A THEORETICAL STUDY OF A THERMOSYPHON SOLAR TOWER

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ABSTRACT

Thermosyphon solar tower can be used to increase the velocity of air and consequently the specific power in locations with reasonable value of solar radiation intensity when there is no enough area beside the tower to construct a solar collector. In this case the tower itself works as a collector. In this work the possibility of generating power by using a very high tower, having rectangular cross section, open to the atmosphere at the top and bottom and heated by the sun, was studied theoretically. In this study, the effect of tower height, tower length, tower depth, solar radiation intensity and inlet air temperature on the performance of the tower was investigated.

It was found that, the temperature inside the tower increases by the increase in solar radiation intensity, inlet air temperature and tower height and decreases by the rise in tower length as well as in tower depth. The inlet air velocity to the tower and consequently specific power was found to be raised by the growth in tower height and solar radiation intensity, and it is found to be decreased by the enlargement in tower length, tower depth and temperature of air at the inlet of the tower. The inlet air velocity and the specific power for tower height of 500 m were found to be 5.2 and 141 times of their values for 50 m tower height respectively. For solar radiation intensity of 1000 W/m^2, the inlet air velocity and the specific power are expected to be 1.32 and 2.28 times of their values for 200 W/m^2 solar radiation intensity respectively.

KEYWORDS

Solar tower, Solar turbine, Thermosyphon, Solar energy, Renewable energy.

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INTRODUCTION

In the present time comprehensive attention is paid towards the use of renewable energy sources because of their advantages over the traditional energy sources [1,2,3]. Special attention is given to the use of wind energy and solar energy. It is known that, the power of wind turbine depends mainly on the wind speed at wind turbine inlet. Therefore any increase in wind speed results in a gross increase in specific power of wind turbine or in other words a gross increase in power from the same wind turbine.

Therefore the recent researches attempt to study how to increase the wind speed at the inlet of wind turbine by using different ways [4,5]. Some of them investigated the use of solar energy to increase the velocity of air flowing through tall tower connected with large collector [6,7], or through only tall tower without collector [8]. They decided that, this art of thermosyphon solar turbines needs further study.

The aim of this work is to study theoretically the parameters that affect the performance of the thermosyphon solar tower. In other words the effect of tower height, tower length, tower depth, solar radiation intensity, and inlet air temperature on the performance of solar tower as well as on the performance of wind turbine located at tower bottom was studied in this work. In this study, the effect of the above mentioned parameters on temperature difference inside and outside the tower, velocity of air at the inlet of the tower and specific power of wind turbine was investigated.

MATHEMATICAL MODEL

Figure 1 shows a sketch of the rectangular cross section tower used in this study. In the theoretical model, the following parameters are considered: tower height, length, and depth, solar radiation intensity and inlet temperature to the tower. The heat losses through the tower walls, the head losses through the tower due to friction and the variation in density and air velocity through the tower are also considered in this model.

For a fluid element of height dz flowing vertically through the solar tower at velocity v, subject to pressure force P.A at its bottom surface and (P+dP)A at its top surface, weight force $\rho_{av} gAdz$, and resistance force dF, an approximate equation of motion for flow through the tower can be driven using Newton's 2nd law as follows

$$h\left(\frac{\rho_{atm}}{\rho_{av}}-1\right)-\frac{V_2^2-V_1^2}{2g}-\frac{(\rho_{local} h_{turb}+\rho_{local} h_{l_{fric}})}{\rho_{av}}=0 \qquad (1)$$

Where h is the height of the tower, ρ_{atm} is the average atmospheric density at inlet and exit of the tower, ρ_{av} is the average air density inside the tower, g is the gravitational constant, v_1 is the velocity of air at inlet, v_2 is the velocity of air at outlet, ρ_{local} is the local air density, h_{turb} is the head corresponding to turbine power and h_{lfric} is the head losses through the tower due to friction.

