IOSR Journal of Electronics and Communication Engineering (IOSR-JECE)
e-ISSN: 2278-2834,p- ISSN: 2278-8735.Volume 11, Issue 2, Ver. I (Mar-Apr .2016), PP 67-76
www.iosrjournals.org

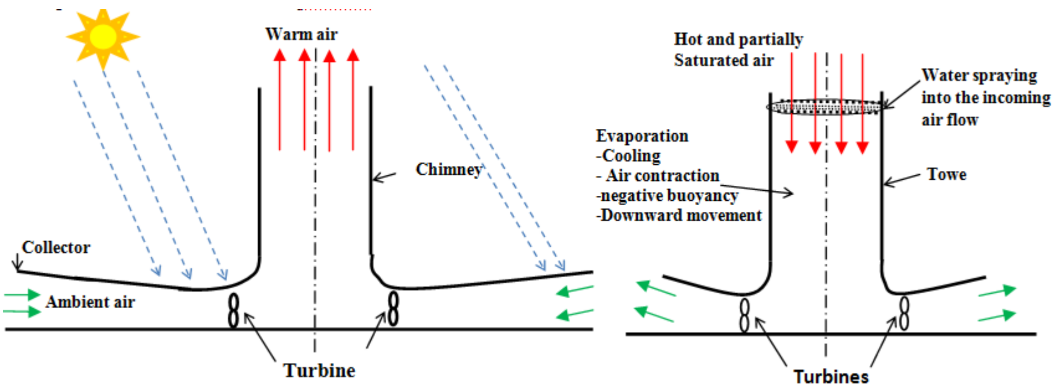
Solar Chimney Power Plant without Collector

A.M.K. El-Ghonemy
Department of Mechatronics Engineering High Institute of Engineering and Textile Technology, Egypt.

Abstract: *The solar chimney power plant without collector is a large-scale solar power plant proposed for future applications. It is so called energy towers power plant (ETPP). Its working principle is based on cooling of large masses of hot and dry air resulting in downdraft within a large chimney used to drive wind turbines for electricity generation. So, it is effectively applicable in hot and dry weather.This paper is directed to evaluate the performance of ETPPs. A mathematical model was developed to estimate the power output from a certain chimney geometry and weather condition.The results showed that, the power tower, in which the height and diameter of the chimney are 1200 m and 400 m, respectively, is able to produce a monthly average electric power between 111.8MW(in OCT.) and 137.8MW (in Jan) for a whole year.*
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. 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 column inside a large chimney (figure 1). This density difference causes a pressure difference □ □ pchimney that is used to drive a turbine installed inside the chimney. The fraction □ □ pdynof this pressure difference is used to accelerate the air, the rest is used to drive a pressure staged turbine (□ □ pturbine) and to compensate friction losses (□ □ pfriction)[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), using a large collector greenhouse with a central chimney. Hot air is produced by direct and diffuse solar radiation under a large glass roof (i.e. solar air collector). The heated air flows to a chimney positioned in the center of the collector resulting in updraft. This updraft drives wind turbines installed at the base of the chimney. The ground under the collector is used as a thermal storage. This effect can be increased, by covering the ground under collector with black water-filled tubes. Consequently, it is possible to operate a Solar Chimney during night, i.e. 24 h/day [9]

For energy tower, Figure(1-b) [4-8,14], the air is denser than the adjacent air outside the chimney. This is achieved 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 produce electricity, pressure staged turbines are capable of working on a small pressure difference (in the range of 1000 Pa), but large volume flow rates, are required. In practice, the turbines are placed close to the ground.

Energy towers are vertical, hollow towers constructed in dry desert regions 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 so that it cools the air. This creates a downwards draft through the tower which is transferred into mechanical energy through wind turbines.

The technology is still under research and development stage. The business in energy towers is affected by: the relatively high capital costs, the requirement of large water resource, and the long distance from the end users.

This technology can help to eliminate salinity by using brackish drainage water to spray into the tower. This could help protect irrigation projects.

The optimal dimensions of an energy tower can reach over 1000 meters in height and four to five hundred meters in diameter. For instance, air cooled by 12 ^{0}C is approximately 4% heavier than the ambient air), and will flow downwards in the hollow chimney. This air will flow strongly through openings near the tower's bottom, so that it can drive large wind turbines connected to electricity generators.

The STPPs technology can be applied in regions with hot, dry climates (deserts) which are relatively close to the sea or oceans as a water source. The world potential for this technology is estimated and summarized in table (1)[4-8,14].

