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Performance of a solar chimney power plant without collector for application in Saudi Arabia

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Abstract: *The solar chimney power plant without collector is a large-scale solar power plant for future applications. It is so called energy towers power plant (ETPP). Its principle is based on cooling of large amount of hot and dry air resulting in downdraft inside a large chimney used to drive wind turbines for electricity generation. So, it is applicable in hot and dry weather.This paper is directed to evaluate the performance of ETPPs under weather conditions of Kingdom of Saudi Arabia. A mathematical model was used to estimate the power output from a certain chimney geometry and weather conditions.The results showed that, the power tower, withchimney height and diameter of 1200 m and 400 m, respectively, can produce a monthly average electric power between 111.8MW(in OCT.) and 137.8MW (in Jan).*

Keywords -*Renewable energy, Energy tower power plant(ETPP), wind turbines.*

I. INTRODUCTION

The solar chimney power plant (SCPP) without collector is a large-scale solar power plant for future applications. It is used to produce electrical energy by cooling of large masses of hot and dry air resulting in downdraft within a large chimney (a tall of 500-1200m and diameter between (100-400m). It doesn't require a solar radiation collector and it works continuously day and night. It is so called Energy tower (ET) power plants (ETPPs). The hot dry air and seawater are used to produce electricity. So, additional benefit of the ETPPs is sea water desalination at a low price[1-2]. Usually, the water required for the air cooling is sea water or brackish water [1-2]. Both of updraft and downdraft solar chimneypower plant are based on the density difference between the air columns inside a large chimney (figure 1). This density difference causes a pressure difference $\Delta p_{chimney}$that is used to drive a turbine installed inside the chimney. The fraction $\Delta p_{dyn}$of this pressure difference is used to accelerate the air, the rest is used to drive a pressure staged turbine ($\Delta p_{turbine}$) and to compensate friction losses ($\Delta p_{friction}$) [8].

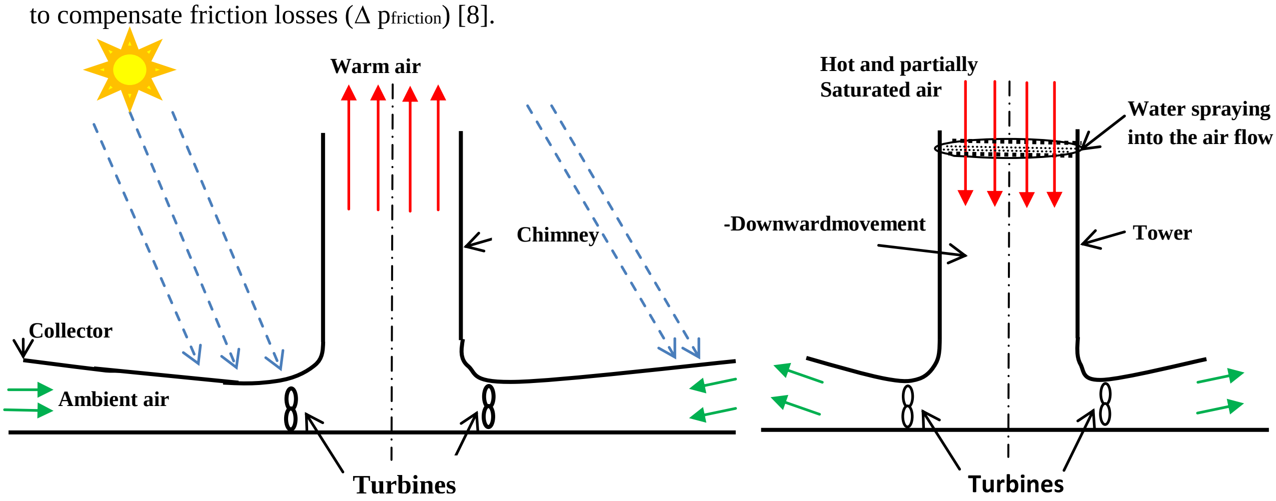


Figure (1-a): Solar chimney power plant with collector [8].
Figure (1-b): Solar chimney power plant without collector (Energy Tower) [8].

