out to consider the effect of the geometric characterizations of solar chimney power plant on the fluid flow and the heat transfer. Then, by considering output power of plant, multi-objective optimization was carried out. To obtain optimum dimension of the geometric parameters, a multi objective genetic algorithm was utilized to optimize the objective function. This optimization approach was very helpful and effective for selecting optimal geometric parameters of a solar chimney power plant. Based on demanded output power which is determined by a decision maker, optimum configuration of the plant can be selected from genetic algorithm results. It was concluded that, output power of the plant could be considerably increased with increasing solar chimney height while increasing collector radius could slightly reduce output power.

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