The atmospheric density at any height h is calculated using the following relation [8,9]

$$\rho(h) = \rho_{sea\ level}(1 - 0.000027h) \tag{2}$$

The average density inside the tower ρ_{av} is calculated by averaging the inlet and exit densities (ρ_1 and ρ_2), assuming the pressure at inlet as atmospheric and the exiting pressure is the same as the atmospheric pressure at the exit. The exit pressure can then be determined as [8,9]

$$P(h) = P_a(1 - 0.003566h/T_a)^{5.26} \tag{3}$$

Where P is the pressure at height h, T_a and P_a are the ambient temperature and pressure respectively.

The exit temperature T_2 can be estimated from the following relation

$$T_2 = (Q_{sol} - Q_{loss})A_t/(\dot{m}C_v) + T_1 \tag{4}$$

Where Q_{sol} is the net solar radiation being received by the tower surface, Q_{loss} is the heat lost by conduction and convection through the walls, A_t is the surface area of the tower, $\dot{m}$ is the mass flow rate of air through the tower, T_1 is the inlet temperature to the tower and C_v is the constant volume specific heat of air, assumed to be 0.718 kj/kg°k.

The surface area of the tower can be calculated as follows

$$A_t = 2\ h(d_t + L_t) \tag{5}$$

Where d_t and L_t are tower depth and tower length respectively.

The heat losses through the wall Q_{loss} is determined from the following relation, [10].

$$Q_{loss}=(T_{ins}-T_{out})/R_{th} \tag{6}$$

Where T_{ins} is the mean temperature inside the tower, T_{out} is the temperature outside the tower and R_{th} is the overall thermal resistance.

$$R_{th}=\frac{1}{\alpha_{ins}}+\frac{\Delta x}{k_w}+\frac{1}{\alpha_{out}} \tag{7}$$

Where α_{out} is the heat transfer coefficient between the tower wall and outside air, assumed to be constant and is equal to 28.4 $W/m^2{}^\circ k$ [8,11], Δx is the wall thickness taken as 0.32 cm, k_w is the thermal conductivity of the wall, equal to 1.18 $W/m^\circ k$ and α_{ins} is the heat transfer coefficient between the air inside the tower and the wall. α_{ins} is determined from the following relation, [8].

$$\alpha_{ins}=Nu\ k_{air}/D_H \tag{8}$$

Where;

$$Nu=0.023\ Re^{0.8}\ Pr^{0.3} \tag{9}$$

and k_{air} is the thermal conductivity of air, assumed constant as 0.026 $W/m^\circ k$ [10], D_H is the hydraulic diameter of the tower, Nu is the Nusselt number, Re is the Reynolds number and Pr is the Prandtl number, assumed constant at 0.7 [8].

$$D_H=4L_t d_t/(2L_t+2d_t) \tag{10}$$

Where L_t is the tower length and d_t is the tower depth.

The density of air at exit ρ_2 is determined from the ideal gas law as

$$\rho_2=P_2/R_a T_2 \tag{11}$$

Where R_a is the gas constant for air.

The mass flow rate of air inside the tower is obtained from the continuity equation as

$$\dot{m}=\rho_1 A_1 V_1=\rho_2 A_2 V_2 \quad (12)$$

Where A_1 and A_2 are the cross sectional area of the tower at inlet and outlet respectively, assuming A_1 and A_2 are equal, and v_2 is the velocity of air at the top of the tower.

The frictional head losses through the tower $h_{l\,fric}$ were calculated from the relation

$$h_{l_{fric}}=f\ h\ v_t^2/2\ g\ D_H \quad (13)$$

Where v_t is the average flow velocity through the tower and f is the friction factor. The friction factor in the above equation is determined from Prandtl and von Karman's equation as follows, [12]

$$\frac{1}{f}=4\,(2\log\frac{D_H}{2y}+1.74)^2 \quad (14)$$

Where y is the height of roughness, assumed to be 0.09 mm.

The head corresponding to turbine power h_{turb} is calculated according to the following relation

$$h_{turb}=V_1^2\ \eta_{total}/2\ g\ c_q \quad (15)$$

Where c_q is the discharge coefficient through the turbine, assumed to be 0.6, and η_{total} is the total efficiency of converting kinetic energy of wind to elctric energy, can be taken in practice as 0.405 [13].