For Solar Chimney, Figure (1-a), Hot air is produced by a large solar air collector (direct and diffuse solar radiation). The heated air flows to a chimney positioned in the center of the collector resulting in updraft. This updraft drives wind turbines located at the chimney base. The ground under the collector is used as a thermal storage. This thermal storage can be increased, by using black water-filled tubes. Consequently, it is possible to operate a Solar Chimney during night[9]

For energy tower, Figure (1-b) [4-8, 14], by spraying water at the chimney top. The water evaporates, resulting in cooling the air inside the chimney. As cool air is denser than the surrounding, it flows down inside the chimney to drive turbines located at the tower base and produce electricity as well.

Energy towers are used in dry desert areas with heights of 400 meters or more. Water from available sources (such as a sea) is pumped up to the top of the tower and sprayed into it to cool the air. This causes a downwards draft through the tower which is converted into mechanical energy through wind turbines.

This technology is still under research stage,where itis characterized bythe high capital costs, and large water consumption.

The recommended dimensions of an energy tower can reach over 1000 meters in height and four to five hundred meters in diameter.

According to many authors [4-8, 14-19], about a third of the power generated is used for pumping the water to the top of the tower to be sprayedacross its diameter. However, estimated net deliverable energy for a 1200m (height) by 400m (diameter) tower is in the range of 370 MW [14].

The objective of this paper is to evaluate the performanceof solar tower power plants. A mathematical model isused to estimate the power output.

II. THE KEY ELEMENTS OF ENERGY TOWER POWER PLANT [4-9, 14]

II.1. The water spraying system

The water spraying systemcan be obtained from the market with its control system;to get a good distribution over the top of tower. The excess sprayed water is collected from the air at the bottom of towerand removed during operation.

II.2. Turbines and generators:

For large volume flow rate and small head, axial flow turbines can be used. The typical turbine would be 30 m diameter. 100 turbines can be arranged in two rows around the bottom of the tower. The average production of one turbine would be in the order of 7 MW [14].

II.3. Tower material

Many designs of the tower were made of reinforced concrete. Steel frame structure can be used in some cases. More efforts are needed to reduce the investment cost in Energy Towers.

III. CLIMATE DATA REQUIRED FOR ESTIMATING THE PERFORMANCE OF STPP [17]

The climate conditions for a complete year for Skaka city located in northern Saudi Arabia are given in table (1) (mean ambient temperature (^{o}C) , average sunshine hours, and RH%) [8]. other parameters can be obtained using Psychometric chart.

Table (1): the average daily mean temperature, average sunshine hours and Ø% for a complete year for SKAKA city in northern Saudi Arabia [17].

Month	T_{amb} ^{o}C	PSSH hrs/day	Ø%
Jan	8.86	10.4	52
Feb	11	11.1	40
March	15.4	11.9	34
April	21.3	12.8	26.9
May	26.6	13.6	19.1
June	29.7	14	16.4
July	31.7	13.8	17.2
August	32.2	13.2	17.9
Sept.	29.9	12.3	18.7
Octob.	24.5	11.4	27.5
Nov.	16.5	10.6	43.7
Dec.	10.8	10.2	52.2
Annual average	21.6	12.10833	30.5

From these results, the annual Average Relative Humidity (%) is 30.5% which is the critical parameter in design of ETPPs [17].

IV. THEORETICAL MODEL

To study the performance of the STPP, the following mathematical modeling is given below with the aid of fig.(2)[8].

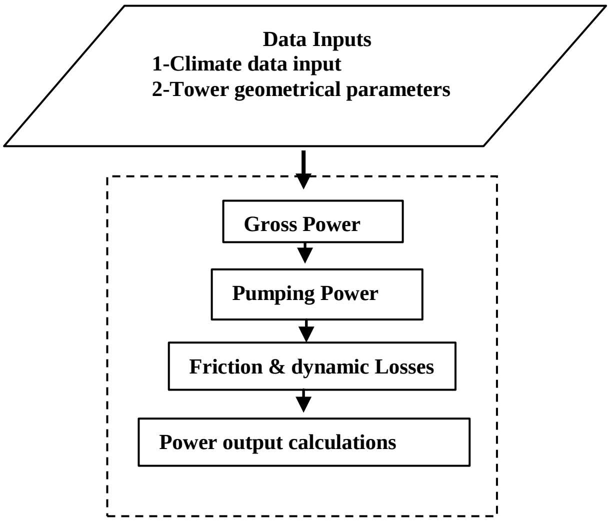


Figure (2): A program flow chart to evaluate the Energy Tower Performance.

