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Performance of a solar chimney power plant with collector for application in Saudi Arabia

A.M.K. El-Ghonemy

Department of Mechatronics Engineering,High Institute of Engineering and Textile Technology, Egypt.

Abstract: *The solar chimney power plant (SCPP) is known as a large scale power plant. This technology is applicable in desert areas, where solar radiation is good.Using a solar collector of large diameter, a great volume of air can beheated by a solar radiation to flow up in a higher chimney.This paper is aimedto evaluate the performance of SCPP under weatherconditions of Kingdom of Saudi Arabia. A mathematical model was developed to estimate the following parameters: power output, pressure drop across the turbine, the chimney height, airflow temperature & velocity, and the overall efficiency.The results showed that, the solar chimney power plant, witha chimney height and diameter of 200 m and 10 m, respectively, and a collector diameterof 500 m, can produce a monthly average of 118~224 kW electric power.*Finally some recommendations for reducing the construction cost of a SCPP werementioned.

Keywords -*Solar energy, solar collectors, solar chimney, wind turbines.*

I. INTRODUCTION

Electric power can be generated from a solar energy by photovoltaic solar cells, solar thermal systems. and solar chimney power plants (SCPPs). Thistechnology is known as solar updraft towers (SUTs). It is equipped with solar collectors and thermal storage system of low cost. So it can be used to generate electricity for 24h/day. The famous 50 kW plant located in Manzanares was constructed and operated in 1980s. This power plant had a solar collector of 122 m in radius and a chimney of 194.6 m in height with a radius of 5.08 m[1-5]. The Key elements of SCPPsare :

1-The solar air collector,
2-The chimney,
3-Wind turbines with generators, which are so called power conversion unit (PCU).
4- Thermal Energy Storage system.

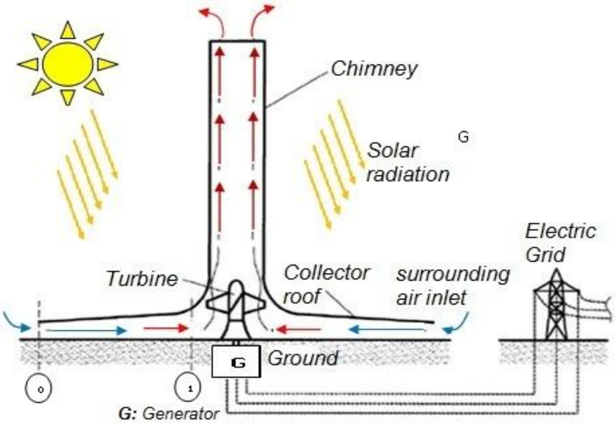


figure (1).Main components of solar chimney [1].

As shown in Fig. (1),the air below thesolar collector (transparent cover), is heated by solar radiation. In the center of this collector, the base ofa vertical chimney is connected. As hot air is lighter than cold air it rises up inside the chimney. Consequently solar radiation causes a continuousair up-draught inside the chimney. Finally,the resultant hot air updraft movement is converted into electrical energy using wind turbines-generators located at the base of the chimney.

The solar chimney power plant was studied and reported by many authors [1-29]. A summary is given below:

The large area air collector is made from a transparent glass or plastic roof which is stretched out horizontally many meters and supported above the ground by a vertical column structure. The height of the roof slowly increases along a radius from the periphery to the center to guide airflow with minimum friction losses. A secondary roof can be used to divide the collector into a top and bottom sections, was advised to improve the performance [1-3]. Using a regulating mechanism for air flow is recommended to control the output power. This is useful when less power is required. Water packagesare preferred as a thermal storage systemthan soil storage system, since the specific heat capacity of water is much higher than that of soil. Thiswater is contained inside bags which remains closed (no evaporation). The upper surface of the bags is transparent to let solar beam be transmitted and the lower surface is painted black to absorb solar radiation effectively. Using solar ponds as thermal storage system was proposed, where the hot brine is extracted from the lower convective zone to the heat exchanger to heat air under the collector, during night time and cloudy day[1-3].

