THE EFFECT OF WIND SPEED AT THE TOP OF THE TOWER ON THE PERFORMANCE AND ENERGY GENERATED FROM THERMOSYPHON SOLAR TURBINE

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ABSTRACT

Energy generated from wind turbine depends to a great extent on the wind speed at its inlet. The use of thermosyphon solar tower is an attempt to increase the air velocity at inlet of the wind turbine and of course to increase its power. The wind speed in a certain location changes always with time and with the height above ground surface. In this work, the effect of wind speed at the top of the tower on the performance as well as on the energy generated from thermosyphon solar turbine was studied theoretically. One location in Egypt was chosen for this study. The calculations were achieved mainly with the solar turbine located at tower bottom. For the purpose of comparison, the energy generated from the solar turbine was compared with that generated from free wind turbine at tower height with the absence of solar tower.

It was found that, the wind speed at the top of the tower results in a pressure drop which affects the performance of the thermosyphon solar turbine. This pressure drop increases with the rise in wind speed and will be zero only when the wind speed at the top of the tower reaches zero. It was also found that, there is an increase in friction losses through the tower and a decrease in both temperature difference between inlet and outlet of the tower and in heat losses from tower walls with the rise in wind speed. The inlet air velocity to the solar turbine and consequently its specific power were found to be increased with the increase in wind speed at the top of the tower. Therefore, the effect of wind speed at the top of the tower must be taken into account during thermosyphon solar tower calculations. By comparing the performance of solar turbine and the free wind turbine located at tower height with the absence of thermosyphon solar tower, it was found that the mean inlet air velocity to the solar turbine located at tower bottom and consequently its specific power are higher than those values for free wind turbine. The increase in mean inlet air velocity to the solar turbine is found to be 17 % of its value for a free wind turbine. The increase in yearly specific energy generated from solar turbine is expected to be 57 % of its value for free wind turbine.

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KEYWORDS

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

INTRODUCTION

In the last decade intensive attention was paid to reduce the pollution of the air resulting mainly from the use of the conventional sources of energy in the thermal power plants. A way in this direction is the use of renewable energy sources [1,2]. The major disadvantage of renewable energy sources is their low specific power compared to the conventional sources of energy. In the field of wind energy, the specific power of a wind turbine can be improved by increasing the air velocity at the inlet of wind turbine [3,4]. Therefore the recent researches attempt to study how to increase the wind speed at the inlet of wind turbine by using different ways [5]. Some of them investigate 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, which named thermosyphon solar tower [8,9].

In references [8,9], the effect of different parameters on the performance of thermosyphon solar tower was studied theoretically. In the previous works the effect of wind speed at the top of the tower was not studied and there is a need to study this effect on the performance of thermosyphon solar tower and on the energy generated from solar turbine. This is the aim of the present study.

The mathematical model used in this study is explained in the next sections, followed by the results and conclusions of this work.

LOCATION OF STUDY

One location in south Egypt, named Kharga, where the solar radiation intensity is suitable, was chosen for this study. The wind speed frequency distribution for this location, at 10 m level above ground surface, is shown in Table 1 [10].

The solar wind turbine is located at the bottom of the tower. For the purpose of comparison, the energy generated from solar turbine is compared with that generated from free wind turbine at tower height with the absence of thermosyphon solar tower.

MATHEMATICAL MODEL

A rectangular cross section tower with 150 m length, 10 m width and 300 m height is chosen for this study [8]. The solar radiation intensity and the inlet temperature of air are assumed to be 600 W/m² and 293 k° respectively. The following parameters are considered in the present study, heat losses from the tower walls, the head losses through the tower due to friction, the variation in density and air velocity through the tower and the variation of the wind speed in location. Fig. 1 shows the solar tower and the location of the solar turbine and free wind turbine.

The flow problem under consideration can be represented by the following equations:

$$h\left(\frac{\rho_{atm}}{\rho_{av}} - 1\right) - \frac{v_2^2 - v_1^2}{2g} - \frac{(\rho_{local} h_{turb} + \rho_{local} h_{l\,fric})}{\rho_{av}} = 0 \qquad (1)$$

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 vertical velocity of air at the inlet of the tower, v_2 is the vertical velocity of air at the outlet, ρ_{local} is the local air density, h_{turb} is the head corresponding to turbine power and h_{lfric} is the head loss through the tower due to friction.

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

$$h_{turb} = v_1^2\, \eta_{total} \,/\, 2\, g\, c_q \tag{2}$$

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 electric energy, can be taken in practice as 0.405 [11,12].

