Solar Chimney Power Plant in Basrah

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Abstract

The solar chimney is a natural draft device which uses solar radiation to provide upward momentum to the in-flowing air, thereby converting the thermal energy into kinetic energy through an air turbine which in turn can be converted into electrical energy. The main parts of the solar chimney power plant are a large circular solar collector , tall chimney and air turbine. In this paper a theoretical study was performed to evaluate the performance of a solar chimney power plant system in Basrah city where the sunny days and the solar radiation is high. A mathematical model was developed to study the effect of various parameters on the output power of the solar chimney. It was found that the output power depends strongly on the chimney tall and the difference between the collector air temperature and the ambient air temperature as well as the outside heat transfer coefficient which essentially depends on the wind speed.

محطة القدرة الكهربائية ذي المدخنة الشمسية في البصرة

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المدخنة الشمسية هي وسيلة طبيعية لتحريك الهواء من الاسفل الى الاعلى بتسخينه بواسطة الاشعاع الشمسي والاستفادة من زخم الهواء الصاعد الذي تسببه قوة التعويم الناتجة من انخفاض كثافته والتي يمكن تحويلها الى طاقة ميكانيكية باستخدام توربين هوائي ومن ثم الى قدرة كهربائية. تتكون محطة القدرة الكهربائية ذي المدخنة الشمسية من أجزاء رئيسية وهي مجمع شمسي كبير ومدخنة طويلة وتوربين هوائي. في هذا البحث اجريت دراسة نظرية لتقييم أداء محطة كهرباء ذي مدخنة شمسية في مدينة البصرة نظرا لتوفر الاشعاع الشمسي العالي والايام المشمسة في معظم ايام السنة. تم انشاء نموذج رياضي لدراسة تأثير عوامل مختلفة على أداء هذه المحطة وقد تبين ان الطاقة الناتجة من المحطة تعتمد بشكل اساسي على طول المدخنة وفرق درجة حرارة الهواء داخل المجمع الشمسي وخارجه بالاضافة الى معامل انتقال الحرارة الخارجي الذي يعتمد على سرعة الرياح السائدة بشكل رئيسي.

Nomenclature

A_{ch} Cross sectional area of the solar chimney (m^2)
A_{coll} Area of the solar collector (m^2)
C_p Specific heat of air (kJ/kg K)
G Solar heat flux (W/m^2)
H Solar chimney height (m)
h Outflow heat transfer Coefficient(W/m^2 K)
$\dot{m}$ Air mass flow rate (kg/s)
P_{max} Max. output mechanical power (W)
Q Heat absorbed by air in the collector (W)
T_{coll} Temperature of air in the collector (K)
T_o Ambient temperature (K)
u Air velocity of the solar chimney (m/s)

Greek Symbols

α Absorbance of the solar collector
η_{coll} Efficiency of solar collector
η_e Electrical generator efficiency
ρ_{coll} Air density in the collector (kg/m^3)
ρ_o Ambient air density (kg/m^3)
Δp Pressure difference between the chimney base and the surroundings

1. Introduction

One of the most important renewable energy used for generation electricity from the sun is solar chimney power plant. A typical solar chimney power plant is sketched in fig. 1. A solar chimney consists of three main components: (1) the solar collector, (2) the chimney, and (3) the turbine. The collector supported several meters above the ground is covered by transparent roof. Its main objective is collecting solar radiation to heat up the air mass inside it. Buoyancy drives the warmer air into the chimney which is located at the center of the collector. A turbine is set in the path of the air flow to convert the kinetic energy of the flowing air into electricity.

The solar chimney was originally proposed by Schlaich 1968 but the first power plant based on the solar chimney effect was constructed in Manzanares, Spain in 1981. This is a 50 kW experimental plant was built which produce electricity for eight years, thus providing the feasibility of this new technology. The results and a theoretical description of this plant was presented by Haaf[1,2] 1983, 1984.

Dai et al. [3] 2003 studied solar chimney power plant in China of 110-190 kW electric power on a monthly average solar radiation. The collector diameter is 500 m and the height and diameter of the chimney are 200 m and 10 m respectively.Dos et al. [4] 2003 developed an analysis for solar chimneys. Their model were developed to estimate power output of solar chimneys as well as to examine the effect of various ambient conditions and structural dimensions on the power output. The results show that the height of chimney, the diameter and optical properties of the collector are important parameters for the design of solar chimneys.

