Solar Updraft Tower Power Plant with Thermal Storage

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Abstract

A mathematic model is presented for solar updraft tower power plant with water-storage system. This model is developed to evaluate the effect of geometrical parameters of the solar tower power plant and thermal storage system as well as the wind velocity on the power production of the plant. The analysis based on variable solar incident radiation along the day. The results show that the tower tall, the tower diameter, the wind velocity, and the collector diameter have a significant effect on the power production while the thickness of the water-storage layer is shifted the peak value of the output power far away from mid-day and more smoothing the output power curve. The results are compared with other model and experimental data. A good agreement is obtained.

محطة كهرباء البرج الشمسي ذي الخزان الحراري

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ألخلاصة

تم انشاء نموذج رياضي لمحطة القدرة الكهربائية ذات البرج الشمسي والمجهزه بالماء كمنظومة خزن حراري.الهدف من النموذج الرياضي هو لايجاد تاثير العوامل المتعلقة بالابعاد الهندسية لمكونات المحطة وتأثير منظومة الخزن الحراري بالاضافة الى تأثير سرعة الرياح على القدرة الخارجة من المحطة . استندت التحليلات النظرية على كمية الاشعاع الشمسي المتغير خلال ساعات النهار. أظهرت النتائج ان العناصر المؤثرة على أداء المحطة هي طول وقطر البرج الشمسي بالاضافة الى قطر المجمع الشمسي وسرعة الرياح. أما تأثير الخزن الحراري للماء فقدعمل على تأخير وقت وصول القدرة الخارجة لقيمتها العظمى الى فترة مابعد الظهر واستمرار انتاج القدرة الكهربائية خلال ساعات الليل. تمت مقارنة النموذج الحالي مع نموذج ونتائج عملية أخرى وحصل توافق جيد.

Nomenclature

A_{coll}	collector area	(m^2)
A_t	tower cross section area	(m^2)
cp_a	specific heat of air	(J/kg K)
cp_s	specific heat of water-storage	(J/kg K)
D_{coll}	solar collector diameter	(m)
D_h	hydraulic diameter of the solar collector	(m)
D_t	tower diameter	(m)
G	solar intensity	(W/m^2)
G_g	global solar constant	(W/m^2)
g	gravitational acceleration	(m/s^2)
H_{coll}	height of the collector	(m)
H_t	tower height	(m)
H_s	water-storage layer thickness	(m)
h_i	heat transfer coefficient of inside collector	(W/m^2 K)
h_∞	heat transfer coefficient of outside collector	(W/m^2 K)
k_a	thermal conductivity of air	(W/m K)
$\dot{m}_a$	air mass flow rate	(kg/s)
Pr	Prandtle number ($\frac{\mu_a\, cp_a}{k_a}$)	(-)
Re	Reynolds number ($\frac{\rho_a \bar{u}_{coll} D_h}{\mu_a}$)	(-)
t	time	(s)
$T_{a,i}$	air temperature at the collector inlet	(K)
$T_{a,o}$	air temperature at the collector outlet	(K)
T_∞	ambient temperature	(K)
T_s	water-storage temperature	(K)
$\bar{u}_{coll}$	average air velocity in the collector	(m/s)
u_t	air velocity in the solar tower	(m/s)
u_{wind}	wind velocity	(m/s)
α	absorptivity of water-storage	(-)
ρ_a	air density in the collector	(kg/m^3)
ρ_s	water-storage density	(kg/m^3)
η_{tg}	turbine-generator efficiency	(-)
$\Delta\tau$	day length	(hr)
Δp	Pressure difference between the tower base and the surrounding.	(Pa)

1. Introduction

The solar tower or solar chimney offers a method for large scale generation of electricity from solar energy. Air is heated near the ground by trapping solar radiation in a flat circular glass-roof greenhouse. The heated air rises in the tower, and the updraft is used to drive a turbine.

In order to obtain a more uniform daily solar tower power plant output, the solar collector can be equipped with a thermal storage like water–storage system to increase the power production during the night. The concept of the solar tower was designed and put into use during 1980 by J.Schlaich et al.[1,2]. Hauf et al.[3] provided fundamental investigation for the Spanish prototype system in which the energy balance, design criteria, and cost analysis were discussed. Backstrom and Gannon[4-7] proposed a thermodynamic cycle analysis for the solar tower power plant operation. Papageorgiou[8,9] extended their studies producing analytical results.