The specific power of a wind turbine is estimated as

$$sp_1=0.5\ \rho_1\ V_1^3\ \eta_{total} \quad (16)$$

The above equations (1-16) were solved simultaneously by iteration to obtain the temperature difference between inlet and exit of the tower ΔT, the velocity of air at inlet, the velocity of air at exit and the specific power that obtained from the wind turbine. A computer program was written for this purpose. The calculations were achieved mainly for a constant values of tower height 400 m, tower length 150 m, tower depth 10 m, solar intensity 600 W/m^2 and inlet temperature 293 °k, and during study the effect of the above parameters on the performance of the tower, the calculations were made for 50-500 m tower height, 25-350 m tower length, 5-100 m tower depth, 200-1000 W/m^2 solar intensity and 273-313 °k inlet temperature. While studying the effect of any parameter on the others, the remaining parameters are kept constant at the above mentioned values.

RESULTS AND DISCUSSION

Effect of Tower Height

Fig. 2 shows the effect of tower height on the temperature difference between outlet and inlet of the tower ΔT. The variation in air velocity at inlet of the tower v_1 with tower height is also shown. The effect of tower height on the specific power of wind turbine loacated at tower bottom is shown on Fig. 3. It is seen that, the increase in tower height causes an increase in temperature difference and inlet air velocity, and consequently a large increase in specific power is obtained. The inlet air velocity for tower height 500 m is 5.2 times of its value for 50 m tower height and the corresponding specific power will be 141 times greater than specific power for 50 m tower height.

Effect of Cross-Sectional Area of the Tower

The effect of cross-sectional area of the tower can be studied by changing tower length and tower depth. The effect of tower length on solar tower performance is shown on Fig. 4. There is a decrease in both inlet air velocity and temperature difference with tower length increases. It is seen also that, the variation rate of decrease for the inlet velocity and temperature difference becomes very small for the large values of tower length.

Fig. 5 represents the variation of temperature difference and inlet air velocity with tower depth. One can see that, the increase in tower depth brings a decay in both inlet air velocity and temperature difference. The tower depth has the same influence of tower length on the performance of the tower. The main reasons for the decay in ΔT and v_1 with the increase in both tower length and depth are the increase in mass flow rate of air entering the tower at the constant value of solar radiation intensity and the increase in temperature gradient between the wall and the center of the tower by the enlargement in tower length or tower depth.

Effect of Solar Radiation Intensity

Fig. 6 shows the variation of temperature difference and inlet air velocity with solar radiation intensity. The variation of specific power of wind turbine with solar radiation intensity is shown on Fig. 7. There is an enlargement in ΔT, v_1 and specific power with the growth in solar intensity. The rise in inlet air velocity by increasing solar radiation intensity is due to the growth in the temperature difference of air inside and outside the tower and the accompaining increase in density difference of air outside and inside the tower. For solar intensity of 1000 W/m^2, the inlet air velocity v_1 is 132 % of its value for 200 W/m^2 solar intensity. The corresponding increase in specific power between 200 and 1000 W/m^2 solar radiation intensity is found to be 228 %.

Effect of Inlet Temperature

Although the growth in inlet temperature results in an enlargement in temperature difference, it reduces the inlet air velocity as shown in Fig. 8. Therefore it is expected that, the solar tower will work good when the inlet temperature is low.

Comparing the effect of the different parameters together, one can see that, the tower height and solar intensity having the major effect on improving the performance of the tower. The increase in one of them alone or in them together will results in a considerable increase in inlet air velocity and of course a grosser increase in specific power.

CONCLUSIONS

In the present work, the thermosyphon solar tower, that can be used when there is no enough area near the tower to construct a solar collector and the solar tower itself works as a collector, was studied theoretically. The calculations were done for a model where tower height, tower length, tower depth, solar radiation intensity and inlet air temperature were cosidered. In this model, the heat losses through the tower walls, the head losses through the tower due to friction and the variation in density and air velocity through the tower were also considered.

It was found that, the increase in both tower height and solar radiation intensity results in an improvement in the performance of the tower. This appears in a considerable increase in both inlet air velocity to the tower and specific power of the wind turbine. The inlet air velocity and the specific power for tower height of 500 m were found to be 5.2 and 141 times of their values for 50 m tower height respectively. For solar radiation intensity of 1000 W/m^2, the inlet air velocity and the specific power are expected to be 1.32 and 2.28 times of their values for 200 W/m^2 solar radiation intensity respectively. The increase in tower length, tower depth and inlet temperature of air brings a decay in inlet air velocity and of course a decrease in specific power.