Bilgen and Rheault [5] 2005 designed a solar chimney system for 5 MW power production at high latitudes in Canada. The results showed that the solar chimney power plants at high latitudes may have satisfactory thermal performance and produce as much as 85% of the same plants in southern locations with horizontal collector field. Schlaich et al[6]2005 presented a simplified theory, practical experience, and economy of solar updraft towers. The results from designing, building and operating a small scale prototype in Spain are presented. Also they presented eventually technical issues and basic economic data for future commercial solar tower systems of one being planned for Australia in 2008.

Pretorius and Kroger[7] 2006 studied the influence of convective heat transfer coefficient , turbine inlet loss coefficient, quality collector roof glass and various types of soil on the performance of a large scale solar chimney power plant. The results indicate that the outdoor heat transfer coefficient is of considerably effect on the plant power output while the better quality glass enhances plant power production.

A pilot experimental solar chimney power setup consisted of an air collector 10 m diameter and 8 m tall chimney has been built by Xinping Zhou et al [8] 2007.The temperature difference between the collector outlet and the ambient reach 24.1 °C. They found from the analysis of temperature distribution in the solar chimney that air temperature inversion appears in the latter chimney after sunrise.

A 200 MW capacity solar chimney power plant is constructed in Australia during 2008. This plant has a solar collector of 7000 m diameter, a chimney of 1000 m height and 130 m diameter as well as 32 turbines.

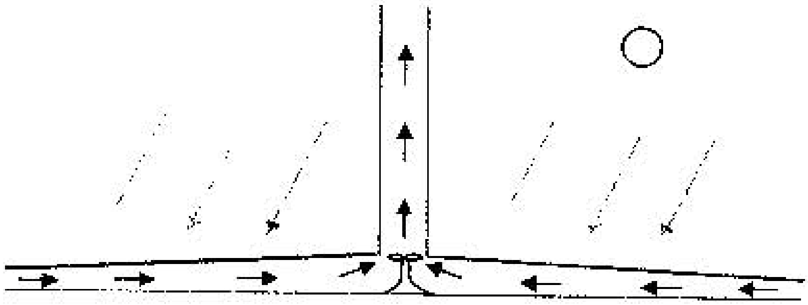

Fig.1. Solar chimney power plant

2. Mathematical Model

The analysis presented in this paper is based on the following simplifying assumptions:

1- Uniform heating of the solar collector surface.
2- No temperature gradient of the air inside the collector.
3- No heat loss from the chimney walls.
4- Friction losses of the flowing air in the chimney are neglected.

2.1. The Solar Collector

The heat balance equation of the collector can be simplified as:

$$\alpha G A_{coll} - h A_{coll}(T_{coll} - T_o) = \dot{m} c_p (T_{coll} - T_o) \quad (1)$$

Where

$$\dot{m} = \rho_{coll} A_{ch} u \quad (2)$$

The efficiency of the solar collector can be defined as[3]:

$$\eta_{coll} = \alpha - \frac{h(T_{coll} - T_o)}{G} \quad (3)$$

2.2. The Chimney

Pressure developed due to the air density between entrance at temperature T_{coll} and exit at T_o in the chimney is calculated as:

$$\Delta p = g \int_0^H (\rho_o - \rho_{coll}) dz \quad (4)$$

For a vertical adiabatic chimney, the integration of equation (4) gives:

$$\Delta p = g(\rho_o - \rho_{coll}) H \quad (5)$$

The air velocity in the chimney can be evaluated using Bernoulli equation as follows:

$$u = \sqrt{\frac{2\Delta p}{\rho_{coll}}} \quad (6)$$

Substitution of equation (5) into equation (6) gives:

$$u = \sqrt{\frac{2gH(\rho_o - \rho_{coll})}{\rho_{coll}}} \quad (7)$$

Using the following approximation for ideal gas[11]:

$$\frac{\rho_o - \rho_{coll}}{\rho_{coll}} \approx \frac{T_{coll} - T_o}{T_o} \quad (8)$$

The air velocity in the chimney can be written as:

$$u = \sqrt{\frac{2gH(T_{coll} - T_o)}{T_o}} \quad (9)$$

Combine equations (1) and (9) yields:

$$\frac{u^2 T_o}{2gH} - \frac{\alpha G A_{coll}}{h A_{coll} + \rho_{coll} A_{ch}\, u\, c_p} = 0 \quad (10)$$

The last equation can be solved numerically to evaluate the air velocity through the chimney.

