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Solar Chimney Power Plant with Collector

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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 larger solar collector diameter, a greater volume of air is warmed to flow up in a higher chimney.This paper is directed to evaluate the performance of SCPP. A mathematical model was developed to estimate the following parameters: power output, pressure drop across the turbine, the max chimney height, airflow temperature & velocity, and the overall efficiency.The results showed that, the solar chimney power plant, in which thechimney height and diameter are 200 m and10 m, respectively, and the diameter of the solar collector diameter is 500 m, can produce a monthly average of 118~224 kW electric power during all the year.*

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

I. Introduction

Electric power can be obtained from solar energy by two ways, photovoltaic solar cells and solar thermal generators. However, there is also another technique, namely solar chimney power plants (SCPPs). The concept was designed and put into operation during the 1980s as reported by many authors [1,2]. The operational experience of this type of plants indicates that the power production cost is about DM 0.1/kWh [2].

The SCPPs technology is also 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 simple roof hot air collector,
2-The chimney,
3-Wind turbines with generators, which are so called power conversion unit (PCU).
4- Thermal Energy Storage system.

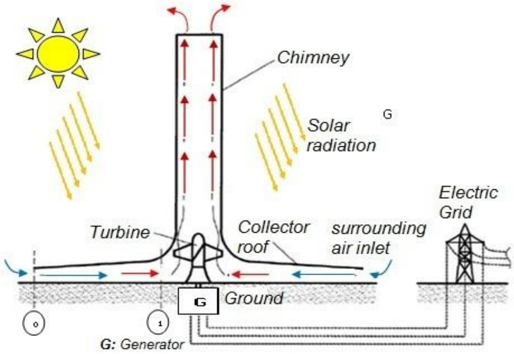


figure (1).Main components of solar chimney [1].

A typical solar chimney power plant consists of a solar hot air collector, a solar chimney and a turbo-generator (turbine with generator), as shown in Fig. (1). Using a low level circular transparent cover opened at its periphery, the air below this transparent cover is heated by solar radiation. This is known as a hot air collector. In the middle of this collector, the base of a vertical chimney is connected. The joint between the collector and the chimney base is airtight. As hot air is lighter than cold air it rises up inside the chimney. Consequently solar radiation causes a continuous 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.

Review

The SC power technology was studied and reported by many authors [1-26]. Since 1975, several patents had been granted in Australia, Canada, Israel and the USA. A summary is given below:

The large air collector is made from a transparent glass or plastic roof which is stretched out horizontally many meters and supported above the ground by 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, is advised to improve the performance [1-3]. Using a regulating mechanism for air flow at the collector bottom section is recommended to control the output power. This is useful when less power is required. Water blocks water can be used as a thermal storage system .this is more efficient than soil storage system , since the specific heat capacity of water is much larger than that of soil. The water 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 for thermal storage of SCPP was proposed [1-3], where the hot brine is extracted from the lower convective zone to the heat exchanger to heat dry operating air in the collector, driving turbine generators to produce power during night time and cloudy day.

The turbine generators arecalled Power Conversion Units(PCU)which arethe 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 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]. As a sample, the chimney can reached 1000 m and 170 m height and outer diameter respectively [1]. The shell thickness decreases from 0.99 m just above the support on radial walls to 0.25 m halfway up. Then the thickness remains constant all the way to the top. The compression ring stiffeners are installed with a vertical spacing to support the high, gigantic 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 was analyzed in the Mediterranean region by Nizetic et al.[9].It was found that the price of produced electric energy by solar chimney power plant in Mediterranean region is 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 numerical simulations were performed for the geometry of the prototype in Manzanares, Spain. First, the governing equations were solved numerically using an iterative technique. Then, the numerical simulation was performed using the CFD software (FLUENT). Both predictions were compared with the available experimental data to assess the validity of the model. a good agreement was obtained between the experimental data of the Manzanares prototype and both the numerical results.A simplified analytical approach for evaluating the factor of turbine pressure drop in solar chimney power plants was presented 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 for preliminary analysis of solar chimney power plants.