It was found also that, the temperature difference of air at the inlet and exit of the tower will be increased by the growth in tower height, solar radiation intensity and inlet temperature. A reduction in the temperature difference will be occured by the extension in tower length and tower depth.

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NOMENCLATURE

A_1 cross-sectional area of the tower at inlet
A_2 cross-sectional area of the tower at exit
A_t surface area of the tower
C_v constant volume specific heat of air
c_q discharge coefficient through the turbine
D_H hydraulic diameter of the tower
d_t tower depth
f friction factor
h height of the tower
$h_{l\,fric}$ head losses through the tower due to friction
h_{turb} head corresponding to turbine power
k_{air} thermal conductivity of air
k_w thermal conductivity of the wall
L_t tower length
$\dot{m}$ mass flow rate of air through the tower
Nu Nusselt number
P pressure
P_a ambient pressure

Pr Prandtl number
Q_{loss} heat lost by conduction and convection through the wall
Q_{sol} net solar radiation being received by the tower surface
R_a gas constant of air
Re Reynolds number
sp_1 specific power of wind turbine
T_1 inlet temperature to the tower
T_2 exit temperature
T_{ins} mean temperature inside the tower
T_{out} temperature outside the tower
v_1 velocity of air at inlet
v_2 velocity of air at exit
v_t average flow velocity through the tower
α_{ins} heat transfer coefficient between air inside the tower and the wall
α_{out} heat transfer coefficient between the tower wall and outside air
η_{total} efficiency of converting kinetic energy of wind to electric energy
ρ_2 density of air at exit
ρ_{atm} average atmospheric density at inlet and exit of the tower
ρ_{av} average air density inside the tower
ρ_{local} local air density