The basic equations required for an assessment are given below**:**

IV.1. Variation of atmospheric air pressure and temperature with elevation.

Theatmospheric pressure (p) can be expressedas a function of ambient pressure on ground level p_0 and elevation z:

$$P(z) = P_o e^{\left(\frac{g\,z}{R_{air}\;T}\right)} \text{------- (1)}$$

Combining equation (1) with the general equation for ideal gases, to obtain the following temperature gradient:

$$\frac{\boldsymbol{dT}}{\boldsymbol{dz}} = -\frac{\boldsymbol{g}}{\boldsymbol{C_p}} \text{------- (2)}$$

Assuming C_P=1005 J/kgK and g = 9.81 m/s² this gives dT/dz= - 0.98 K / 100m which can be rounded to -1 ^{o}K/100m. This gradient is called 'Dry Adiabatic Lapse Rate (DALR).

IV.2. Density variation with elevation

The STPP is designed based on the density difference between the air column inside the chimney and the outer atmosphere. The density of moist air with a water content $RH\% = \emptyset$ = (P_w / P_s) is less or equal to unity (at saturation). Then the density variation can be calculated as follows:

$$\rho = \frac{P}{R_L\,T}\left[1 - 0.378\,\emptyset\,\frac{P_s}{P}\right] \text{----------- (3)}$$

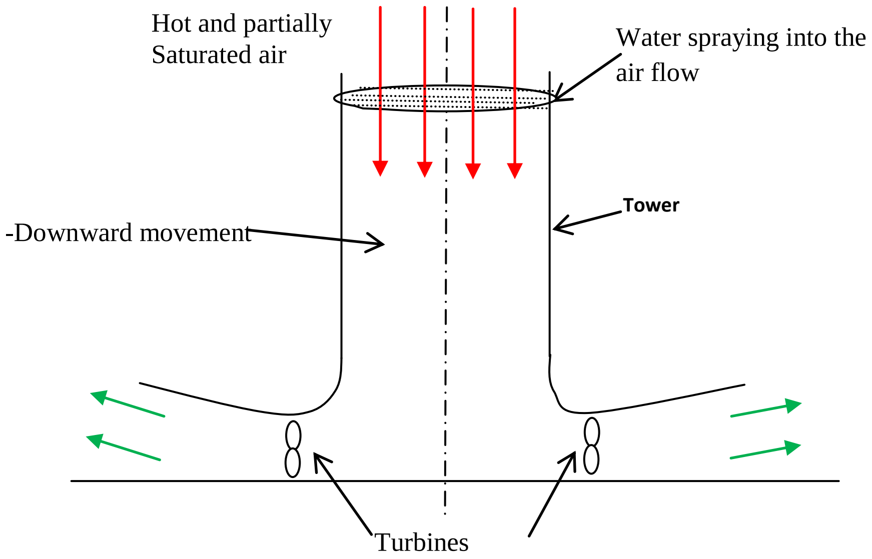
Where, P_w and P_s are the water vapor pressure at normal and saturation conditions respectively. While P is the atmospheric air pressure at elevation z.

Now, the basic equations related to analysis of Energy Tower performance are given below.

IV.3. Water spraying into a hot and dry air flow.

In the proposed Energy Tower, the density difference required to start air flow inside the chimney is obtained by cooling the ambient air sucked in. The air cooling achieved by evaporation of water that is sprayed into the flow at the chimney top. Therefore, the air temperature drop due to water spraying and evaporation process is calculated first (Figure 3). Considering the mixing process as adiabatic.

Figure(3-a):Solar tower power plant layout.



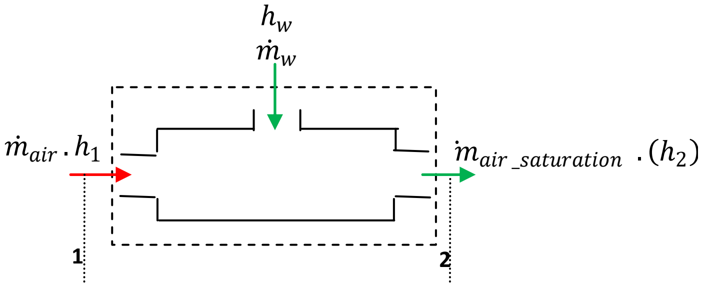


Figure (3-b): Adiabatic Mixing of sprayed water and moist unsaturated air[8].

