Parametric study of large-scale solar chimney power plant under conditions of Ber'Alganam area (Azzawia-Libya)

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Abstract

Renewable and sustainable energy sources are nowadays considered to be a key element to provide sustainable development of the worldwide economy. This paper aims to perform the parametric study of large scale Solar Chimney Power Plant (SCPP). This technique is one of techniques which can be used to produce electrical power from the sun, and that fit our local situation in Libya, because it does not need water in operation like CSP technology. Ber' Alganam area was proposed as a plant site, and average monthly solar radiation and meteorological data of Ber' Alganam were used in the calculation. A mathematical model was developed and experimentally validated in a previous work. The model was programmed to evaluate thermo-hydraulic behavior of the SCPP as well as estimating the effect of changing the geometrical dimensions and its limitations on the productivity and efficiency. Four configurations of solar chimney plants with nominal power was studied as follows (5MW, 30MW, 100MW and 200MW). The results showed that the height and diameter of the chimney and the diameter of the solar collector are the most important dimensions affecting the productivity and efficiency of SCPP, while the collector height has no effect. Finally, the study concluded that productivity and efficiency increase with increasing the height and chimney diameter and solar collector diameter, but both the solar collector and the chimney diameter has the optimum ranges. Also, this paper recommended that, the geometrical dimensions of the SCPP should be choosing in the optimum ranges to avoid meaningless cost.

Keywords: renewable energy, solar energy, solar chimney, solar updraft tower, SCPP, greenhouse, large-scale solar power plant.

1. INTRODUCTION

A solar chimney is a promising technology, which has been proved to produce electricity by the sun. Solar chimney consists of three main components; solar air collector (greenhouse), chimney and wind turbine. The solar air collector is a circular ground area covered by transparent roof made by plastics sheet or glass plate opened at periphery, the height of roof at collector center is higher than at the peripheral side, the main function of solar air collector is to heating air under the collector roof by a greenhouse. The chimney is located at a center of collector; the main function of the chimney is to convert the thermal energy of the air inside the collector to kinetic energy based on buoyancy effect. The wind turbine is located at the entrance of the chimney, which used to convert some of kinetic energy to the useful mechanical (shaft) work to drive the electrical generator.

The main advantage of solar chimney lies on, this technology do not need water for operation. For that, the conditions in Libya are very favorable for this type of solar thermal power plant: Solar radiation levels are high; there are large suitably flat areas of land available, demand for

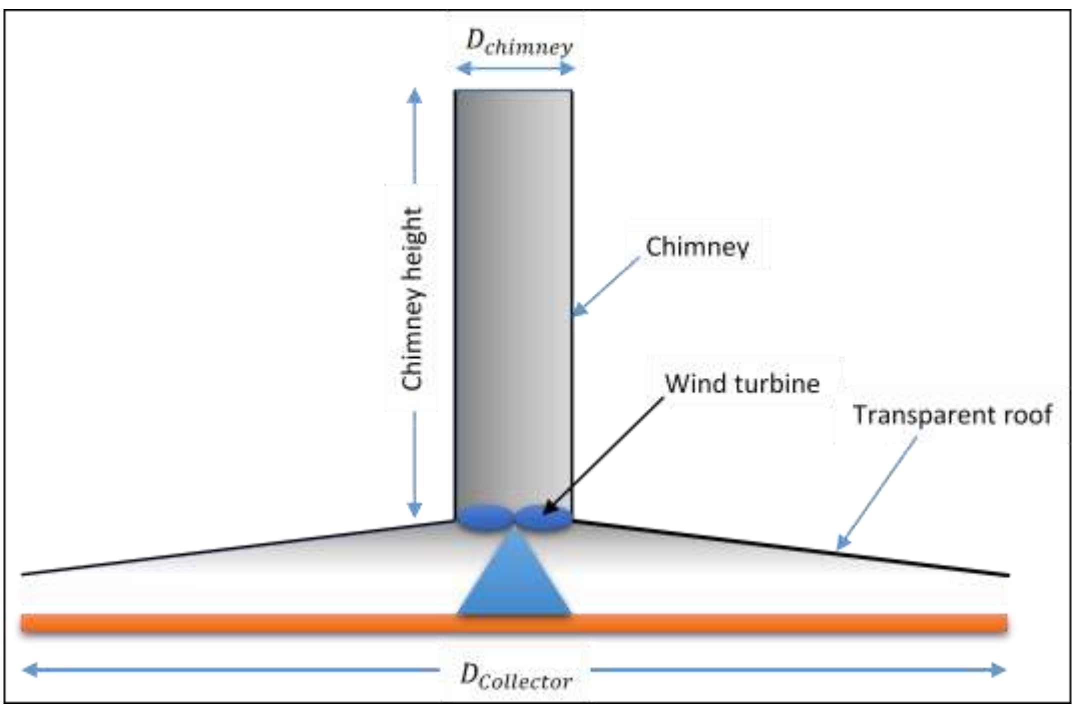

Figure (1) a schematic of solar chimney power plant

electricity increases, and the water resources are limited Figure (1) a schematic of solar chimney power plant.