Many other investigators studied the effect of the thermal storage on the performance of the solar tower plant. Among these studies, the investigation of Bernardes et al.[10] 2003 which provided a thermal and technical analysis of solar tower plant with water-storage system. Their results show that the height of the tower, the the diameter and the optical properties of the collector are important parameters for the design of solar towers while the ground properties andwater-storage presented no significant variation on the energy output, but on power output vs. time. Also Schlaich et al. [11] 2005, presented, theory, practical experience, and ecomomy of solar updraft towers. They found that the thermodynamic efficiency of the plant increases with tower height.

2. Mathematical Model

A mathematical model of solar updraft tower power plant has been developed under the following assumptions:

1. The heat loss through the tower wall is neglected.
2. The air flow through the collector is considered as flow between parallel plates.
3. No heat loss into the ground.
4. The storage water temperature is uniform.
5. The air flow in the system is due to bouncy force.

The simplified heat balance equation of the solar collector shown in fig.1. is given as:

$$\alpha G A_{coll} - h_i A_{coll} (T_s - T_a) = m_s cp_s \frac{dT_s}{dt} \tag{1}$$

Where

$$m_s = \rho_s A_{coll} H_s \tag{2}$$

And the energy equation for the air stream through the collector is:

$$h_i A_{coll} (T_s - T_a) - h_\infty A_{coll} (T_a - T_\infty) = \dot{m}_a cp_a (T_{a,o} - T_{a,i}) \tag{3}$$

Where

$$T_a = \frac{T_{a,o} + T_{a,i}}{2} \tag{4}$$

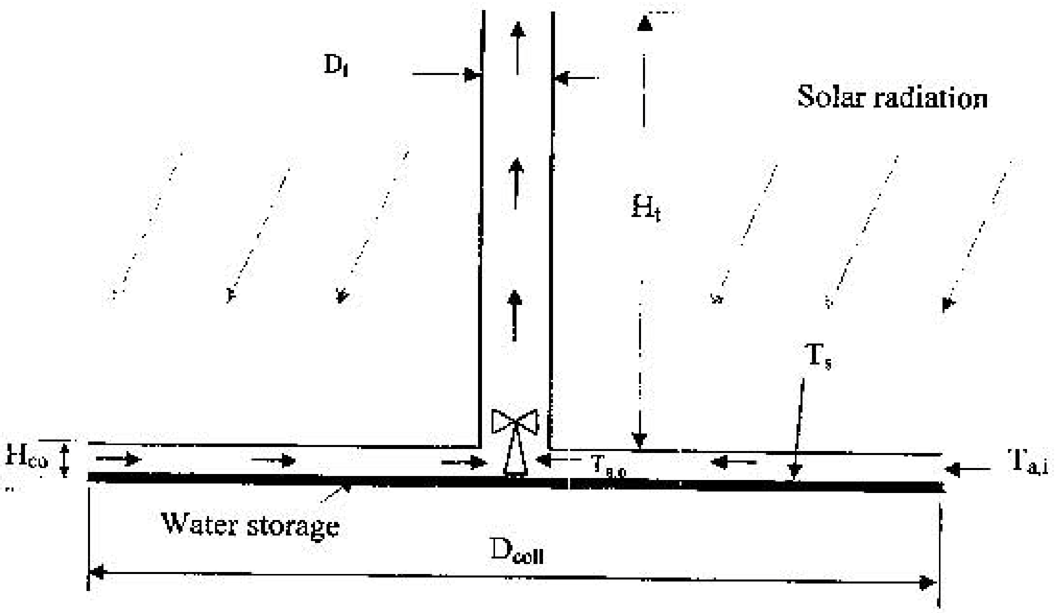

Fig.1 The schematic diagram of solar tower power plant.