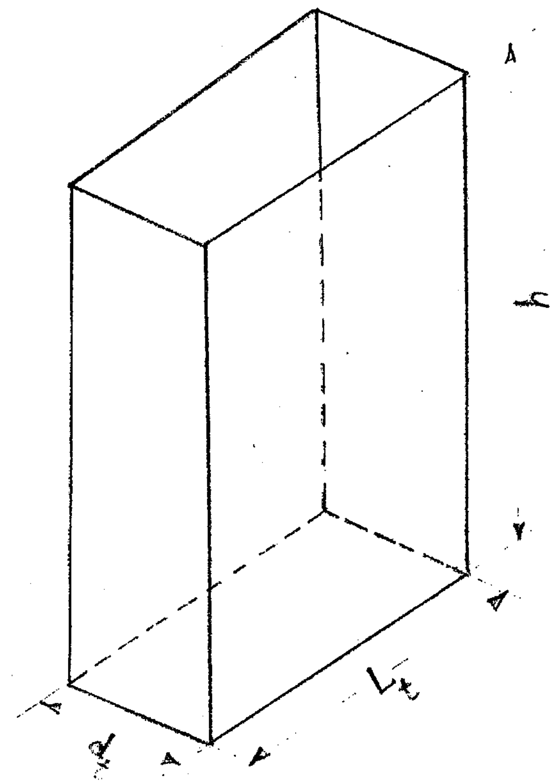

Fig. 1 Sketch of the rectangular cross section tower used in this study

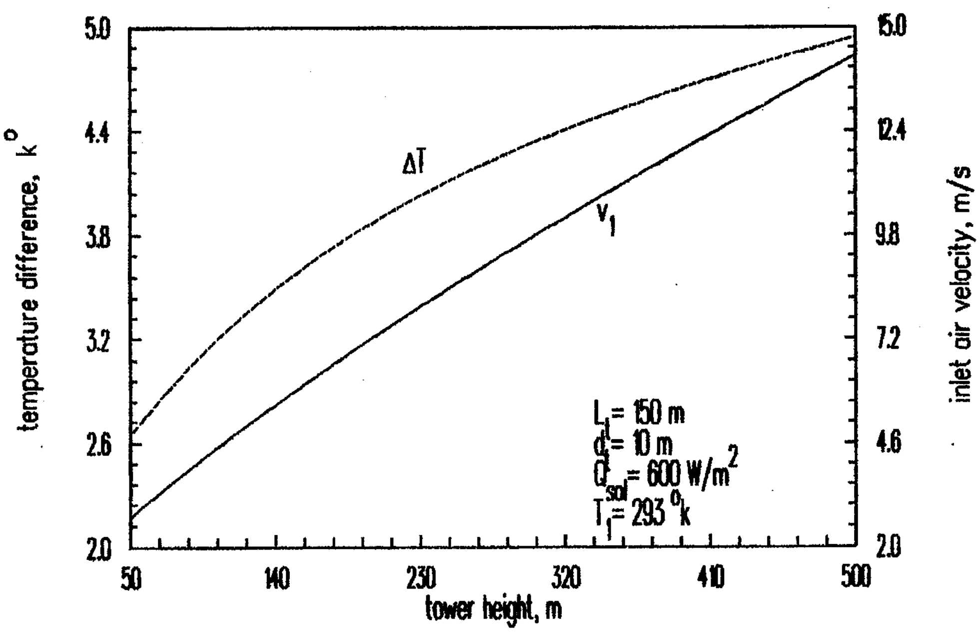

Fig. 2 Variation of temp. difference between inlet and outlet of the tower and inlet air velocity with tower height