The first prototype of solar chimney power plant was constructed at Manzanares in Spain 1982 [1], The 50 kW prototype produced electricity for seven years, proving that the solar chimney is a technology capable to generating electrical power from the sun. Several researchers examined the effects of various geometrical parameters on the plant performance. Haaf et al., showed that an increase of the collector radius increased output power but reduced plant efficiency. On the other hand, efficiency increased with the tower height, and mass flow rate increased with the tower radius while the flow velocity remained constant [1]. Pasumarthi and Sherif, reported that increase of tower height resulted in higher velocity and mass flow rate; and when the insolation was fixed, an increase in the mass flow rate was accompanied by a lower air temperature at the collector outlet [2, 3]. Chitsomboon found that efficiency of the plant was invariant with respect to the insolation level, the size of the roof and the tower diameter. He also found that the functional relationships between the power and the efficiency with the tower height were linear [4]. Gannon, Backström, and Schlaich et al., proposed that the overall efficiency was influenced only by the tower height [5, 6]. Bernardes et al. developed a thermal and technical analysis to estimate the power output and examine the effect of various ambient conditions and structural dimensions on the power output [7]. Dai et al., demonstrated that the power output increased nonlinearly with the size of the plant, rapidly when the size was small and at a slower rate when the size was larger [8]. Pretorius et al., also developed a numerical model simulating the performance of a large-scale reference solar chimney power plant, indicating that greater power production is possible by optimizing the collector roof shape and height [9]. Pastohr et al. 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 [10]. Koonsrisuk A. and Chitsomboon T., the influence of tower cross-sectional area changes on the potential of a solar tower power plant was investigated, the results show that, the divergent tower helps increase mass flow rate and kinetic energy over that of the constant area tower [11]. More recently, Tingzhen et al., a mathematical model was proposed that could predict the effects of various parameters, such as the tower height and its radius, the collector radius and the solar radiation, on the relative static pressure, the driving force, the power output and the efficiency of a solar chimney [12]. The present study extends the efforts [13], [14] to evaluate the large scale Solar Chimney Power Plant (SCPP) under the Libyan conditions. In order to identify the optimum size parameters, this study will focused on consider the effects of change main size parameters on the power output and efficiency. Chimney height, chimney diameter, collector diameter and collector height are common parameters will be considered. Four configurations of large scale SCPP proposed by Jorge Schlaich are taking as a sample sizes.

2. METHODOLOGY

Methodology section consists of the following steps

- Mathematical model description
- Site selection
- Definition of the reference case.

2.1Mathematical model description

The previous work of [8] developed a mathematical model for simulate SCPP. The model was made the use of well-stablished energy equations, which was then customized and applied. The results obtained compared with experimental data recorded; hence, it will be used as a starting point of this work.

Using the mathematical model, the comprehensive analyzed for the system was conducted by modelling and simulating the SCPP. Figure (1) present the flow diagram of model. All formulation of the analysis was presented in previous work [13, 14]. The model was programmed using Finite Different Method (FDM). This method needs to discretize the solar collector into finite number of annuli. The heat energy equations is applied for each annulus independently using guessed value of mass flow until arrive the last annuli and satisfy the temperature at the chimney entrance, after that, apply the buoyancy force equation and estimate the mass flow through the chimney, the process is iteratively repeated until convergence occur (the mass flow estimated closed with guessed one). It should be noted that, the maximum power theoretically is achieved when two thirds of the total pressure difference is utilized by the turbines.