Substitution of equations (2),(3), and (4) into equation(1) gives the following time dependent differential equation:

$$\frac{dT_s}{dt} = \frac{\alpha G}{\rho_s cp_s H_s} - \frac{h_i}{\rho_s cp_s H_s}$$

$$\left[T_s - \frac{\left(\frac{\dot{m}_a cp_a}{A_{coll}}\right) T_{ai} + \frac{1}{2}(h_i T_s + h_\infty T_\infty)}{\left(\frac{\dot{m}_a cp_a}{A_{coll}}\right) + \frac{1}{2}(h_i + h_\infty)} \right] \quad (5)$$

The inside heat transfer coefficient (h_i) is taken as [12].

$$h_i = \frac{(f/8)(Re - 1000)Pr}{1 + 12.7\sqrt{f/8}(Pr^{\frac{2}{3}} - 1)} \frac{k_a}{D_h} \quad (6)$$

Where

$$f = [0.79 \ln(Re) - 1.64)]^{-2} \quad (7)$$

Where D_h is the hydraulic diameter of the solar collector by considering the flow through the collector as flow between parallel plates of infinite width;

$$D_h = 2H_{coll} \quad (8)$$

And

$$Re = \frac{\rho_a \bar{u}_{coll} D_h}{\mu_a} \quad (9)$$

From continuity equation:

$$\dot{m}_a = \rho_{a,o} \frac{\pi}{4} D_t^2 u_t = \rho_a \pi D_{coll} H_{coll} u_{coll} \quad (10)$$

Where

$$\rho_a = \frac{\rho_{a,i} + \rho_{a,o}}{2} \quad (11)$$

The average air velocity through the collector can be expressed as:

$$\bar{u}_{coll} = \frac{\dot{m}_a}{2\pi\rho_a(r_{coll} - r_t)} \int_{r_t}^{r_{coll}} \frac{dr}{r} = \frac{\dot{m}_a}{2\pi\rho_a(r_{coll} - r_t)} \ln\frac{r_{coll}}{r_t} \quad (12)$$

Where

r_{coll} and r_t are equal to $(D_{coll}/2)$ and $(D_t/2)$ respectively.

The heat transfer coefficient from the collector to the ambient air is given by [12]:

$$h_\infty = 5.7 + 3.8\, u_{wind} \quad (13)$$

2.1. The Solar Tower

The velocity of the hot air at the collector outlet (tower inlet) can be estimated using Bernoulli equation as follows:

$$u_t = \sqrt{\frac{2\Delta p}{\rho_{a,o}}} \quad (14)$$

and the pressure difference due to the buoyancy force between the air at the solar tower base and the ambient air is given by[11]:

$$\Delta p = g\int_0^{H_t}(\rho_{a,o}-\rho_\infty)dH_t = g(\rho_{a,o}-\rho_\infty)H_t \qquad (15)$$

Thus, the equation (14) can be written in term of temperature difference as follows:

$$u_t = \sqrt{\frac{2gH_t(T_{a,o}-T_\infty)}{T_\infty}} \qquad (16)$$

The pressure difference is used to accelerate the air and is thus converted to kinetic energy:

$$P_k = \frac{1}{2}\dot{m}_a u_t^2 \qquad (17)$$

The output electrical power of the plant can be found as [1]:

$$P_e = \frac{1}{3}\eta_{tg}\rho_{a,o}A_t u_t^3 \qquad (18)$$

3. Results and Discussion

The amount of power varies with the variation of incident solar radiation. The equation that describes the amount and variation of solar radiation incident on a clear day is given by the following sinusoidal relation [13]:

$$G = G_g \sin(\frac{\pi t}{\Delta\tau}) \qquad (19)$$

Where G_g is the global solar constant which approximately equal to 1000 W/m^2, t=0 for the sunrise and $\Delta\tau$ is the day length which is given by the difference between the sunrise and the sunset.

The time dependent differential equation (5) is solved numerically for the T_5 as a function of time (t) for different parameters. The data used in the analysis are tabled as follows:

Parameter	Value
Tower height	1000 m
Tower diameter	100 m
Solar collector diameter	5000m
Collector height	3m
Water-storage height	10 cm
Wind velocity	3 m/s
Ambient temperature	25 °C
Day length	12 hour
Water–storage absorptivity	0.9
Efficiency of turbine-generator	0.8

The results are display on figures (2-8). In these figures it's clear that the output power begin to increase after the sunrise hour (6 am) the peak of the power production occurs beyond the mid day due to use of the thermal storage. Fig.(2) shows the effect of water-storage thickness on the output power. This effect can be shown in two ways: a decrease in the peak value and an increase in the min. value of the power and shift them far away from the midday time. It can be deduced that the average output power approximately remain constant and the use of the power of the plant is become more uniform as a result of use the thermal storage.