The turbine generators (Power Conversion Units(PCU))are the core element of any SCPP. Its main function is the efficient conversion of fluid power to shaft power. The typical SC turbine is of the axial flow type. [1].

The Solar chimney (SC) located in the collector center drives the air to flow due to temperature difference. The mass flow of the updraft air is proportional to the collector air temperature rise and to the SC height. For lifetime and cost considerations,the best choice for chimney structure is the reinforced concrete. other materials are possible (e.g., covered steel framework with cable nets, membranes, trapezoidal metal sheet, etc.)[1-3]. Asexample, the chimneycan reach 1000 m and 170 m height and outer diameter respectively [1]. The SC wall thickness decreases from 0.99 m at bottom to 0.25 m at half ofits height. Then the thickness remains constant up to the chimney top. The use of compression ring stiffeners isrecommended with a vertical spacing to support the SC structure [1]. For example a 200MW SCPP with SC of 1000 m height, the SC was constructed using high-performance concrete C 70/85. In order to control possible cracking on the outer surface of shell, concrete C 30/37 can be used. Generally speaking, the best shaping and ring-stiffening of SC should be determined for long lifetime of at least 80 years [1].

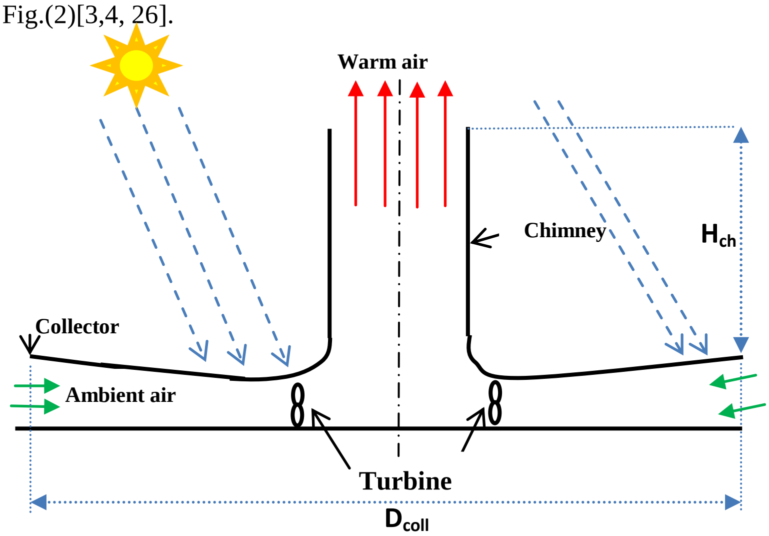
The feasibility of solar chimney power plants in the Mediterranean region was analyzed byNizetic et al.[9].It was found that the price of produced electric energy by solar chimney power plant in Mediterranean region is still high compared to other power sources.More detailed numerical analysis of a solar chimney power plant was conducted by Sangi et al.[10]. Two different methods can be used for modeling and simulation of SCPPs. First, the governing equations can be solved numerically using an iterative technique. The other method is performedusing the CFD software (FLUENT).The turbine pressure drop factor in solar chimney power plants was presented numerically by Nizetic and Klarin[11].This factor is defined as pressure drop ratio in turbines, relative to the total pressure drop in the chimney. It was concluded that for solar chimney power plants, turbine pressure drop factors are in the range of 0.8–0.9. This is useful parameter for preliminary analysis of solar chimney power plants.

The best chimney height for maximum power output were presented and analyzed by Zhou et al.[13]. Apilot SCPP with 10 m collector diameter and 12 m chimney height, was designed and tested byKasaeian et al.[14]. The temperature and velocity readings were recorded for some places of collector and chimney. Because of green house effect under the collector, the temperature difference between collector exit and the ambient reached to 25 ◦C, and this caused air flow from collector to chimney. The maximum air velocity of 3 m/s was recorded inside the chimney, while the collector entrance velocity was zero.