Table (1): potential of Energy Towers[4-8,14]

potential of energy Towers						
Region	200-600MW av. Net output		300-600MW av. Net output		6000 KWh/year per Capita	10,000 KWh/year per Capita
	Annual energy	No. of towers	Annual energy	No. of towers		
	10^9 KWh/year	-	10^9 KWh/year	-	10^6	10^6
North Africa	46 412	18 140	14251	4018	2375	-
South Africa	17 256	6 850	5932	1685	989	-
India	16 086	6 487	4407	1548	734	-
Saudi Arabia	8580	2 580	6072	1089	1,012	-
Persian Gulf	6 884	1 715	6440	1543	1,073	-
California $Mexico	27 182	10 956	4748	1442	-	474
Chile$ Peru	23 653	8 385	9542	2730	1590	-
Australia	111 783	5 004	907	289	151	-
Spain, Italy, Greece	3 320	1 666	-		-	-
The number of people that can be supplied by electricity from Energy Tower are shown in the last two columns (at 6,000 kWh/year/capita or at 10,000 kWh/year/capita).						

According to many authors [4-8,14], 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 is developed to estimate the power output.Also, some general guidelines are given for the selection of STPPs and the parameters that are needed to be considered.

II. The key elements of STPPs [4-9,14]

II.1. The spraying system

The sprayers are available on the market with a good control system, to produce a good distribution over the tower's top.

II.2. Extra Sprayed water collection

The excess sprayed water must be collected from the air at the bottom of tower. If 6 kWh are produced for each cubic meter of sprayed sea water (salt water), the estimated amount of salt will be 6.7 kg for each net kWh to be produced. This is the serious environmental problem related to the operation of the Energy Towers.This problem can be solved by precipitation of the salt in a special area before the air is released. Then it can be collected and removed.

II.3. Turbines and generators :

For large volume flow rates and small heads, the reaction and axial flow turbines are used. Today, wind turbines with variable rotational speed and an AC-DC-AC conversion system are preferred. The typical turbine would be 30 m diameter. 100 turbines can be arranged in two tiers around the bottom of the tower. The average production of one turbine would be in the order of 7 MW and the installed capacity may be double.

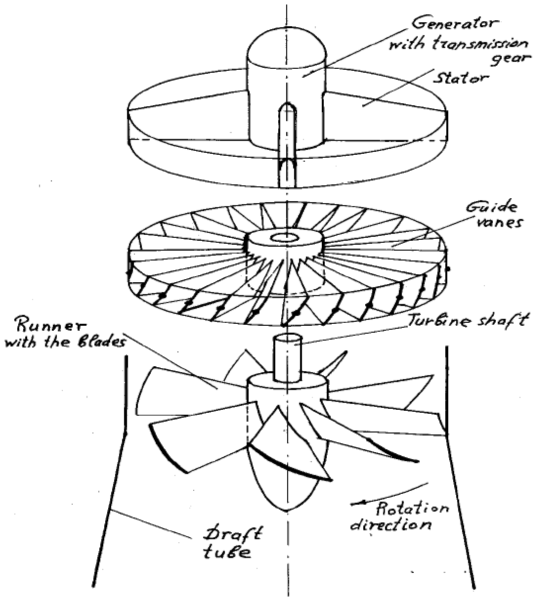


Figure (2): Schematic view of the turbine[14].

II.4. Tower material

Many designs of the tower was 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 through structural design and erection methods. Also measurements of wind speeds and wind drag forces on different structural shapes are required.

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 (2) (mean ambient temperature (^oC) , average sunshine hours, and RH%) [8]. other parameters can be obtained using Psychometric chart.

Table(2): the average daily mean temperature, average sunshine hours and Ø% for a complete year for SKAKA city in northern Saudi Arabia [17].

	T_{amb} ^oC	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].

III. Theoretical model

To study the performance of the STPP, the following mathematical modeling is given below with the aid of fig.(3)[8].