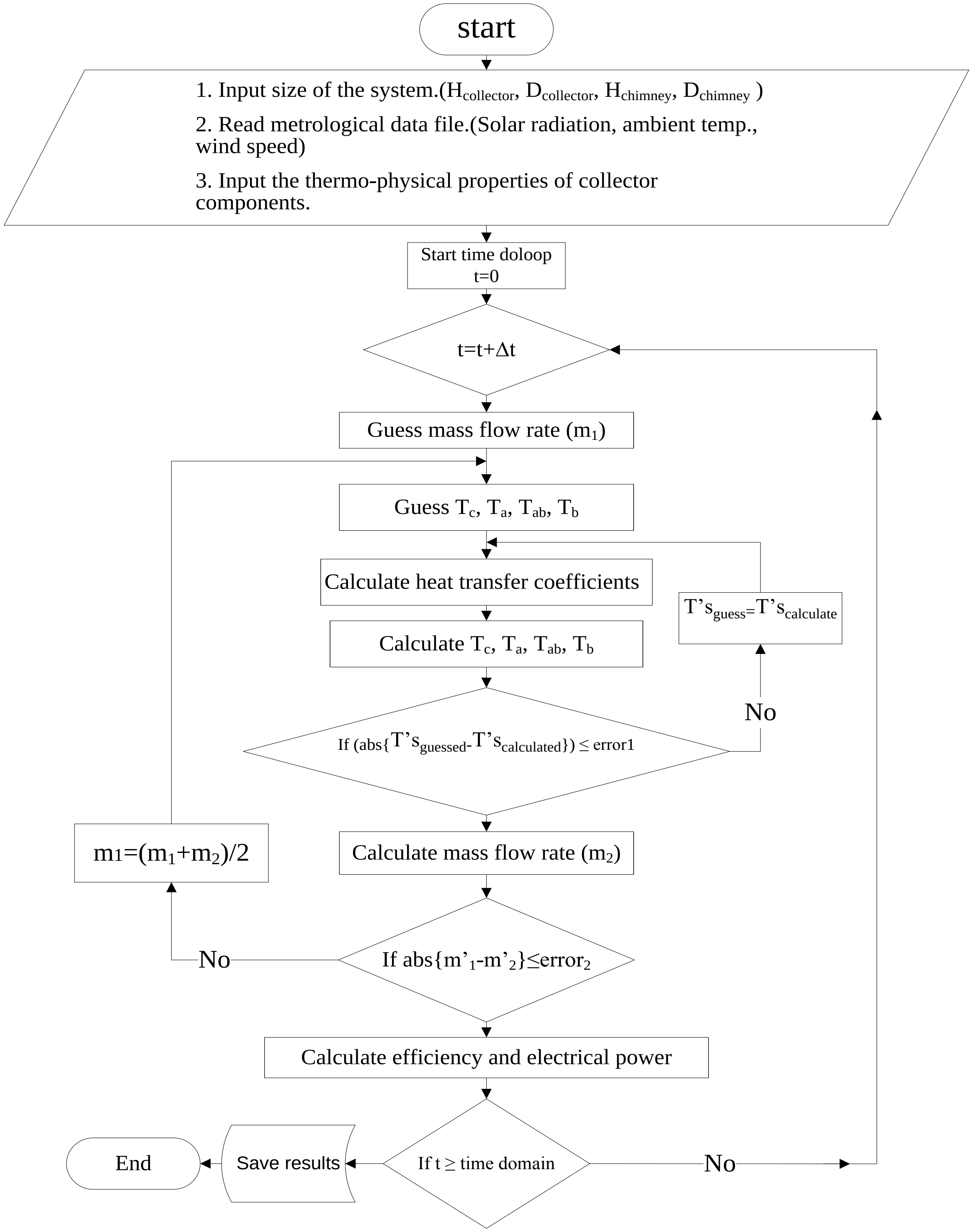

Figure (1) model flow diagram

2.2 Site selection

Libya has a large desert and a low population density especially in the south region and high rates of solar radiation are encouraging factors for investments in the field of solar energy. Solar chimney technology is one of the good choices because this technology requires no water for the operation. The proposed site Bir’Algnam with geographical coordinates (32°17' N, 12° 3' E) is a flat land with low population density, nearby electric network and all the climate data necessary for the analysis were measured and recorded for the year 2011 [15].

2.3 Definition of the reference case

The reference cases means that, the standard configuration of SCPP or the meteorological data, that will be fixed when needs to present the effect of certain parameter, and can be classified as two types:

1. **Reference dimensions**

This study focused on parametric analysis of 5MW, 30MW, 100MW and 200MW large-scale SCPP, typical dimensions and specifications of these plants were reported by Schlaich and others [6, 16] and tabulated in table (1).

Table (1) specifications of four SCPP configurations

Design specification	unit	prototype	proposed configurations for large scale			
			Model 1	Mode1 2	Model 3	Model 4
Chimney height	m	195	550	750	1000	1000
Chimney diameter	m	10	45	70	110	120
Collector diameter	m	240	1250	2900	4300	7000
Collector height (entrance)	m	2	2	4.5	6.5	3.5
Collector height (outlet)	m	2	10	15.5	20.5	25
Type of turbine		axial	Propeller			
Turbine shaft direction		vertical	Horizontal			
Turbine location at		chimney inlet	circumference of the chimney base			
Number of turbines		1	33	35	36	32
Power of single turbine	KW	50	152	857	2778	6250
Turbine pressure drop	%	97.0	82.0	82.0	82.0	67.0
Nominal load	MW	0.05	5	30	100	200
ΔT of air through collector	℃	20	25.6	31	35.7	46
Air speed through chimney	m/s	8	9.07	12.59	15.82	18

Some of the above values were estimated for the site under:

- Annual global horizontal solar radiation of 2301 kWh/(m² annual).
- Ambient temperature of 17℃.
- Average wind velocity 3.5 m/s.

2. Reference conditions

The reference conditions means the site conditions and thermos-physical properties of solar chimney components that will used for calculation.