2.3. The Turbine

Turbines are located at the bottom of the chimney. The maximum mechanical power taken up by the turbines as recommended by Schlaich[9] is:

$$P_{max} = \frac{2}{3} u A_{ch} \Delta p \quad (11)$$

Where

$$\Delta p = \rho_{coll}\, g\, H \frac{(T_{coll} - T_o)}{T_o} \quad (12)$$

The heat absorbed by the solar collector can be written as:

$$Q = \eta_{coll} A_{coll} G \tag{13}$$

Substitution of equations (12) and (13) into equation (11) gives:

$$P_{max} = \frac{2}{3} \eta_{coll} \frac{g}{c_p T_o} H A_{coll} G \tag{14}$$

If the generator efficiency defined as η_e, the electric power from the solar chimney becomes:

$$P_e = \eta_e P_{max} \tag{15}$$

A flow-chart of the solution procedure is shown in the appendix (Fig.7.)

3. Results and Discussion

The maximum horizontal solar heat gain and ambient temperature for Basrah city which will be used in analyzing the solar chimney power plant performance are shown in table(1). The ambient temperature is taken as an average of the monthly maximum temperature for the last four years (2004 - 2007) [10].

The performance of the solar chimney power plant in Basrah is based on the mathematical model mentioned previously. The calculations show the effect of the chimney height and diameter, the solar collector diameter and the outdoor heat transfer coefficient which is related to the wind velocity on the power generation. The results display on Figures (2-5). In general, the output power increase during the summer months as solar heat flux increases. Fig.(2) indicates that the power production(P_e)of the solar chimney power plant increase with increasing the chimney height since the pressure difference increases. Larger chimney diameter gives a higher power production due to the higher air mass flow rate which in turn a higher kinetic energy as shown in Fig.(3) . In Fig. (4), the power production increase as the solar collector diameter increases since the solar energy absorbed increases. As it expected the increase of heat transfer coefficient of the outdoor (or increase in the wind velocity) decreases the power generation due to the increase in the heat losses from the solar collector and then decrease in the air temperature of the collector as the heat transfer coefficient increases as it clear in Fig.(5). The comparison of the present work with that of Schlaich et al.[6] is shown in Fig.(6). A good agreement between the two works is obtained.

Table.1. Maximum horizontal solar heat gain and max. Monthly average temperature for Basrah City for years 2004-2007.

Month	Solar Heat Gain (W/m^2)	Max. Monthly average Temp. (°C)
Jan.	592	16.2
Feb.	714	19.7
Mar.	817	25.8
Apr.	868	31
May	879	38.5
Jun.	874	43.1
Jul.	864	44.8
Aug.	848	44.7
Sept.	795	41.1

Oct.	708	36.2
Nov.	596	24.7
Dec.	544	17.2

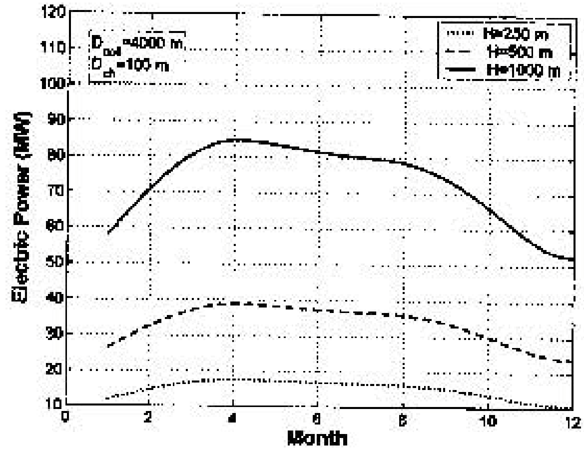

Fig.2. Effect of chimney height on the output power.