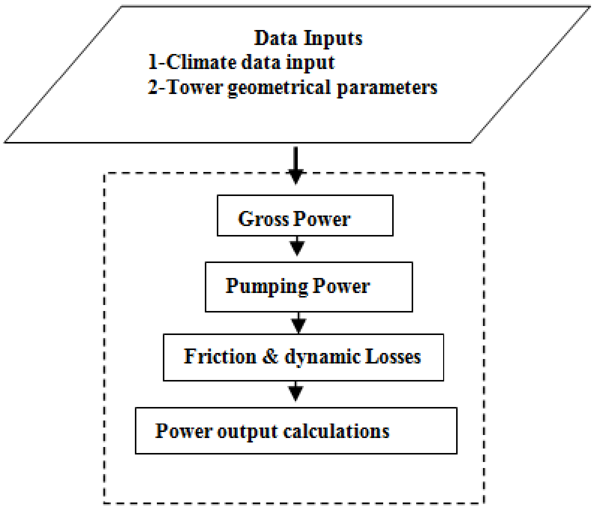


Figure (3): A program flow chart to evaluate the Energy Tower Performance.

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

3.1. 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:

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

Assuming Cp=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).

3.2. 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.

3.3. 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 4). Considering the mixing process as adiabatic (neglecting heat transfer through the chimney walls).

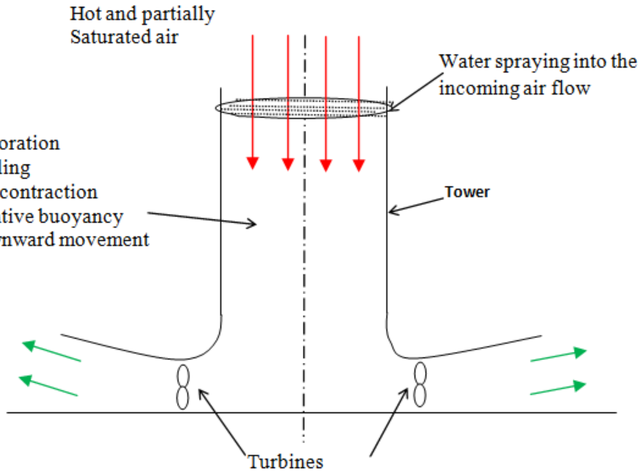


Figure (4-a): Solar tower power plant layout.

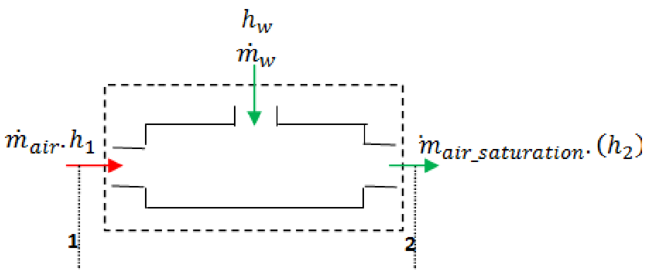


Figure (4-b): Adiabatic Mixing of sprayed water and moist unsaturated air[8].

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:

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

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.

3.4. **Chimney**

Pressure difference of the chimney is calculated using the following relation

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

And

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

Where $\Delta P_{chimney}$ 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.

3.5. 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:

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

Using the standard definition for dynamic pressure

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

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

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

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

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

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

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

Mechanical power ($W_{mec\ h}$) extracted at the turbine can be written as

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

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

3.6. **Complete System**

Themass flow rate of sprayed water is calculated in such a way that the air flow reaches saturation condition at the chimney base level (to prevent the turbines from damage due to water droplets).

3.7. 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 height can be calculated asfollows (including both of the static lift and the friction head loss of the system) [10]:

$W_h = Q\,\rho\, g\, H / (3.6\, X10^6)$ --------------------(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:

$W_s = W_h / \eta_p$ --------------------(14)

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

ASSUMPTIONS

The main assumptions used in the present study are summarized in Table (3)

Table(3): 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%

IV. 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 by simulation using EES software.

V. 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:

5.1. Variations Of Monthly Average RH% And Temperature

As long asthe principle concept of an ETPPs is to cool hot and dry air by partially evaporation of water particles sprayed at the top of tower, the annual variation of both T_{amb}. And RH% are studied first and plotted in fig.(5).

Fig.(5) 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 ^oC, 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 ^oC) And RH%(30.5%), it can be concluded that the weather condition is dry and hot air, which is excellent for ETPPs operation.