The performance of solar chimney power plants in some zones of Iran was evaluated theoretically by Roozbeh[15]. A mathematical model was developed to estimate the power output. It was concluded that, the solar chimney power plant with chimney height of 350 m and collector diameter of 1000 m is capable of producing monthly average 1–2 MW electric power over a year.The performance analysis of a solar chimney power plant was presented by Larbi et al.[16]. It was assumed to provide the remote villages located in Algerian southwestern region with electric power. The results showed that the solar chimney power plant can produce from 140 to 200 kW of electricity on a site like Adrar during the year.The effectiveness of a SCPP for use in remote villages was studied by Onyango[17]. The performance of a solar chimney power plant under local climate condition of Egypt was investigated by Mostafa et al[18]. It was highlighted that the chimney height has the highest influence on the both chimney power and efficiency where the collector radius raises the temperature inside the collector. Dimensional analysis was used to combine eight variables into only one dimensionless variable for a dynamic similarity between a prototype and model [19]. Three physical configurations of the plant were numerically tested for similarity: fully geometrically similar, partially geometrically similar, and dissimilar types. The values of the proposed dimensionless variable for all these cases were found to be nominally equal to unity.

II. MATHEMATICALMODEL

To study the performance of the SCPP, the following mathematical model is given below for each component with the aid of Fig.(2)[3,4, 26].



figure(2). Key dimensions of SCPP.

II.1. Total Efficiency of SCPP

Total efficiencyη_{tot} is determined here as a product of the individual components efficiencies:

$$\eta_{tot} = \eta_{tur}\ x\ \eta_{coll}\ x\ \eta_{ch} \text{---(1)}$$

Where, η_{coll} is the efficiency of the collector (how much solar radiation is converted into heat), η_{ch} is the efficiency of the chimney (how much heat gained by the collector is converted into kinetic energy), and η_{tur} is the turbine-generatorefficiency.

II.2. Solar Collector

The solar radiation (G) onto a collector surface Area (A_{coll}) is converted into heat using solar collectors.So,a Collector efficiency (η_{coll}) can be expressed as a ratio of the heat output (as heated air ($\dot{Q}$)) and the solar radiation (G) measured in W/m^2 times A_{coll} :

$$\eta_{coll} = \frac{\dot{Q}}{GA_{coll}} (2)$$

under steady conditions, the heat output $\dot{Q}$can be expressed as a product of the mass flow $\dot{m}$, the specific heat capacity of the air C_p and the temperature difference between collector inflow and outflow ($\Delta T = T_{out} - T_{in}$).The energy balance equation is given below:

$$\dot{Q} = \dot{m}C_p\Delta T = (\tau\alpha)A_{coll}G - \beta\Delta T_a A_{coll} = GA_{coll}\eta_{coll} (3)$$

Where, ΔT_a is the difference between the mean collector plate temperature T_{pm}, and ambient temperature ($\Delta T_a = \left(T_{pm} - T_{amb\,.}\right)$.And, $\dot{m}$is the mass flow rate of hot air passing through the solar chimney, and can be calculated as follows:

$$\dot{m} = \rho_{air}A_{ch}V_{ch} (4)$$

Substituting by $\dot{Q} = \dot{m}C_p\Delta T\ and\ \dot{m} = \rho_{air}A_{ch}V_{ch}$from equations 3 and 4 into equation (2) gives:

$$\eta_{coll} = \frac{\rho_{air}A_{ch}V_{ch}C_p\ (\Delta T)}{GA_{coll}} (5)$$

using$\dot{Q} = (\tau\alpha)A_{coll}\ G - \beta\ \Delta T_a A_{coll}$. From equation (3) and substituting into equation (2) gives:

$$\eta_{coll} = (\tau\alpha) - \frac{\beta \Delta T_a}{G} \quad (6)$$

By equating equation(5) and (6), the relation between the collector outlet velocityV_{ch} and temperature rise($\Delta T = T_{out} - T_{in}$) can be expressed as:

$$V_{ch} = \frac{(\tau\alpha) A_{coll}\, G - \beta \Delta T_a A_{coll}}{\rho_{air}\, A_{ch} C_p \Delta T} \quad (7)$$

where, $A_{ch}$is the cross-sectional area of the solar chimney, A_{coll} is the collector area that receives solar radiation, G is the solar irradiance in W/m^2, (ατ) represents the product of absorbance and transmittance of the solar collector, β is the heat loss coefficient of the solar collector, ρ_{air} is the density of air at the outlet of the solar collector.