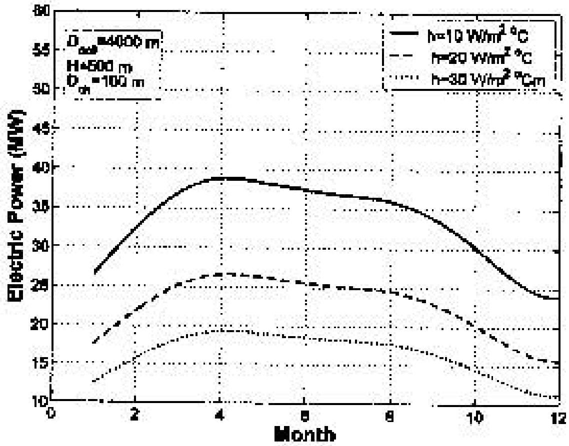

Fig.5. Effect of outdoor heat transfer coefficient on the output power.

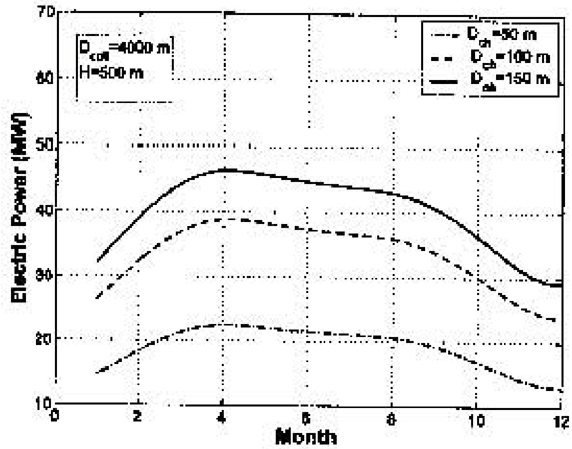

Fig.3. Effect of chimney diameter on the output power.

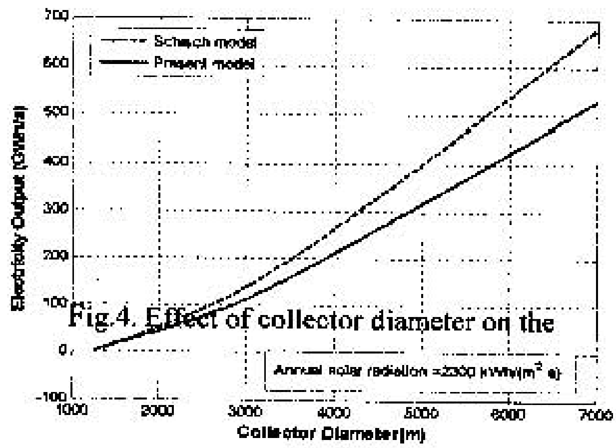

Fig.4. Effect of collector diameter on the

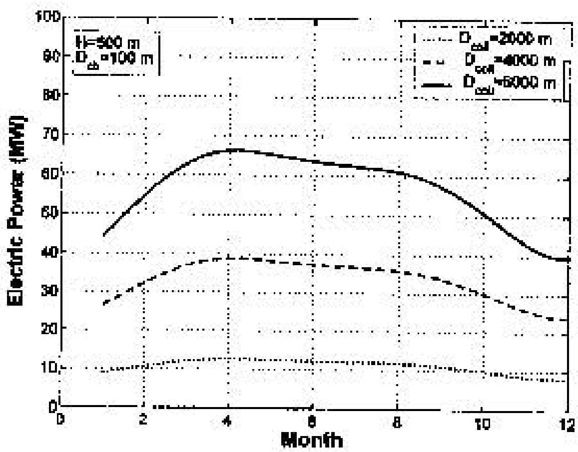

Fig.6. Comparison between the present model and Schlaich model[6].

4. Conclusions

1. A solar chimney power plant has been designed and analyzed according to Basrah climate conditions.
2. Construction of solar chimney power Plant in Basrah is feasible since high solar intensity and long sunny days are available.
3. The capacity of power generation depends on some parameters such as

solar radiation, chimney height and diameter as well as collector diameter.