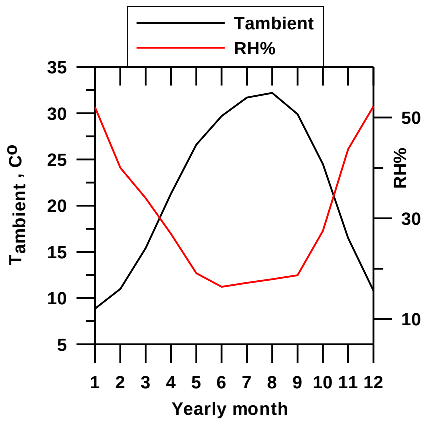


Fig.(5):Variationof monthly average RH% and temperatureat SKAKA region.

5.2. 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(6) 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.

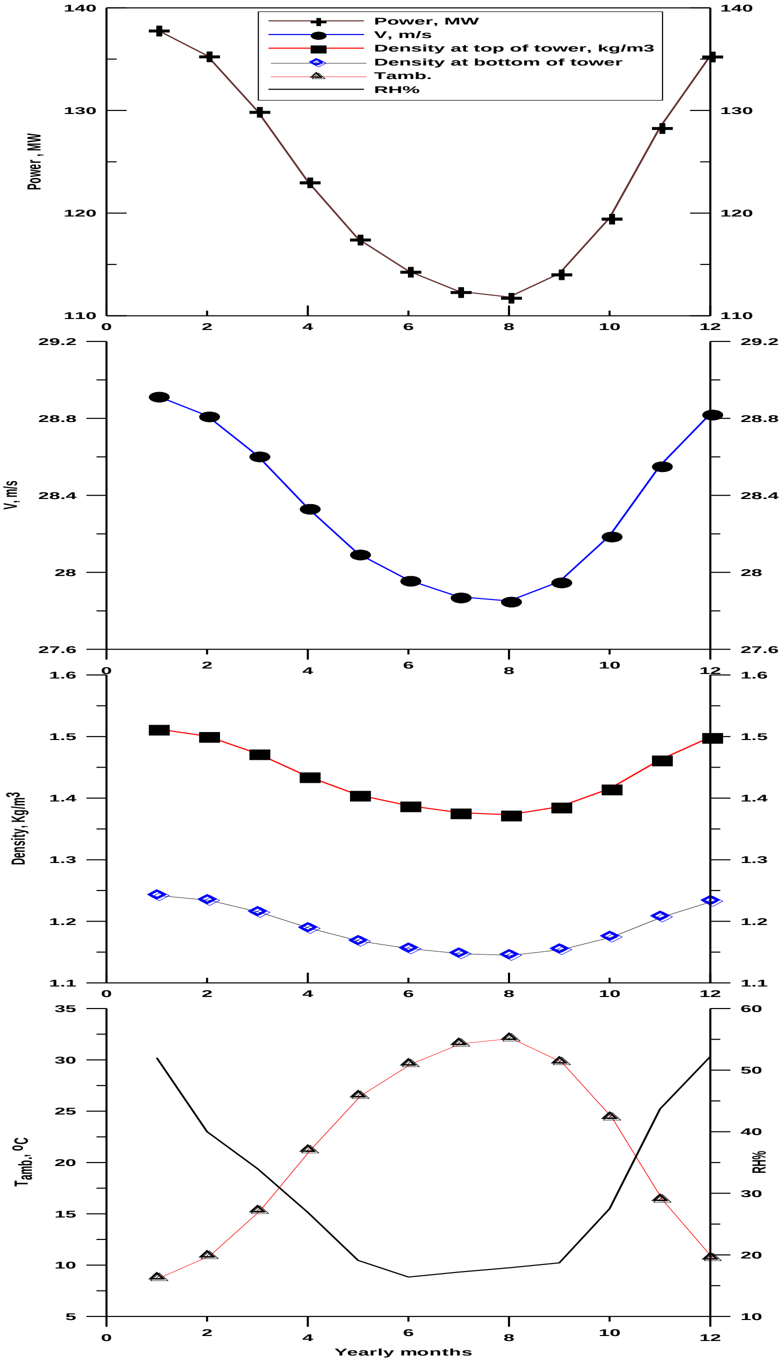


Fig.(6): Effect of the monthly average ambient temperature and the RH% on monthly average power productivity.

5.3. Financial costs

Depending upon site conditions (T &RH%), the estimated investment for building of a ETPP unit with a capacity of 50 MW is about USD 135 million[8]. Other auxiliary costs are estimated at several tens of millions USD. The construction cost of a full-size commercial unit that has output of 370 MW was estimated at USD

850 million (2005)[8]. However, the best way for cost estimation can be obtained by a feasibility study for a specific location.