To evaluate collector performance, the mean fluid and mean plate temperatures, are required which is estimated as follows [1,4, 26].

$$T_{fm} = T_{in} + \frac{\dot{Q}}{A_{coll}\, \beta F_R} (1 - F'') \quad (8)$$

$$T_{pm} = T_{in} + \frac{\dot{Q}}{A_{coll}\, \beta F_R} (1 - F_R) \quad (9)$$

Where, the heat removal factor, F_R, can be expressed as,

$$F_R = \frac{\dot{m} C_p}{A_{coll}\, \beta} \left(1 - exp\left(\frac{A_{coll}\, \beta F'}{\dot{m} C_p}\right)\right) \quad (10)$$

*Where, $F^{\backslash}$*is the efficiency factor of the solar collector, $F^{\backslash\backslash}$ is the collector flow factor which is given as,

$$F'' = \frac{F_R}{F'} \quad (11)$$

The mean fluid temperatureT_{fm} is calculated as follows:

$$T_{fm} = \frac{T_{in} + T_{pm}}{2} \quad (12)$$

Where T_{in} is the air inlet temperature and T_{pm} is the mean collector plate temperature.

II.3. Solar Chimney

The chimney efficiencyis measured by how much heat is converted into kinetic energy. The chimney efficiency is expressed as follows[1]:

$$\eta_{ch} = \frac{W_{tot}}{\dot{Q}} = \frac{g H_{ch}}{C_p T_{amb}} \quad (13)$$

Where, $H_{ch}$is the height of the chimney (m), g is the gravity (m/s^2), $C_p$is the air heat heat [J/kg·K] and T_{amb} is the ambient temperature [K].

As shown in eq.(13) it is clear that the chimney efficiency is only dependent on chimney height. While, flow speed, and temperature rise in the collector are not included.

Thus the power contained in the flow W_{tot} from eq.(13) can be expressed as follows with the aid of Eqs.(13) :

$$W_{tot} = \eta_{ch} \dot{Q} = \frac{g H_{ch}}{T_{amb}} \rho_{air} V_{ch} A_{ch} (T_{out} - T_{in}) \quad (14)$$

The pressure difference, ΔP, which is produced between the chimney base(collector outflow) and the surroundings, is calculated by,

$$\Delta P = \rho_{air}\, g H_{ch} \frac{\Delta T}{T_{amb}} \quad (15)$$

II.4. Turbine Model

Turbines are always placed at the base of the chimney. Using turbines, mechanical output in the form of rotational energy can be derived from the air current in the chimney. Turbines in a solar chimney do not work with staged velocity as a free running wind energy converter, but as a cased pressure-staged windturbogenerator, in whichsimilar to a hydroelectric power station, static pressure is converted to rotational energy using a cased turbine. Schlaich [1] recommended that the maximum mechanical power taken up by the turbine is:

$$W_{t,max} = \frac{2}{3} V_c A_c \Delta P (16)$$

The above equation can rewritten as below,

$$W_{t,max} = \frac{2}{3}\eta_{coll} \frac{g}{C_p T_o} H_{sc} A_{coll} G (17)$$

Multiplying $W_{t,max}$ by η_{tur} which contains both blade transmission and generator efficiency, this produces the electrical powerW_e from the solar chimney to the grid,

$$W_e = \frac{2}{3}\eta_{coll}\eta_{tur} \frac{g}{C_p T_{amb}} H_{ch} A_{coll} G (18)$$

From equation(18), the electrical power output of the solar chimney is proportional to $H_{ch} A_{coll}$, Thus the same power output can be achieved with different combination of chimney height and collector diameter. Optimum dimensions can be determined only by including the cost of individual components (collector, chimney, mechanical components) at a specific site.

II.5. The preferred location for installing SCPPs

To reduce the installation costs of SCPPS, due to the natural need of very hightallof chimney(200:1000m) , the hightall mountain desert areas are recommended, where the solar radiation is also good.[4].