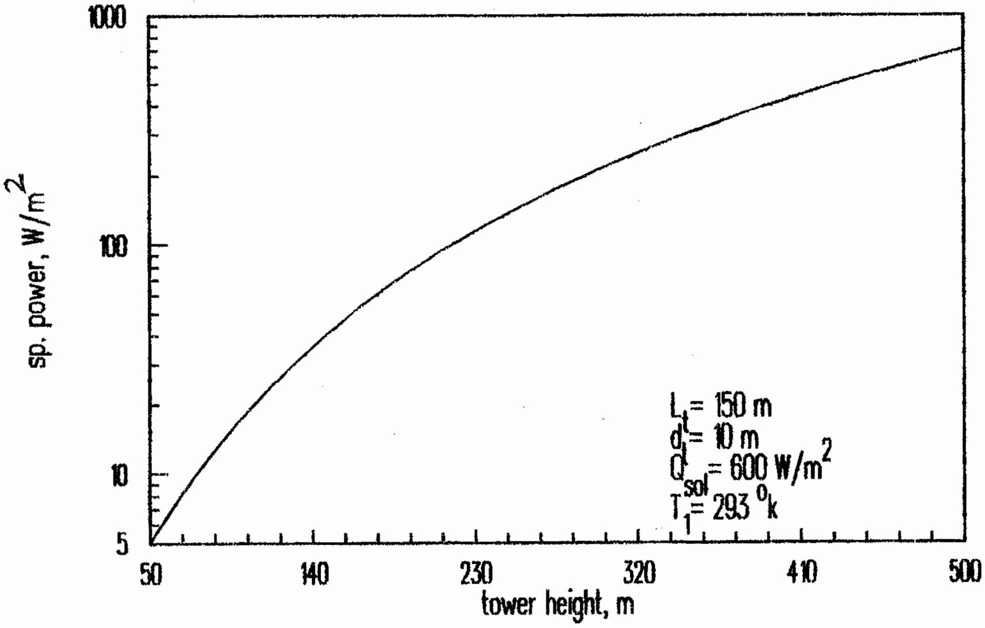

Fig. 3 The effect of tower height on the sp. power of wind turbine

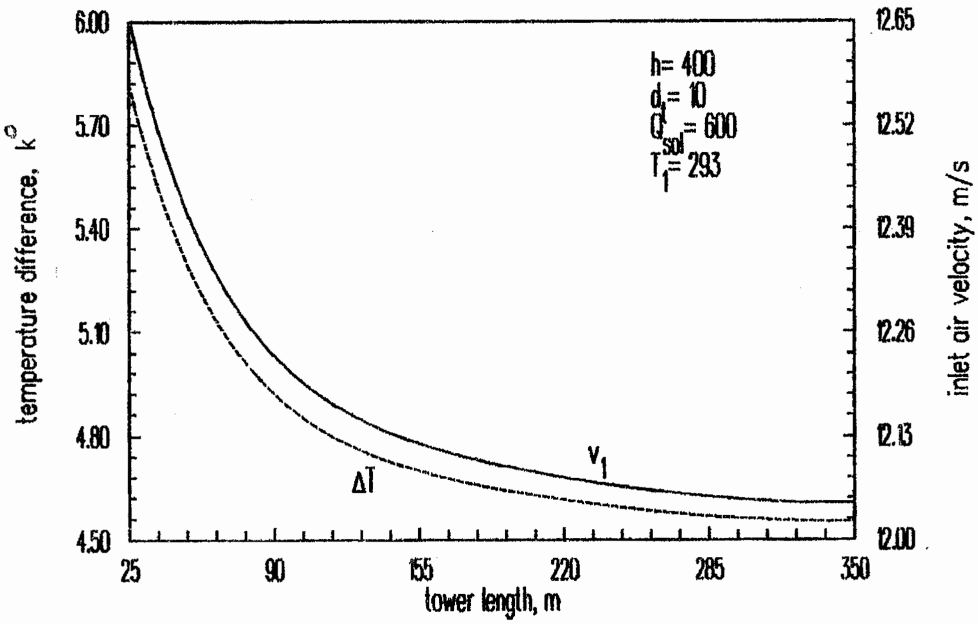

Fig. 4 Variation of temperature difference between inlet and outlet and inlet air velocity with tower length

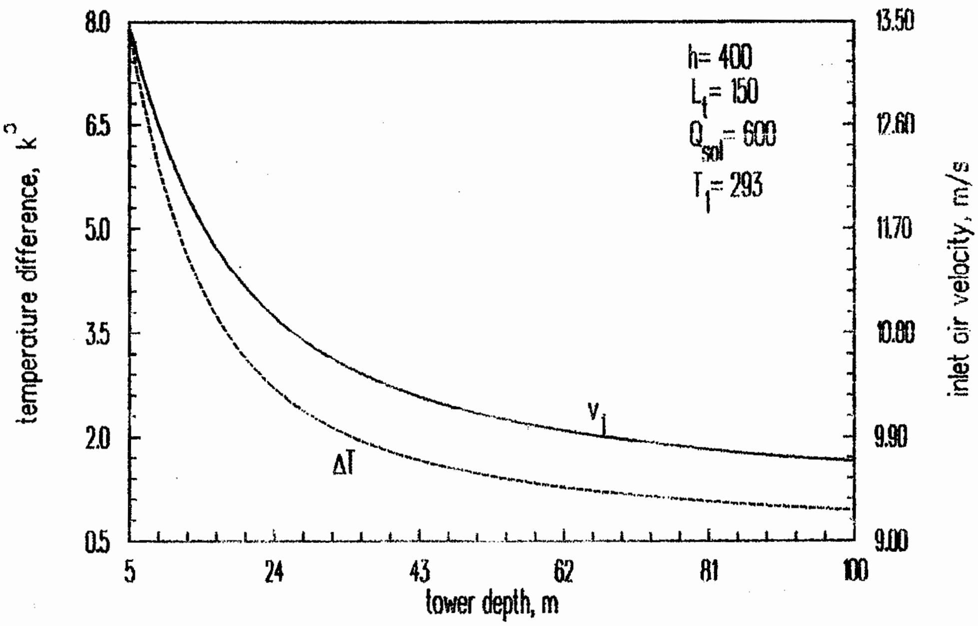

Fig. 5 Variation of temperature difference and inlet air velocity with tower depth