2.1 Meteorological data

The meteorological data that will be choosing at certain time and deals with it as fixed values to calculate the effects of changing each dimension on the performance and efficiency. According to investigation of performance and production potential [15], the nominal power of solar chimney do not means the rated power, but it is the maximum power that reached at peak summer; where maximum solar radiation. Therefore, the reference case is the condition of July at 2 PM, as tabulated in table (2):

Table (2) reference conditions (2 PM on July 2011)

Solar radiation	[W/s]	955
Wind speed	[m/s]	3.69
Ambient temperature	[℃]	46.2

2.2 Thermo-physical properties

In this analysis, the dry soil layer as the insulator and crushed granite layer as the absorber and the 5mm of high transmissivity low-emissivity glass as the transparent cover were selected for the proposal plants. The optical and thermo-physical properties of each component are listed in table (3).

Table (3) fixed thermo-physical and optical properties of the system components

Property	Unit	Granite	Dry soil	**Glass**
Density	Kg/m^3	2640	190	2700
Specific heat	J/(kg K)	820	900	840
Thermal conductivity	W/m k	1.73	0.25	0.78
Absorptivity	-	0.9	-	0.005
Emissivity	-	0.9	-	0.21
Transmissivity	-	-	-	0.9

Results

The four models of SCPPs listed in table (1) are considered for analyses. The metrological data and thermos-physical properties used for calculation are listed in table (2, 3). The analytical model has been developed and experimentally validated in previous work [13, 14]. Some of the figures presents the design point which reported in the literature. The results of this paper consists of:

1. Effect of chimney height on the power generation.
2. Effect of collector diameter on the power generation.
3. Effect of the chimney diameter on the power generation.
4. Behavior of the air velocity through the collector sections.
5. Effect of the chimney height on the power output and overall efficiency.
6. Effect of the collector diameter on the power output and overall efficiency.
7. Effect of the chimney diameter on the power output and overall efficiency.

1. Effect of chimney height on the power generation

Figure (2) shows that the overall efficiency and the power generation are highly dependent on the height of the chimney and that as chimney height increase, one expects that power harvested increases. The higher the chimney means higher driving force that came from buoyancy effect. Table (3) summaries the fixed parameters used for calculation.

Table (3) fixed geometric parameters of four models of large solar chimney power plants

Solar chimney Power plant	Model 1	Model 2	Model 3	Model 4
Collector diameter [m]	1250	2900	4300	7000
Average collector height [m]	6	10	13.5	14.25
chimney diameter [m]	45	70	110	120

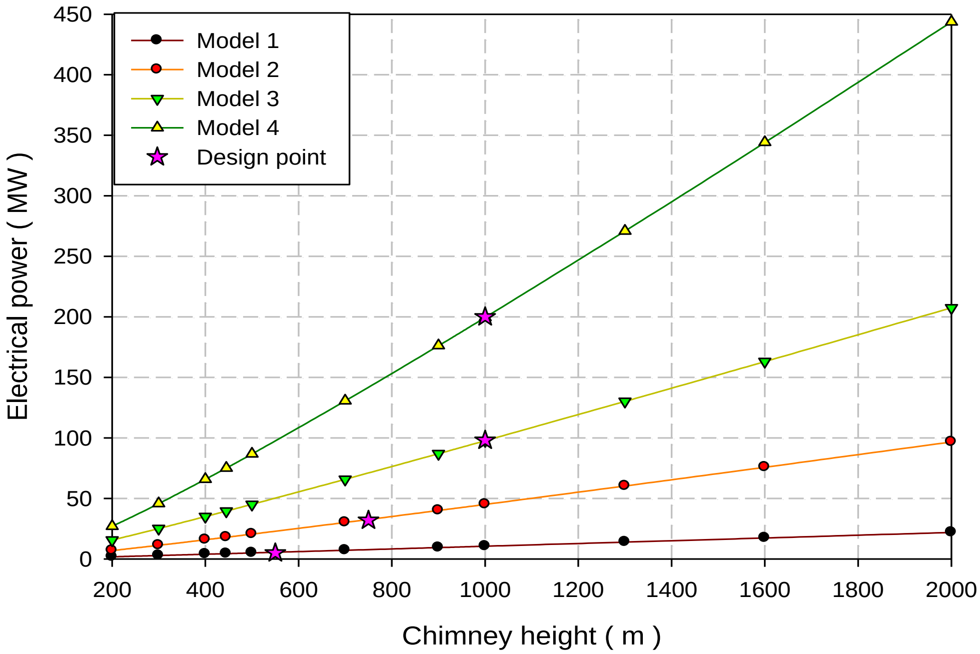

Figure (2) effect of the chimney height on the solar chimney power generation

Figure (2) shows that the chimney height is important physical variables for the solar chimney design; the power increases with the height of the chimney. At certain height, the slop is higher for large SCPP than that of smaller one this is because of increasing in air temperature at chimney entrance $T_{chimney}$.