III. ASSUMPTIONS

The main assumptions used in the present study are summarized in Table (1).

Table(1).Summary of assumptions.

Parameters	Value
Chimney height (*Hch*)	200 m
Chimney diameter (*Dch*)	10 m
Collector diameter (*Dcoll*)	500 m
Distance from ground to the cover (*Hcoll*)	2.5 m
Efficiency of the turbine (ηtur)	0.8
Product of transmittance and absorbance of the collector (τα)	0.65
Cover heat loss coefficient (β)	10.0 $W/m^2.K$
Solar irradiance (*G*)	800 W/m^2
Collector efficiency factor (*F'*)	0.8
Ambient temperature (Tamb.)	21.6 ^oC

IV. SOLUTION TECHNIQUE

For a given SCPP, geometrical parameters (height and diameter of chimney, collector diameter), For a specified thermal conditions(such as ambient air temperature, solar radiation). The performance of the SCPP can be estimated yearly basis by using the set ofEquations(1) to (18).

All calculations were performed using the above mentioned equations and the used assumptions. Performance results are obtained by simulation using EES software.

V. SOLAR INPUT DATA FOR SIZING COMPONENTS

SkAKA city lies in northern of the Kingdom of Saudi Arabia (Degrees 29.97 Latitude & 40.21 Longitudes). However, ground water and sunlight are available, which makes solar energy projects more cost effective especially for desert areas. The average daily solar energy in $kWh/m^2/day$, mean ambient temperature(C^0) and average sunshine hours for a complete year are given in table(2)[6].

Table(2).The average daily solar energy on horizontal and tilted planes, mean temperature and average sunshine hours for a complete year for SKAKA city in KSA [6].

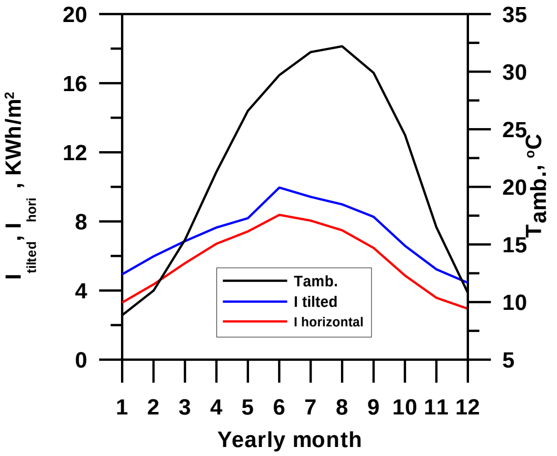
	H_{hori}	H_{tilted}	T_{amb}	PSSH
Jan	3.31	4.94	8.86	10.4
Feb	4.36	5.98	11	11.1
March	5.58	6.86	15.4	11.9
April	6.71	7.65	21.3	12.8
May	7.42	8.19	26.6	13.6
June	8.38	9.96	29.7	14
July	8.05	9.42	31.7	13.8
August	7.49	8.99	32.2	13.2
Sept.	6.47	8.27	29.9	12.3
Octob.	4.87	6.59	24.5	11.4
Nov.	3.58	5.23	16.5	10.6
Dec.	2.95	4.45	10.8	10.2
Annual average	5.77	7.22	21.6	12.10833

VI. RESULTSAND DISCISSION

Based on SCPP geometrical parameters assumed in this study and using the weather data of solar radiation, the performance of the SCPP has been studied and the results are given below:

VI.1. Variations of Monthly Average Solar Irradiance and Temperature

Fig.(3) gives the variations of monthly average solar irradiance and temperature in the northern of KSA[6]. It can be observed that the temperature and solar irradiance variations change similarly. The minimum mean temperature at monthly base occurs in January for each year, about 8.86 ^{o}C, and the maximum mean temperature at monthly base occurs in August at about 32.2^{o}C. The variation in solar irradiance is different from that in the monthly average temperature.Also, it is observed from the figure that, SKAKA region has the best solar irradiance in June.Whilethe minimum solar radiation level is in December.