The mass balance and the energy balance equations are given below:

$$\dot{m}_{air} + \dot{m}_w = \dot{m}_{air\_saturation}$$

$$\dot{m}_{air}.h_1 + \dot{m}_w h_w = \dot{m}_{air\_saturation}.(h_2)_{at\ saturation} \quad \text{---(4\& 5)}$$

Where, $\dot{m}_{air}, h_1$ are air mass flow rate (Kg/s) and its enthalpy (KJ/Kg) respectively.

And $\dot{m}_{air\_saturation}$, h_2 are the air mass flow rate at saturation condition (Kg/s) and its enthalpy (KJ/kg) respectively.

The enthalpy of the air is calculated based on weather data (T, ∅). For illustration, the following equations are given to calculate enthalpy of unsaturated air (∅≤1), water, and the saturated moist air (due to water spraying) respectively.

$$h_{air} = C_{P\_air}\ T$$
$$h_{water\ \_vapor} = r_o + C_{P\_water}\ T$$

Where, h_{air} is the enthalpy of dry air in Kj/Kg,
C_{P_air} is the specific heat of air, 1004 J/Kg.K,
T is the temperature in K,
$r_o$is the evaporation enthalpy of water, 2250KJ/kg.K,
C_{P_water} is the heat capacity of water, 4.18KJ/kg.K.

Then, the enthalpy of moist air after spraying of water is given by:

$$h_{moist\ \_air} = C_{P\_air}\ T + x_s\left(r_o + C_{P\_water}\ T\right) + (x - x_s)C_{P\_water}\ T \text{----(6)}$$

Where, x_s is the water vapor content of moist air at saturation condition due to water spraying,
x is the water vapor content of moist air before water spraying.

From these equations the resulting temperature of the air-water flow can be calculated. Then air densities inside the chimney can be calculated. For the calculations it is assumed that water droplets are to evaporate directly after being sprayed into the tower.

IV.4. **Chimney**

Pressure difference of the chimney is calculated using the following relation

$$\Delta P_{chimney} = g.\ \Delta\rho\ .H$$

And

$$\Delta\rho = \rho_{chimney} - \rho_{atmosp\ hhere} \text{----- (7)}$$

Where Δ $p_{chimney}$ is the total driving pressure potential available,
$\rho_{chimney}$ is the saturated air density at the tower top(at height H, m) due to water spraying, Kg/m^3,which corresponds to air pressure and temperature at the top of tower ,
$\rho_{atmosp\ hhere}$ is the air density at ground level conditions, kg/m^3,
$g$is the gravitational acceleration, 9.81 m/s^2.

IV.5. Turbine

The turbine extracts a fraction (X_{tm}) of the total driving pressure ($\Delta P_{chimney}$), the rest is needed to accelerate the air flow and to make up for friction. This can be expressed as follow:

$$\Delta P_{chimney} = \Delta P_{turbine} + \Delta P_{friction} + \Delta P_{dyn} \text{------ (8)}$$

Using the standard definition for dynamic pressure

$$\Delta P_{dyn} = \frac{1}{2}\ \rho\ v^2 \text{---------- (9)}$$

Also, $\Delta P_{friction}$ can be calculated as follows

$$\Delta P_{friction} = \zeta\ \frac{1}{2}\ \bar{\rho}_{chimney}\ v_{chimney}^2 \text{ ---- (10)}$$

Where, ζ is the overall friction coefficient for the complete air flow.

And air velocity inside the chimney, $v_{chimney}$ is given by:

$$v_{chimney} = \sqrt{2\frac{\Delta P_{himney}}{\bar{\rho}_{chimney}} \cdot \frac{(1-X_{tm})}{(1+\zeta)}} \text{-----}(11)$$

Where, the optimum pressure extraction factor (X_{tm}) is taken equal to 2/3[8].

Mechanical power (W_{mech}) extracted at the turbine can be written as

$$W_{mech} = \Delta P_{turbine}\,\dot{V} = \Delta P_{turbine}\,A_{turbine}\,v_{turbine} \text{ --}(12)$$

Where, $A_{turbine}$ is the cross sectional area, m^2.