The optimal chimney height for maximum power output were presented and analyzed by Zhou et al.[13]. The study was carried out using a theoretical model validated with the measurements of the only one prototype in Manzanares. The results based on the Manzanares prototype showed that the maximum power output of 102.2 kW is obtained for the optimal chimney height of 615 m, which is lower than the maximum chimney height with a power output of 92.3 kW. Also, the results showed that maximum height gradually increases with the lapse rate increasing and go to infinity at a value of about 0.0098 $^0K\ m^{-1}$. In addition, it was found that the maximum height for convection and optimal height for maximum power output increase with larger collector radius. After designing and making a solar chimney pilot power plant with 10 m collector diameter and 12 m chimney height, the temperatures and air velocities were measured by Kasaeian et al.[14]. The temperature and velocity readings were carried out for some specified 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 phenomena caused creation of air flow from collector to chimney. The air inversion at the bottom of the chimney was observed after sunrise, on both cold and hot days. 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 that was expected to provide the remote villages located in Algerian southwestern region with electric power was presented by Larbi et al.[16]. 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. For a given chimney power plant, geometrical data (height and diameter of the tower, diameter of the collector, distance between the soil and the cover), for specified thermal conditions (such as ambient air temperature, solar radiation), the chimney power during the year can be deduced by using a developed computer software based on the numerical solution of the set of equations used in modeling.The effectiveness of a SCPP for use in rural villages and its features 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 found 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 that establishes a dynamic similarity between a prototype and its scaled models[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. Mathematical model

To study the performance of the SCPP, the following mathematical modeling of each component is given below with the aid of Fig.(2).

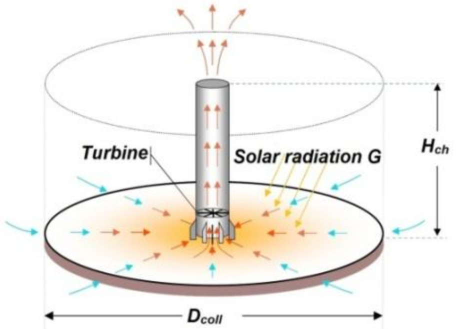


Figure (2). Key dimensions of SCPP.

Total Efficiency of SCPP

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

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

Where, η_{coll} is the efficiency of the collector, in other words the effectiveness with which solar radiation is converted into heat ,η_{ch} is the efficiency of the chimney and describe the effectiveness with which the quantity of heat delivered by the collector is converted into flow energy , η_{tur} stands for the efficiency of the wind turbine generator.

For example, with a chimney height of 1000 m and standard conditions for temperature and pressure, the chimney efficiency η_{ch} achieves the maximal value of 3 %. Considering collector efficiency (η_{coll}) of 60 % and turbine efficiency (η_{tur}) of 80 %, the total system efficiency (η_{tot}) reaches 1.4%, as shown below:

$$\eta_{tot} = \eta_{tur}\, x \eta_{coll}\, x \eta_{ch} =$$

0.8 x0.6 x □ 0.03 □ □ □ 0.014=1.4%

Solar Collector Modeling

The earth itself, which is covered by glass or other transparent materials, acts as a heat absorption layer (collector). The periphery of the solar air collector is open to the atmosphere, and its center is connected with the base of the solar chimney. A solar collector converts available solar radiation (G) onto the collector surface Area (A_{coll}), into heat output. Collector efficiency (η_{coll}) can be expressed as a ratio of the heat output of the collector as heated air ($\dot{Q}$) and the solar radiation (G) measured in W/m^2 times A_{coll} .

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

Heat output $\dot{Q}$under steady conditions 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:

$\dot{Q} = \dot{m} C_p \Delta T = (\tau\alpha) A_{coll}\, G - \beta \Delta T_a A_{coll} = G A_{coll}\, \eta_{coll}$ (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 using the following equation.

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

Substituting by $\dot{Q}$ *and* $\dot{m}$from equations 2 and 3 into equation (1) gives:

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

The efficiency of the solar collector can also be expressed, using$\dot{Q} = (\tau\alpha) A_{coll} \ G - \beta \ \Delta T_a A_{coll}$. From equation (2) and substituting into equation (1) gives:

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

By equating equations(5) and (6), the link between air speed at the collector outflow velocityV_{ch} and temperature rise($\Delta T = T_{out} - T_{in}$) can be expressed as:

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

Theabove equation is independent of collector roof height because friction losses and ground storage in the collector are neglected.

where, $A_{ch}$is the cross-sectional area of the solar chimney, A_{coll} is the area to receive solar radiation, *G* stands for solar irradiance measured 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, it is necessary to know the mean fluid and mean plate temperatures, which could be estimated as follows [1,4, 26].

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

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

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

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

Where, F\\is the efficiency factor of the solar collector, F\\\\ is the collector flow factor which is given as,

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

The mean fluid temperature is required to solve the model, which could be found from the arithmetic mean of the inlet temperature and the mean plate temperature.