2. Effect of collector diameter on the power generation

Table (4) lists the data was used to evaluate the effect of the collector radius on the power output of SCPP. Figures (3& 4) show that the collector diameter is important physical variable for the solar chimney design. For certain size of the solar power plant; the power output increases with increasing in the collector diameter to a certain value of diameter and beyond that value the power stays constant; that mean for certain size of the solar power plant, there is optimum value of collector diameter. From figures (3& 4), the optimum values of collector diameters for model 1 and model 2 are about 3500 m and 15000 m respectively.

Table (4) fixed geometric parameters of four models of large solar chimney power plants

Solar chimney Power plant	Model 1	Model 2	Model 3	Model 4
Chimney diameter [m]	45	70	110	120
Chimney height [m]	550	750	1000	1000
Average collector height [m]	6	10	13.5	14.25

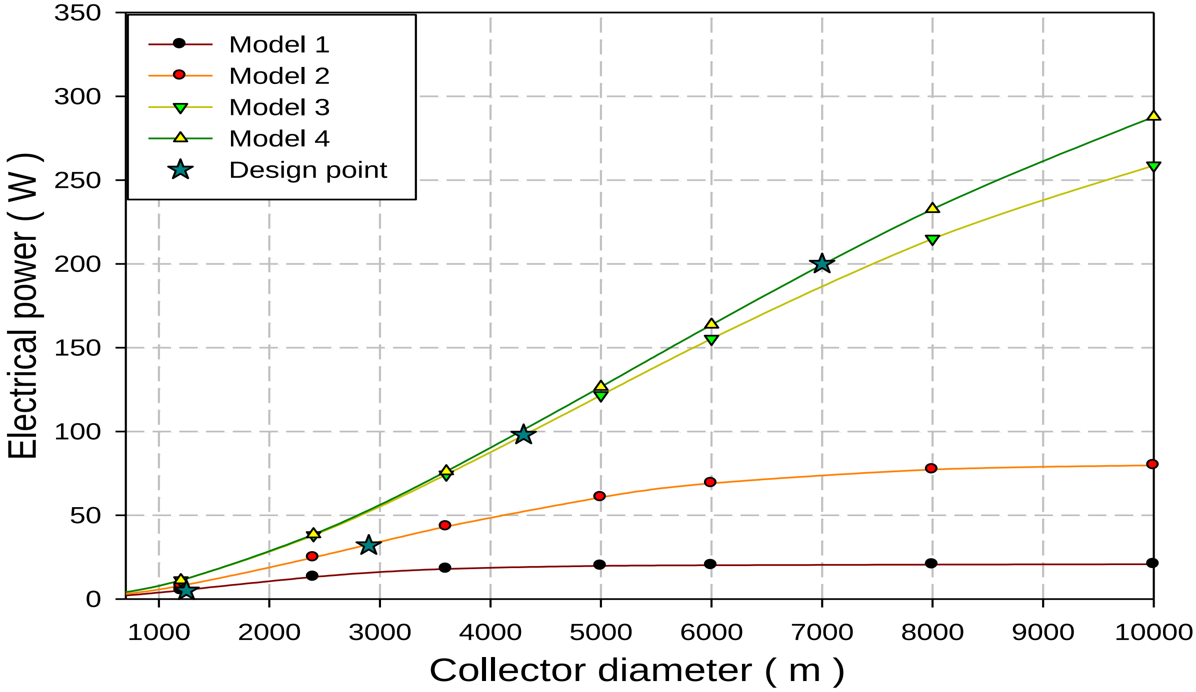

Figure (3) effect of the collector diameter on the solar chimney power production