In Fig.(3) , the power production of the plant increases with increasing the collector diameter due to a more solar energy absorbed as the collector area increases. Fig.(4) shows a significant increase in the power with the tower height due to the increase of the pressure difference between air at the tower base and ambient air as the tower height increases. The increase of tower diameter increases the upward air mass flow rate and in turn increase of the kinetic energy as shown in Fig.(5).

A slightly decrease in output power with the collector height since the air velocity through the collector decreases as the collector height increases causing a decrease in the heat transfer to the flowing air across the collector as it clear in Fig.(6) As it expected the increase of wind velocity decreases the power production of the solar plant due to the increase in heat losses from the collector roof as the wind velocity increases as it clear shown in Fig.(7). Fig.(8) shows the water-storage temperature and air temperature at the tower base are closed to each other, since the air spends a long time to heat up from the perimeter to the collector center. A comparison between the present model and experimental data of prototype solar tower plant of Manzanares (Spain) presented by Bernardes et al. [10] is shown in Fig.(9). It is clear that the present model output is closed to the experimental data and Bernardes et al. model. This provides evidence for validity of the present analysis.

power.

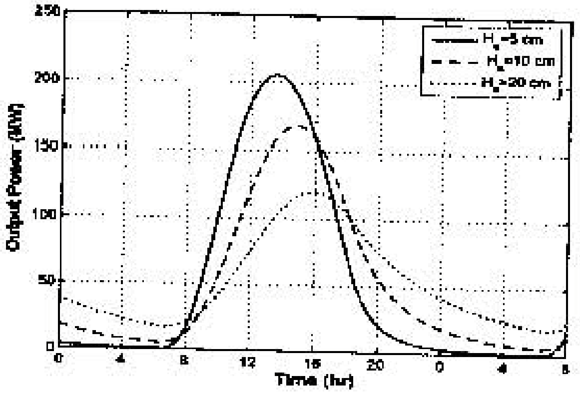

Fig.2. Effect of the water-storage layer thickness on output power.

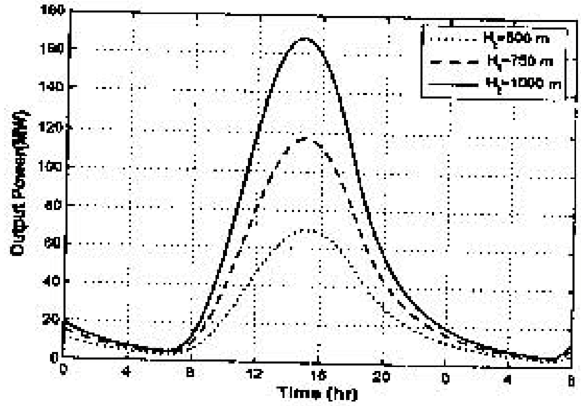

Fig.4. Effect of the tower height on output power.

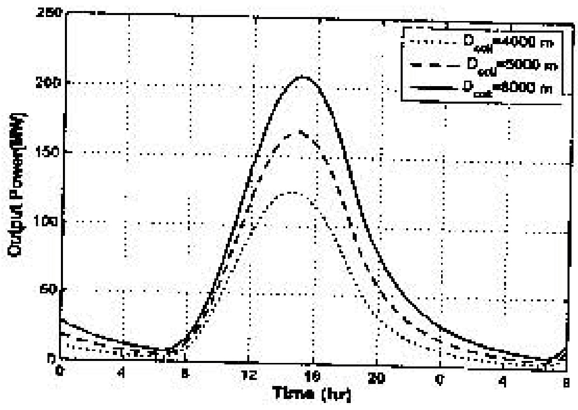

Fig. 3. Effect of the collector diameter on output

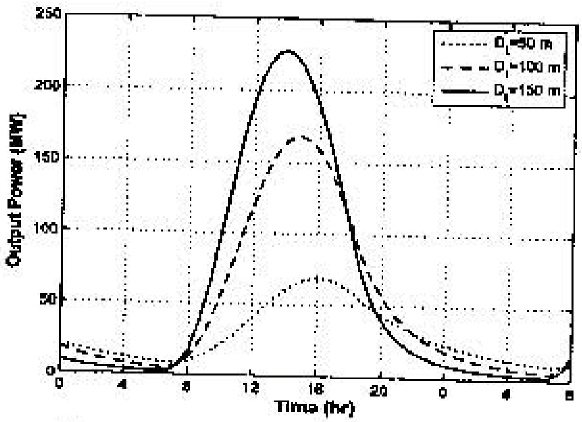

Fig.5. Effect of the tower diameter on output power.