4. The wind velocity has important effect on the power generation of solar chimney power plant.

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Appendix

The solution procedure of the mathematical model may be summarized in the following flow-chart:

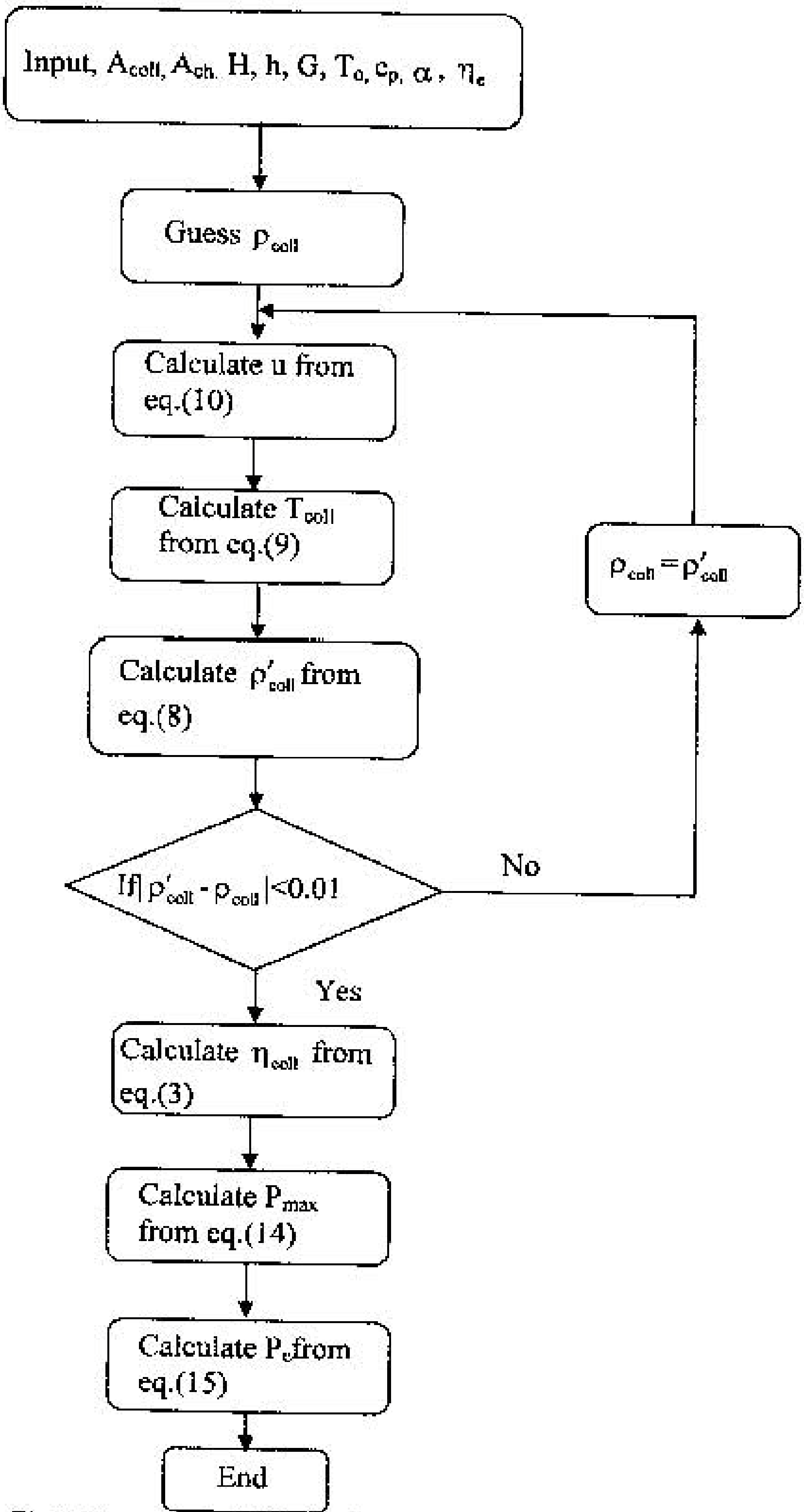

Fig.7. Flow chart of the solution procedure.