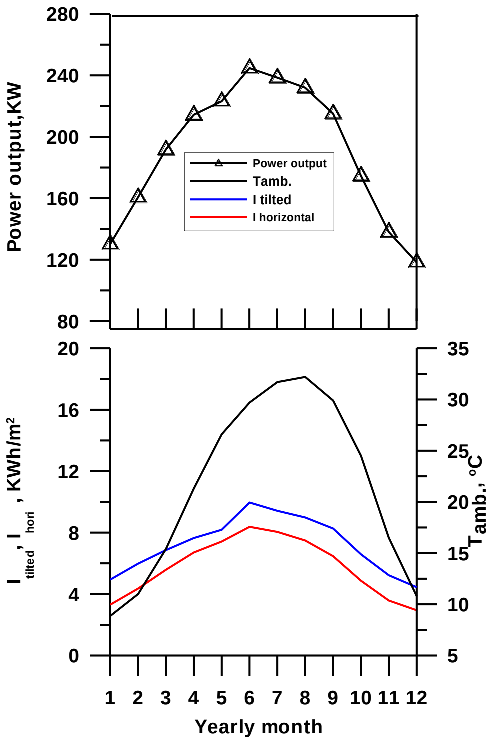
figure(3). Variation of monthly average solar irradiance and temperature at SKAKA region.

VI.2. Effect of Ambient Temperature and Solar Irradiance on Power output

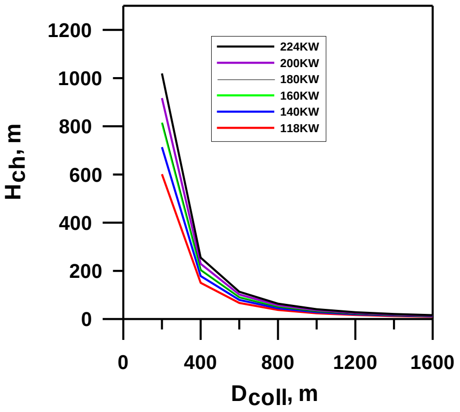
Fig(4) shows the effect of the ambient temperature and the solar irradiance on the chimney power output. It is clear that power output increases with the increase of solar irradiance and the ambient temperature. The solar radiation is the dominant factor that affects the power output. The solar chimney power plant is able to output electric power up to 244, when the ambient temperature is 29.7 ^{o}C, and the solar irradiance is 600 W/m^2. The monthly average power generation ranges between 118 and 244 kWh for a whole year.Also it is clear that,The better the solar radiation, the higher the capacity of power output will be.

VI.3. Effect of Collector Diameter and the Chimney Height

Fig. (5) Indicates that the higher the chimney height, the greater is the power output of the solar chimney power plant. Also from Fig.(5) it is clear that the power decreases nonlinearly with the increase of collector diameter. To get the maximum power, the recommended geometrical parameters are: the collector diameter is chosen within 200m (max 400m) and chimney height is ≥ 600m. Finally, for a given plant geometrical parameters, this figure can be used to estimate the output power. For instance, about 200kW electric power can be produced in the solar chimney when the diameter of the collector is 400 m, and the chimney height is 250 m (at solar irradiance of 600 KWh/m^2).



figure(4). Effect of the monthly average ambient temperature and the solar irradiance on monthly average power productivity.



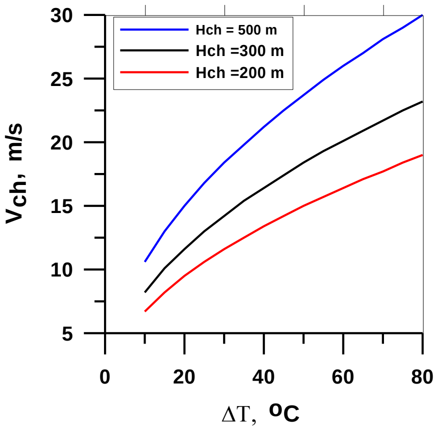
figure(5). Effect of solar chimney height and diameter of collector on power generation.