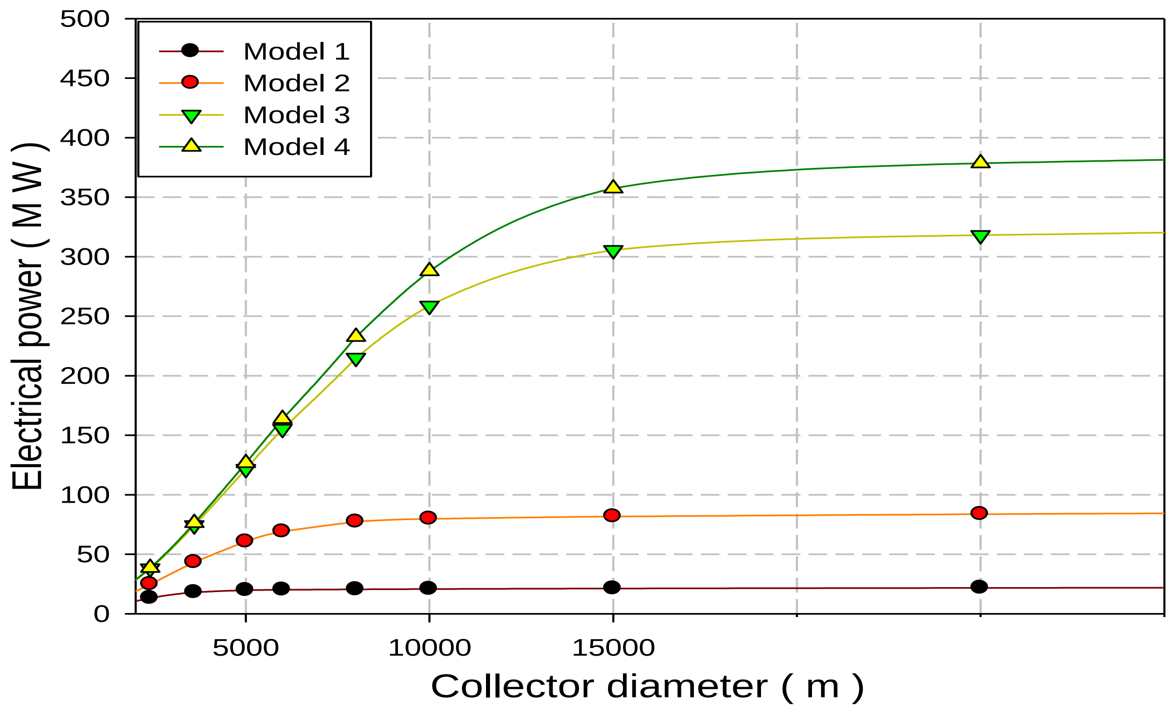

Figure (4) optimum collector diameter

3. Effect of the chimney diameter on the power generation

Table (5) lists the data used to evaluate the effect of the chimney diameter on the power generation of SCPP. Figure (5) shows that the chimney diameter has strong effect on harvested power when chimney diameter is below a critical value. The critical diameter depends on the boundary and the relation of inertia force with respect to viscous force or the Reynolds number. If chimney diameter is larger than the critical diameter value, the effect of chimney diameter is minimal. As chimney diameter increase, the friction losses decrease as air velocity inside the chimney decreases.

Table (5) fixed geometric parameters of four models of large solar chimney power plants

Solar chimney Power plant	Model 1	Model 2	Model 3	Model 4
Collector diameter [m]	1250	2900	4300	7000
Average collector height [m]	6	10	13.5	14.25
chimney height [m]	550	750	1000	1000

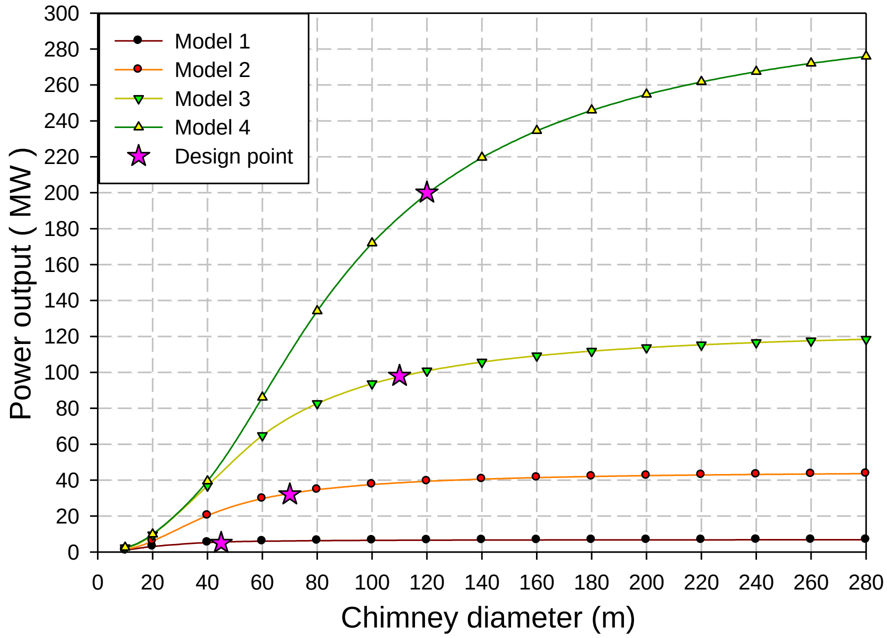

Figure (5) effect of the chimney diameter on the solar chimney power production

4. Behavior of the air velocity through the collector sections

The behavior of the air velocity through the collector sections for proposed models presented in figure (6). It should be noted that, the slop of the collector cover is accounted in this calculation. The air velocity varies along the collector radius due to change of cross section area and the air density.