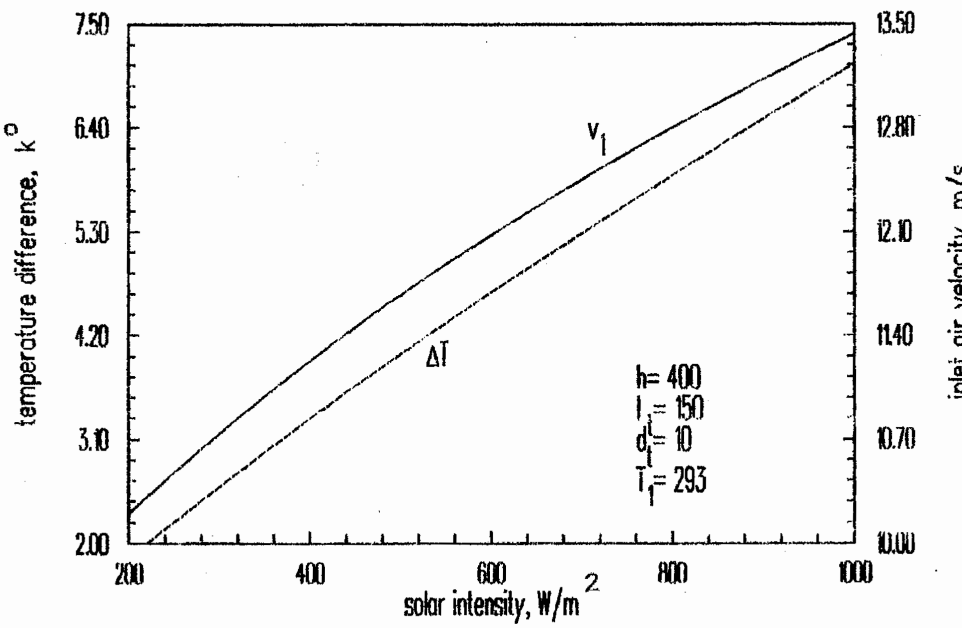

Fig. 6 Variation of temperature difference and inlet air velocity with solar intensity