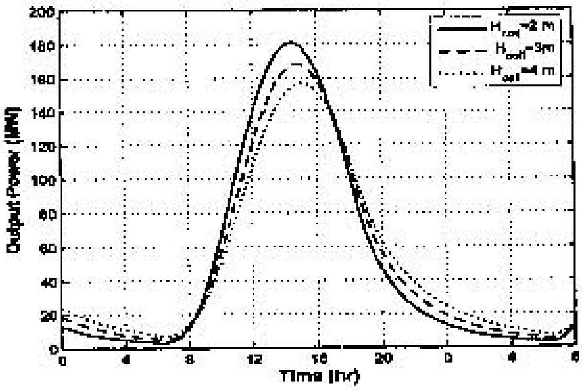

Fig.6. Effect of the collector height on output power.

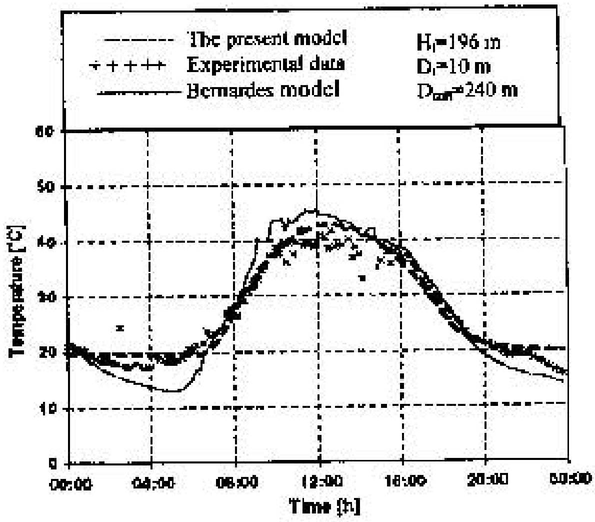

Fig.9. Comparison of the present model and experimental data presented by Bernardes model[10].

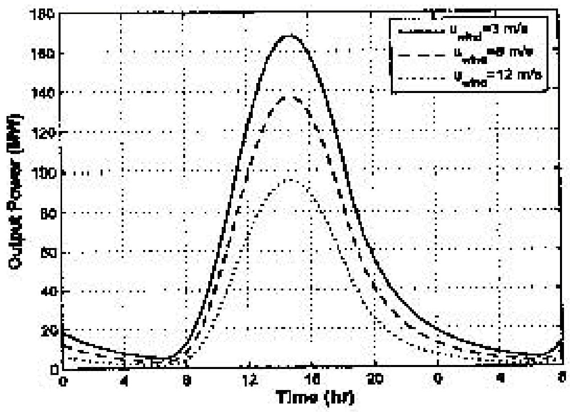

Fig.7. Effect of wind velocity on output power.

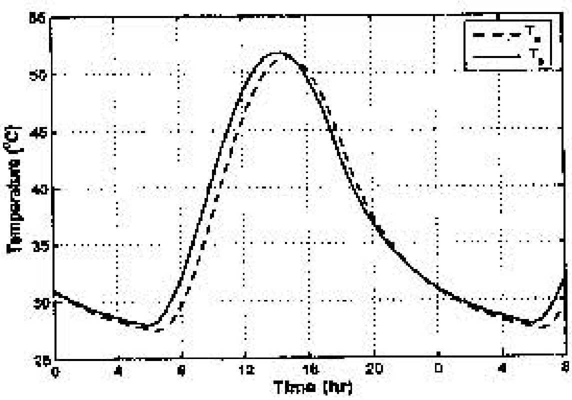

Fig.8. The water storage and air temperature profiles as a function of time.

4. Conclusions

1- Mathematical model for the solar updraft power plant with water-storage system is presented.
2- The tower and collector dimensions are of significant effect on the power production of the solar tower power plant.
3- The water storage effect on the power output with time but no significant effect on the energy output.

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