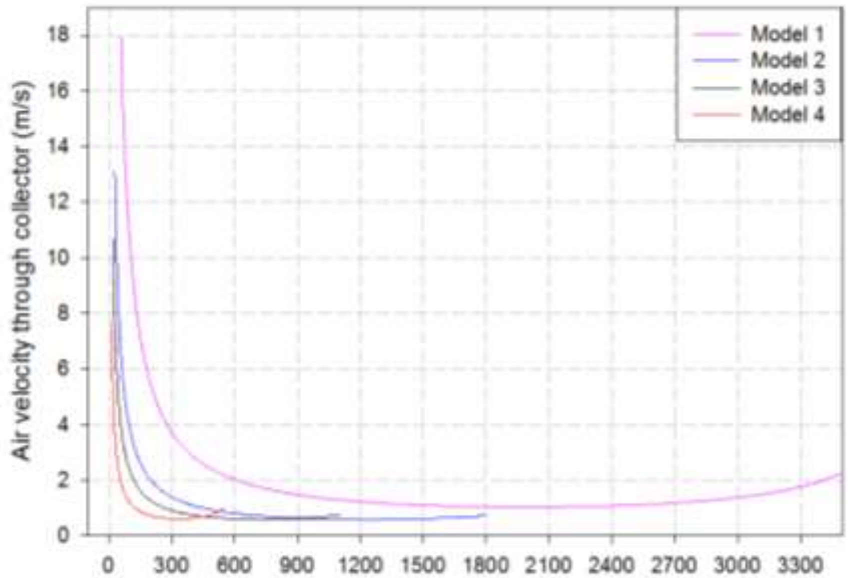

Figure (6) air velocity through the collector sections (m/s)

5. Effect of the chimney height on the power output and overall efficiency

A major problem of Solar Chimney Power Plant (SCPP) is its low conversion efficiency as determined by the thermal performance of the system. Figure (7) indicated that, the chimney height has significant effect on the power output and overall efficiency of SCPP. The figure indicates that the power and overall efficiency significantly increases with increasing the chimney height.

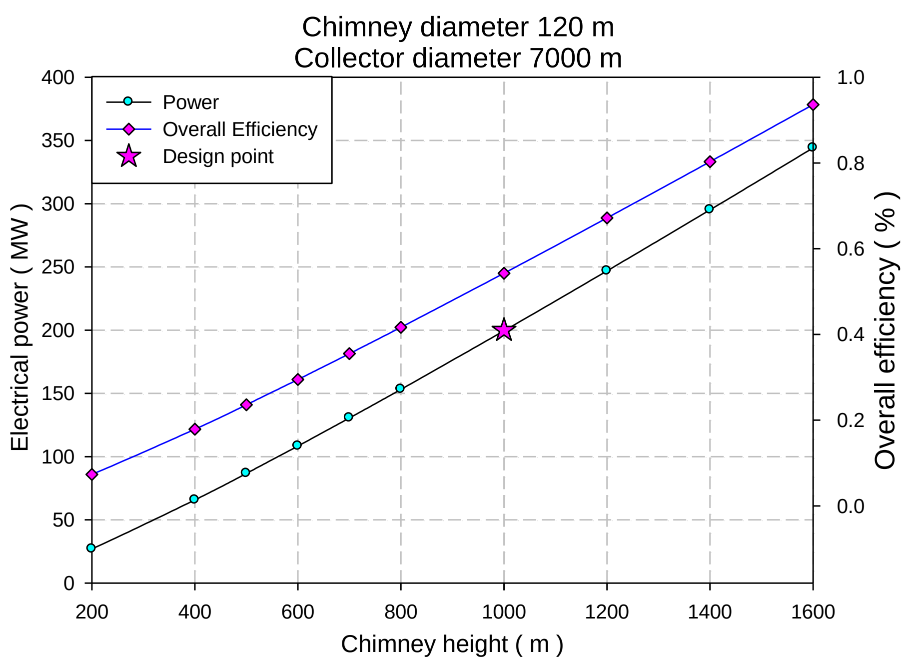

Figure (7) effect of chimney height on the power output and overall efficiency of SCPP

6. Effect of the collector diameter on the power output and overall efficiency

Figure (8) show that the collector diameter has significant effect on the power output and overall efficiency of solar chimney plant. The figure indicates that, the power increases with the increase of the collector diameter but the efficiency decreases with the increase in the collector diameter**.** However for certain size of the solar power plant; the power output increases with increasing the collector diameter to a certain value of diameter, beyond that value the power stays constant; that mean for certain size of the solar chimney power plant, there is a maximum value of collector diameter. Beyond that value there is no any benefit on power production that is because the air does not gain any heat after that size due to the equality of the air temperature with the absorber temperature. From figures (4), the useful maximum value of collector diameter for SCPP of chimney height of 1000 m is about 15000 m.