IV.6. Complete **System**

Themass flow rate of sprayed water is calculated based on the air flow reaches saturation condition at the chimney base level.

IV.7. Calculations of pumping power consumption [22]

The ideal hydraulic power of a pump depends on the mass flow rate, the liquid density and the differential heightcan be calculated asfollows (including both of the static lift and the friction head loss of the system) [10]:

$$W_h = Q\,\rho\,g\,H / (3.6\,X10^6) \text{--------------------}(13)$$

Where

W_h = Hydraulic power (kW)

Q = Flow capacity (m^3/h)

ρ = Density of water (kg/m^3)

g = Gravity (9.81 m/s^2)

H = Differential head (m)

The shaft power is the power transferred from the motor to the shaft of the pump, which depends on the efficiency of the pump and can be calculated as:

$$W_s = W_h / \eta_p \qquad \text{--------------------}(14)$$

Where, η_p is the overall pump efficiency, which is taken equal to 0.6 during the present study.

V. ASSUMPTIONS

The main assumptions used in the present study are summarized in Table (2)

Table (2): summary of assumptions used in numerical model.

Parameters	Value
Chimney height (*Hch*)	1200 m
Chimney diameter (*Dch*)	400 m
Efficiency of the turbine (ηtur)	0.8
The total overall net plant efficiency	1.2%
Pump overall efficiency	60%

VI. SOLUTION TECHNIQUE

For a given STPP, geometrical parameters (height and diameter of chimney) and for a specified site weather conditions (such as ambient air temperature, relative humidity), the performance of the STPP can be estimated yearly basis by using the set of Eqs. (1) to (14). All calculations were performed using the above mentioned equations and assumptions. Performance results are obtained using EES software.

VII. RESULTS AND DISCUSSION

Based on STPP geometrical parameters assumed in this study and using the weather data of northern KSA, The performance of the STPP has been studied and the results are given below:

VII.1. VARIATIONS OF MONTHLY AVERAGE RH% AND TEMPERATURE

As mentioned above,the principle of an ETPPs is to cool hot and dry air by water particles sprayed at the top of tower, the annual variation of both T_{amb}. And RH% are studied first and plotted in fig. (4).

Fig. (4) gives the variations of monthly average ambient temperature (T_{amb}.) and relative humidity (RH%) in the northern KSA[6,7]. It can be observed that the temperature and RH% variations change oppositely. 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. On the other hand the variation in RH% is different, where the maximum mean and minimum mean are 52.2 %(in December) and 16.4(in Jan.) respectively. With more focus on the annual average values of both $T_{amb.}$ (21.6 ^{o}C) And RH % (30.5%), it can be concluded that the weather condition is dry and hot air, which is excellent for ETPPs operation.

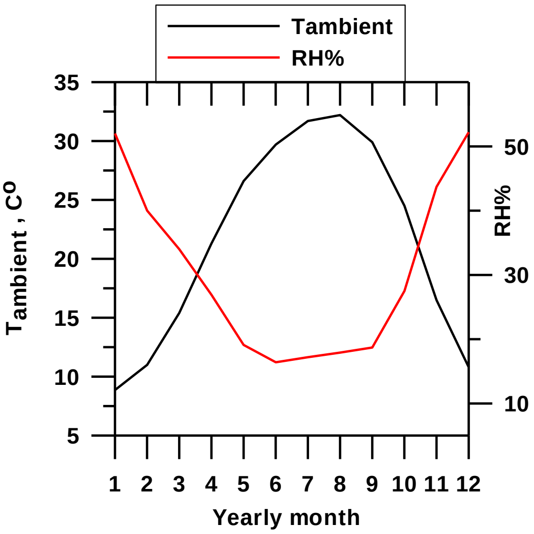


Fig. (4):Variationof monthly average RH% and temperatureat SKAKA region.

VII.2. Effect of ambient conditions (temperature and RH %) on power output

As explained, the power output is obtained from the air movement from top to bottom inside a large chimney due to density difference. This density difference causes a pressure difference $\Delta p_{chimney}$ that is used to drive a turbine installed inside the chimney.

Fig. (5) shows the effect of the $T_{amb.}$ and the RH% on the density difference, then on the air velocity and finally the effect on power output. It is found that power output increases with the increase of density difference. The capacity of power generation ranges between 111.8(in OCT.) and 137.8MW (in Jan) for a whole year.