VI.4. Variation of Air Velocity at Chimney Inlet with Temperature Rises in the Collector

Fig.(6) shows the variation of air velocity at chimney inlet with air temperature rises in the collector(at different chimney heights). It is noticed that, at specific height of chimney, the air velocity V_{ch} is directly proportional to Temperature Rise in the collector ΔT. Finally The figure highlights that both of ΔT and H_{ch} are the key parametersfor designing of SCPPs .

VI.5 Construction cost reduction of aSCPP

Saudi Arabia is rich by high tall mountains(>1000m). Consequently, to decrease the installation cost of a SCPP, its solar chimney can be constructed beside a high tall mountain as shown in fig.(7) [3,4,26]. Also, construction of SCPP with a floating solar chimney (FSC) is recommended than concrete chimney, as FSC power plants are 5 to 6 times cheaper than CSC power plants. Also, the necessary area for the solar collector of the Floating SCPPs is 4 to 10 times smaller compared to the corresponding one of concreteSCPPs[26].



figure(6). Variation of V_{ch} with ΔT At different H_{ch} =200, 300,500 m.

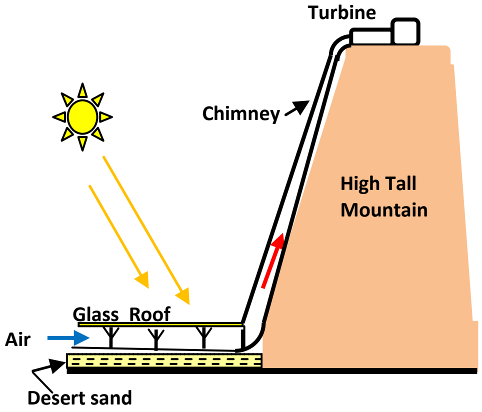


figure (7). Schematic of SCPP located beside high tall mountains[4].

VII. Conclusions

The performance of SCPP was studied for application under weather conditions of northern Saudi Arabia. It is concluded that:

1. The solar chimney power plant,with chimney height and diameter of 200 m and10 m, respectively, and collector diameter of 500 m, can produce a monthly average of 118~224 kW electric power during the year. The solar collector can also be used as a greenhouse for agricultural purpose.

2. Under given conditions, the power generation capacity increases with the increase in solar chimney height and solar collector area.

3-For construction cost reduction: the floating solar chimney(FSC) can be used instead of concrete solar chimney(CSC). Also, locating the chimney beside a high tall mountain is recommended.

Nomenclature

Ac	Cross-sectional area of solar chimney, m^2
Acoll	Solar collector area, m^2
C_P	Specific heat of air, kJ/kg./C
FSC	Floating solar chimney
FSCPPs	Floating solar chimney power plants
g	Acceleration of gravity, m/s^2
G	Solar irradiance, W/m^2

Hch	Solar chimney height, m
HTVTS	Horizontal-to-vertical transition section
IGV	inlet guide vanes
$\dot{m}$	Mass flow rate of air, kg/s
PCU	power conversion unit
P_{tot}	Useful energy contained in the airflow, kW
$P_{wt,max}$	Maximum mechanical power taken up by the turbine, kW
$I_{hori.}$, I_{tilt}	The average daily solar energy on horizontal and tilted planes in kWh/m^2/day,
We	Electric output from the solar chimney, kW
$\dot{Q}$	Heat gain of air in the collector, kW
SC	solar chimney
SCPPs:	solar chimney power plants
SUTPP:	solar updraft tower power plants
To	Ambient temperature, ^{0}C
Vch	Inlet air velocity of solar chimney, m/s
Greek symbols	
$(\alpha\tau)$	Effective product of transmittance and absorbance
β	Heat loss coefficient, W/m^2.K
ηcoll	Solar collector efficiency
ηch	Solar chimney efficiency
ηtur	Turbine efficiency
ρ	Air density, kg/m^3
ΔPtot	Pressure difference produced between chimney base and the surroundings, Pa
ΔT	Temperature rise between collector inflow and outflow, ^{o}C

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Appendix(A): Materials Used to Produce SCPP Components

component	material
collector	Glass or polycarbonate materials that the gardeners use to build greenhouses..
chimney	Reinforced concrete or steel
heat storage during sunrise hours	Water and plastic bags
Working fluid	Air