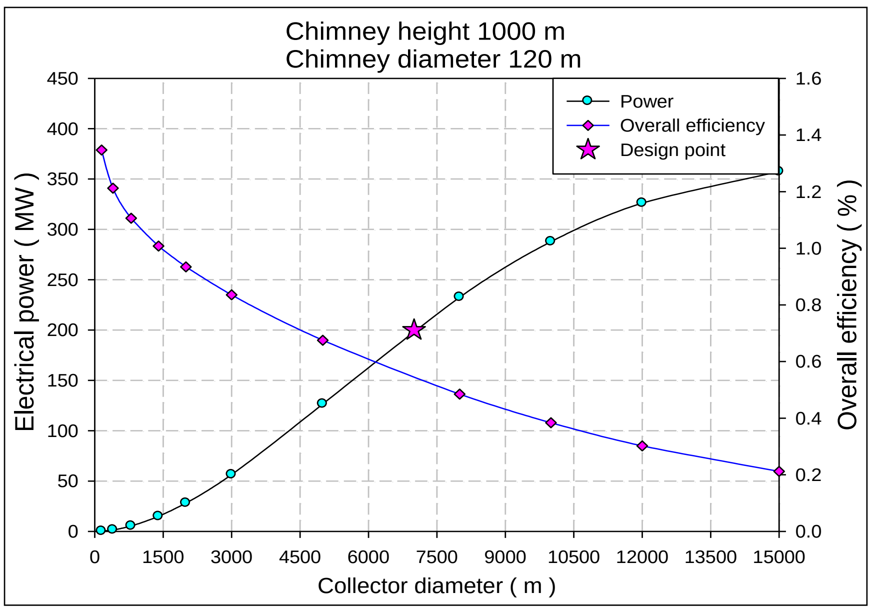

Figure (8) effect of collector diameter on the power output and overall efficiency of SCPP.

7. Effect of the chimney diameter on the power output and overall efficiency

Figure (9) indicated that, the chimney diameter has strong effect on harvested power and overall efficiency of solar chimney plant when chimney diameter is below a critical value. The critical diameter depends on the boundary and the relation of inertia force with respect to viscous force or the Reynolds number. If chimney diameter is larger than the critical diameter value, the effect of chimney diameter is minimal. As chimney diameter increase, the friction losses decrease which decrease as air velocity inside the chimney decreases.

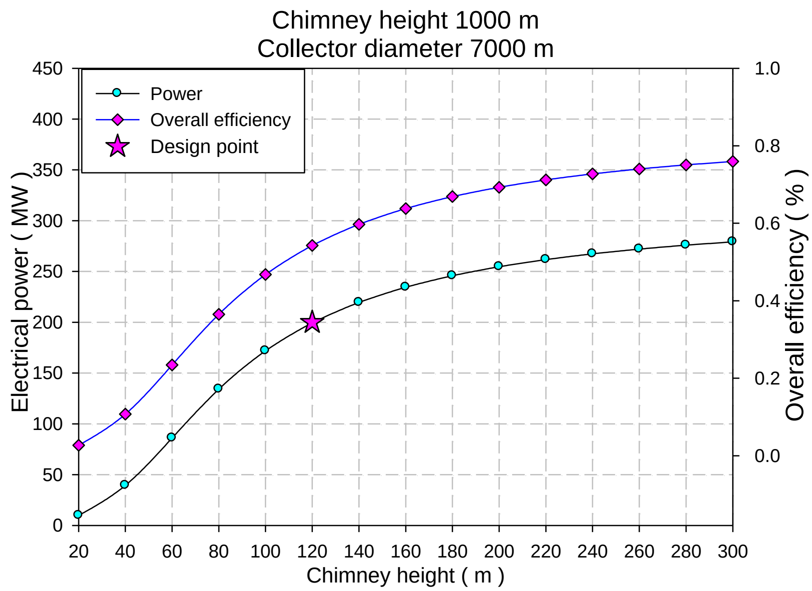

Figure (9) effect of chimney diameter on the power output and overall efficiency of SCPP

CONCLUSION

Solar chimney technology is an innovative way, to produce electricity from sun and provide the sustainability development. This work presents an parametric study of solar chimney power plant under Ber' Alganam condition. The mathematical model implement to simulate the behavior of production and efficiency of SCPP with changing the main designing parameters; chimney height, chimney diameter and collector diameter. The model shows that chimney height, chimney diameter, and collector diameter are critical geometrical parameters should be considering before building solar chimney power plant. The results showed that the height and diameter of the chimney and the diameter of the solar collector are the most important dimensions affecting the productivity and efficiency of SCPP, while the collector height has no effect. The study concluded that, the overall efficiency and total power harvested has very strong effected by chimney height; power and efficiency increase with increasing chimney height. Noteworthy, the chimney diameter has a critical value for each solar chimney should be calculated. Because if the chimney diameter is less than the minimum value it causes an increase of friction losses inside the chimney which leads to reduces the power output of plant. The solar collector has the optimum range, beyond this range the curves of power generation and efficiency become flatten and there are no meaning to increase collector diameter. The figures presents the design point of each dimensional parameter that reported in the literature and found in the reasonable range. Finally, this paper recommended that, the geometrical dimensions of the SCPP should be choosing in the optimum ranges to avoid meaningless cost.

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