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

Solar Chimney Modeling

The efficiency of the chimney, i.e. the conversion of heat into kinetic energy is determined by the ambient temperature at the ground level and the height of the chimney. According to Ref [1], the chimney efficiency is expressed as follows:

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

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) :

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

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

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

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 windturbo-generator, 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 power W_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)

Based on equation(18), It is clear that the electrical 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 particular site.

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. Results and Discussion

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:

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.

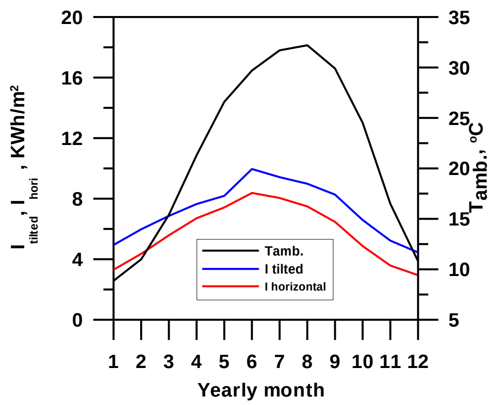


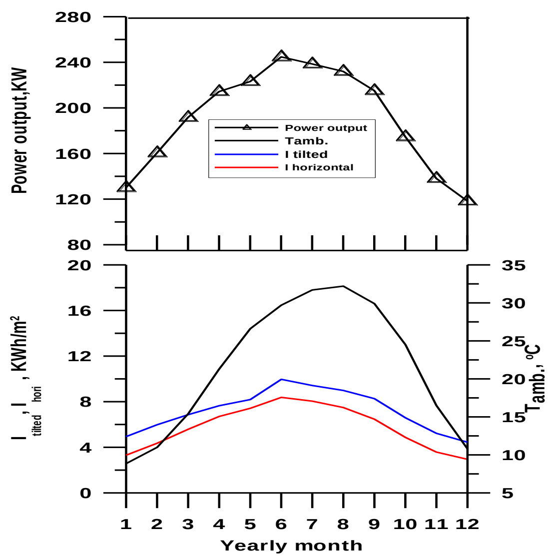
Figure (3). Variation of monthly average solar irradiance and temperature at SKAKA region.

Effect of Ambient Temperature and Solar Irradiance on Chimney Power Productivity

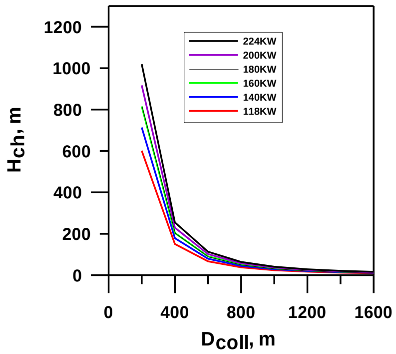
Fig(4) shows the effect of the ambient temperature and the solar irradiance on the chimney power productivity. It is noticed that power productivity increases with the increase of solar irradiance and the ambient temperature. The solar radiation is the dominant factor that affects the power output. The 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 variations in solar irradiance and power production behave similarly. The better the solar radiation, the higher the capacity of power production will be.

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).



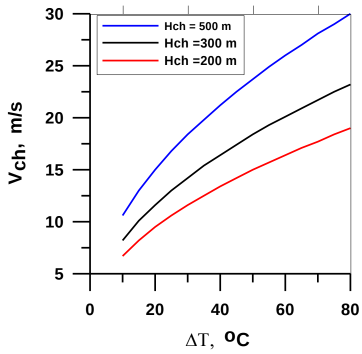
figure(4). Effect of the monthly average ambient temperature and the solar irradiance on monthly average power productivity.



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

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 collectorΔT. Finally the figure highlights that both of ΔT and H_{ch} are the key parametersfor designing of SCPPs.



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

VII. Conclusions

Many encouraging studies were reported about the use of solar chimney to produce electrical power. Performance studies were related to geometrical and operating parameters. The present study provides a review of SCPP technologies. A mathematical model was used to estimate the power output under different geometrical and thermal conditions. 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, in which the height and diameter of the chimney are 200 m and10 m, respectively, and the diameter of the solar collector cover is 500 m, can produce a monthly average of 118~224 kW electric power during all the year. The solar collector in the plant can also be used as a greenhouse for agricultural purposes.

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

3-For consideration of construction cost reduction, the floating solar chimney(FSC) can be used instead of concrete solar chimney(CSC).

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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

Nomenclature

Ac	Cross-sectional area of solar chimney, m2
Acoll	Solar collector area, m2
Cp	Specific heat of air, kJ/kg./C
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
Ptot	Useful energy contained in the airflow, kW
Pwt,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

(ατ)	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