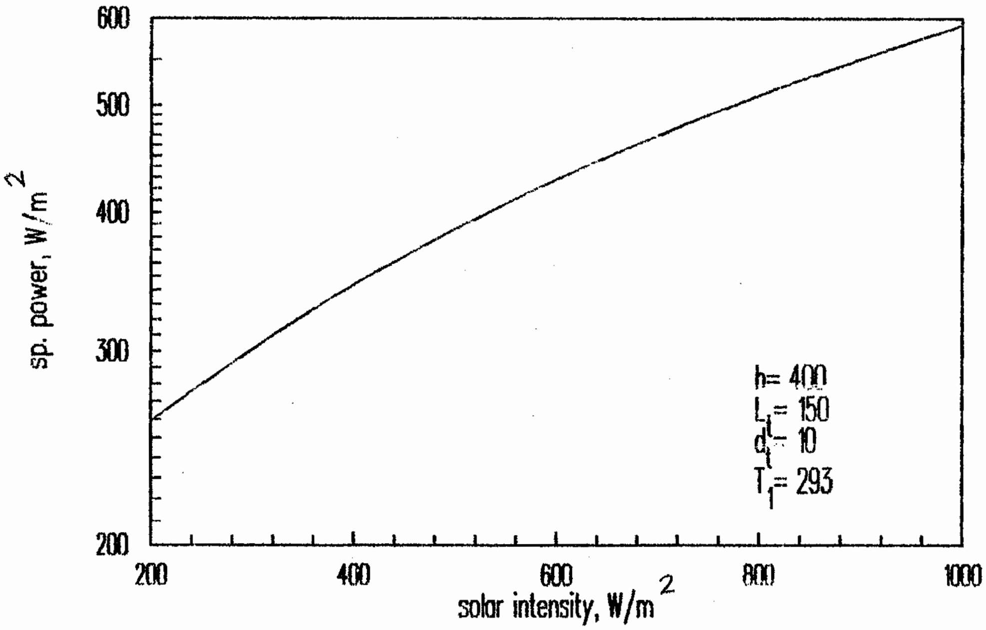

Fig. 7 The effect of solar intensity on the specific power of wind turbine

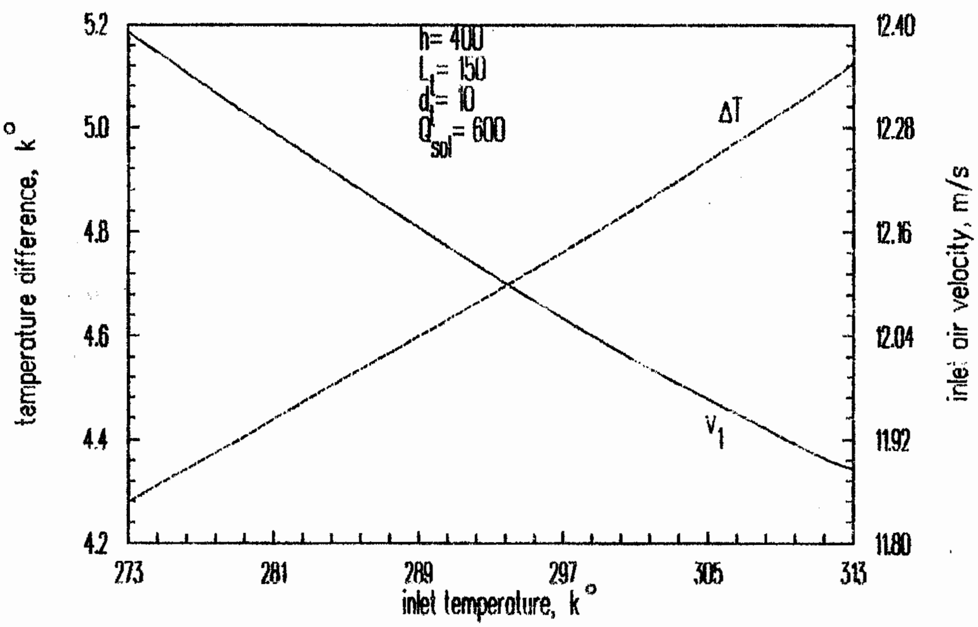

Fig. 8 Variation of temperature difference and inlet air velocity with inlet air temperature

الدراسة النظرية لآداء البرج الشمسي المستغل لظاهرة السيفون الحرارى

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ملخص البحث

يستخدم البرج الشمسي هذا بغرض زيادة سرعة الهواء الداخل إلى التربينة الهوائية وبالتالى زيادة قدرتها النوعية وذلك فى المواقع ذات القيم المعقولة من شدة الإشعاع الشمسى عندما لايكون هناك مساحة كافية بجوار البرج لإنشاء مجمع شمسي. وفى هذه الحالة يستخدم البرج نفسه كمجمع شمسي.

فى هذا العمل تمت الدراسة النظرية لإمكانية توليد طاقة بإستخدام برج عالى، مستطيل المقطع، مفتوح من أعلى ومن أسفل على الجو، ويسخن عن طريق الشمس. ولقد تم دراسة تأثير إرتفاع البرج، طول البرج، عرض البرج، شدة الإشعاع الشمسى، وكذلك درجة حرارة الهواء الداخل إلى البرج على آداء البرج.

ومن أهم نتائج هذا البحث مايلى:

وجد أن درجة الحرارة داخل البرج تزداد بزيادة شدة الإشعاع الشمسى، وبزيادة درجة حرارة الهواء عند المدخل، وكذلك بزيادة إرتفاع البرج. وتقل درجة الحرارة داخل البرج بالزيادة فى طول البرج وكذلك بالزيادة فى عرضه.

كما وجد أن سرعة الهواء عند مدخل البرج وبالتالى القدرة النوعية للتربينة تزداد بالزيادة فى إرتفاع البرج وشدة الإشعاع الشمسى، وتقل بالزيادة فى كل من طول البرج، عرض البرج، ودرجة حرارة الهواء عند المدخل. فعلى سبيل المثال وجد أن سرعة الهواء عند المدخل وكذلك القدرة النوعية للتربينة الهوائية، لبرج إرتفاعه 500 متر، تساوى 5.2 و 141 مرة على التوالى من قيمهم عندما يكون إرتفاع البرج 50 مترا. وكذلك فإنه من المتوقع أن تكون سرعة الهواء عند المدخل وكذلك القدرة النوعية للتربينة، فى حالة شدة إشعاع شمسى تساوى 1000 W/m^2، 1.32 و 2.28 مرة على التوالى من قيمهم فى حالة شدة إشعاع شمسى تساوى 200 W/m^2.