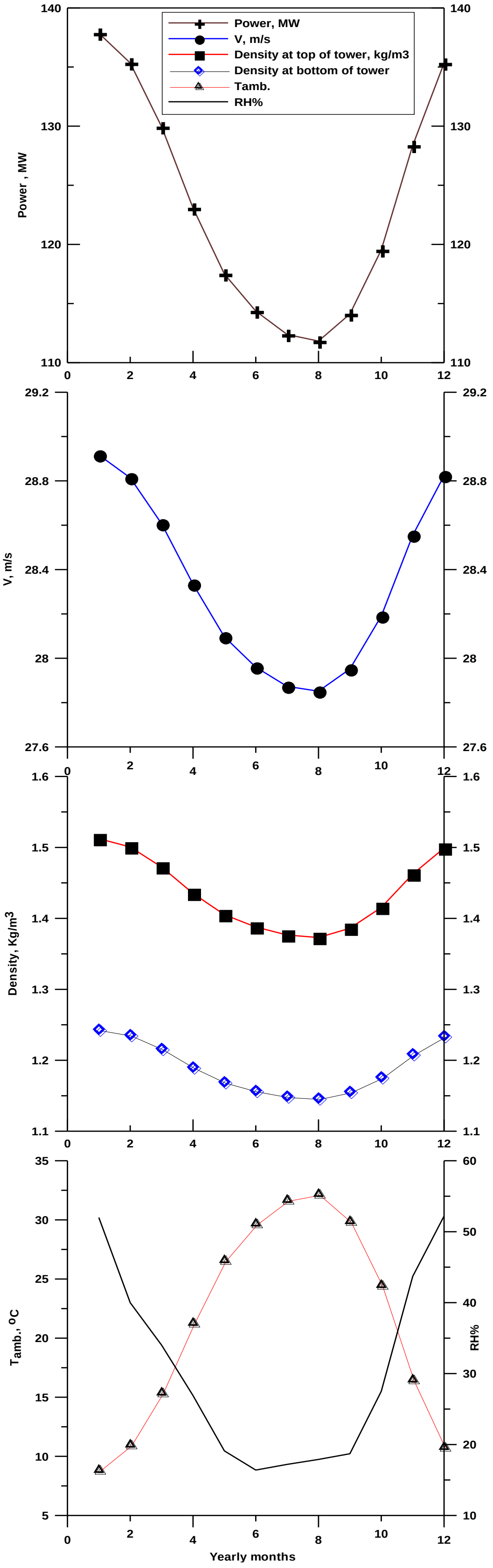


Fig.(5): Effect of the monthly average ambient temperature and the RH% on monthly average power productivity.

Conclusions

Many studies were focused on the use of power tower for electrical power generation. The present study was directed to evaluate*its*performance under weather conditions of KSA. A mathematical model was used to estimate the power output, airflow velocity and density.The performance of STPP was studied for application under weather conditions of northern Saudi Arabia.It is concluded that:

1-For northern KSA, the annual average values of both $T_{amb.}$and RH% are (21.6 ^{o}C) and (30.5%) respectively, which is good for ETPPs operation.

2- The capacity of power generation is mainly related toambient Air relative humidity and temperature. Under givenAmbient conditions, the power generation capacity increases with the increase in tower height.

3-The capacity of power generation ranges between 111.8(in OCT.) and 137.8MW(in Jan) for a whole year.This is based on tower dimensions of 1200m height and 400m diameter.

Nomenclature

A_c Cross-sectional area of solar chimney, m_2
A_{coll}Solar collector area, m_2
C_pSpecific heat of air, kJ/kg.°C
g Acceleration of gravity, m/s^2
H_{ch}Solar chimney height, m
IGV inlet guide vanes
KSA Kingdom of Saudia Arabia
$\dot{m}$ 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
W_e Electric output from the solar chimney, kW
SC solar chimney
SUTPP solar updraft tower power plants
T_o Ambient temperature, °C
v_{ch}Inlet air velocity of solar chimney, m/s

Greek symbols
η_{tur}Turbine efficiency
ρAir density, kg/m^3
ΔP_{tot}Pressure difference produced between chimney base and the surroundings, Pa

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