VI. Conclusions

Many encouraging studies were published about the use of power tower to produce electrical power. The present study was directed to evaluate*its*performance. 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. Based on this, it can be concluded that the weather condition is dry and hot air, which is good for ETPPs operation. The annual Average Relative Humidity (%) is 30.5% which is the critical parameter in design of ETPPs .
2- The capacity of power generation is mainly dependent on Ambient Air relative humidity and temperature. Also the system performance is affected by tower height, turbine efficiency and surface roughness inside the chimney. Under given 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

Ac Cross-sectional area of solar chimney, m2
AcollSolar collector area, m2
CpSpecific heat of air, kJ/kg.□ C
g Acceleration of gravity, m/s^2
HchSolar chimney height, m
IGV inlet guide vanes
$\dot{m}$ Mass flow rate of air, kg/s
PCU power conversion unit
PtotUseful energy contained in the airflow, kW
Pwt,maxMaximum mechanical power taken up by the turbine, kW
We Electric output from the solar chimney, kW
SC solar chimney
SUTPP solar updraft tower power plants
To Ambient temperature, □ C
$v$chInlet air velocity of solar chimney, m/s

Greek symbols

ηturTurbine efficiency
ρAir density, kg/m^3
ΔPtotPressure difference produced between chimney base and the surroundings, Pa

References

[1]. R.D. Rugescu, Solar Energy (INTECH, Croatia, 2010
[2]. T.Altman, D.Zaslavsky, R.Guetta and G. Czisch,Evaluation of the potential of electricity and desalinated water supply by using
[3]. technology of "Energy Towers" for Australia and America, INTERIM REPORT, 2005.
[4]. Vertical Motion and Atmospheric Stability, lesson4, google.com
[5]. A.Talia, R. Guetta, D.Zaslavsky and G.Czisch,Estimating the potential of "Energy Towers" in a GIS environment,INTERIM
[6]. REPORT, 2002.
[7]. T. Altmann, R.Guetta, D.Zaslavsky and G.Czisch, A model for estimating the potential of "Energy Towers" in a GIS Environment,
[8]. INTERIM REPORT, 2003.
[9]. Israel - India Steering Committee, Energy towers for Producing Electricity and Desalinated Water without a Collector,ET-
[10]. BROCHURE,2001.
[11]. E. Omer, R. Guetta, I. Ioslovich, P.O. Gutman, and M. Borshchevsky,Energy Tower combined with pumped storage and
[12]. desalination:Optimal design and analysis,Renewable Energy, 2007, under press copy.
[13]. G.Weinrebe, W.Schiel, Up-Draught Solar Chimney and Down-Draught Energy Tower–A Comparison, ISES Solar World Congress,2012.
[14]. H. ROESCH, Downdraft GasificationOf Various BiomassFeedstock For Energy Production, MSc thesis, THE FLORIDA STATE
[15]. UNIVERSITY, FAMU-FSU COLLEGE OF ENGINEERING.
[16]. D. Zaslavsky, R. Guetta and S. Hassid,Energy towers A renewable energy technology for producing electricity and desalinated water in arid climates" PALENC 2007 –(2) , pp. 1167-1171.
[17]. I.Khoo, A.Khor, and H.W. Lee," Solar Chimney for Desalination" The University of Adelaide School of Mechanical Engineering, Final Report Project 1061, 2011.
[18]. S. Hassid, I. Merksamer, and R. Guetta,2012" Energy Towers – The effect of droplet coalescence on power and the environment" Solar Energy 86 (2012) 1443–1453.
[19]. Fundamentals of Renewable Energy Processes"chapter 15: wind energy" DOI: 10.1016/B978-0-12-374639-9.00015-4.

[20]. Denis BONNELLE,2004" Solar Chimney, water spraying Energy Tower, and linked renewable energy conversion devices : presentation, criticism and proposals"PhD thesis, UNIVERSITY CLAUDE BERNARD - LYON 1 –FRANCE.
[21]. A. Akbarzadeh, P. Johnson, R. Singh, 2009" Examining potential benefits of combining a chimney with a salinity gradient solar pond for production of power in salt affected areas" Solar Energy 83 (2009) 1345–1359.
[22]. MohamadKordab, 2007 "Priority option of photovoltaic systems for water pumping in rural areas in ESCWA member countries" Desalination 209, 73–77.
[23]. NASA Surface Meteorology and Solar Energy, Available from http://eosweb.larc.nasa.gov/sse/.