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

$$h_{l_{fric}} = f\, h\, v_t^2 \,/\, 2\, g\, D_H \tag{3}$$

Where v_t is the average flow velocity through the tower, D_H is the hydraulic diameter of 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 [13]

$$\frac{1}{f} = 4\left(2 \log \frac{D_H}{2y} + 1.74\right)^2 \tag{4}$$

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

The hydraulic diameter can be calculated from the following relation

$$D_H = 4\, A_c \,/\, U \tag{5}$$

Where A_c is the cross sectional area of the tower and U is the circumference.

The atmospheric density at tower height h is calculated using the following relation [8,14]

$$\rho(h) \quad \rho_{sea\ level}\,(1 - 0.000027\, h) \tag{6}$$

The horizontal wind speed at the top of the tower v_{2h} , corresponding to its value at 10 m level above ground v_o , can be calculated using the Hellmann equation [11]

$$v_{2h} = v_o \left(\frac{h + h_o}{10}\right)^a \tag{7}$$

Where h_o is the tower bottom height above ground, assumed to be 0.5 m and a is the height constant, depends on the smoothness and topography of location, and can be taken for this location as 0.2 [4,11].

To study the effect of wind speed at the top of tower, the Newton's second law of motion is applied near the top of the tower and the following equation is obtained

$$\Delta P = \rho_{av} v_{2h}^{2} \left(v_{2h}^{2} + 2 v_{2}^{2} \right) / \ 2 \left(v_{2h}^{2} + v_{2}^{2} \right) \tag{8}$$

The horizontal wind speed at the top of the tower results in a reduction in pressure *ΔP*, which increases with the rise in its value and will be zero, when the horizontal wind speed reaches zero.

The exit pressure, without the effect of wind speed at the top of the tower, can be taken as the atmospheric pressure at the exit altitude according to the following relation [8,14]

$$P(h) = P_a \left(1 - 0.003566 h / \ T_a \right)^{5.26} \tag{9}$$

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

The exit pressure with the effect of wind speed at the top of the tower P_2 can be estimated as

$$P_2 = P_a \left(1 - 0.003566 h / \ T_a \right)^{5.26} - \Delta P \tag{10}$$

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 the inlet as atmospheric.

The exit temperature T_2 can be estimated using the following relation

$$T_2 = \left(Q_{sol} - Q_{loss} \right) A_t \Big/ \left(\dot{m} C_v \right) + T_1 \tag{11}$$

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

$$A_t = h U \tag{12}$$

The heat losses through the wall Q_{loss} is calculated from the following relation [15]

$$Q_{loss} = (T_{ins} - T_{out}) / R_{th} \tag{13}$$

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.

$$R_{th} = \frac{1}{\alpha_{ins}} + \frac{\Delta x}{k_w} + \frac{1}{\alpha_{out}} \tag{14}$$

Where α_{out} is the heat transfer coefficient between the tower wall and outside air, assumed to be constant at 28.4 W/m^2 k [8,16], Δx is the wall thickness taken as 0.32 cm, k_w is the thermal conductivity of the wall and is equal to 1.18 W/m 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];

$$\alpha_{ins} \quad Nu\, k_{air} \quad D_H \tag{15}$$

$$Nu = 0.023\,Re^{0.8}\,Pr^{0.3} \tag{16}$$

where k_{air} is the thermal conductivity of air, assumed to be constant as 0.026 W/m k [16], Nu is the Nusselt number, Re is the Reynolds number and Pr is the Prandtl number, assumed constant at 0.7 [8].

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

$$\rho_2 = P_2 / R_a T_2 \tag{17}$$

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

$$\dot{m} = \rho_1 A_1 v_1 = \rho_2 A_2 v_2 \tag{18}$$

Where A_1 and A_2 are the cross sectional area of the tower at inlet and outlet respectively, assuming to be equal.

The specific power of the turbine is estimated as

$$sp = 0.5\rho_{local} v^3{}_{local}\,\eta_{total} \tag{19}$$

Where v_{local} is the local inlet air velocity to the turbine.

The yearly specific energy generated from the turbine can be estimated using the relation [17]

$$E = F_a \int_{\tau_{unl}}^{\tau_{unh}} sp\, dt \tag{20}$$

Where F_a is the availability factor of wind turbine, taken as 0.95, τ_{unl} is the unworking time due to low wind speed and τ_{unh} is the unworking time due to high wind speed. The wind turbine works only between start wind speed v_s and stop wind speed v_{st}, where $v_s = 0.3\ v_r$, $v_{st} = 2\ v_r$ and v_r is the rated wind speed. The rated wind speed depends on the mean wind speed in location. The optimum ratio between rated and mean wind speed can be estimated from [17]. The actual yearly working time for the turbine τ_w can be estimated according to the following relation.

$$\tau_w = F_a\,(8760 - \tau_{unl} - \tau_{unh}) \tag{21}$$

The above equations (1-21) were solved simultaneously by iteration to calculate the heat losses from tower walls, the friction losses through the tower, temperature difference between inlet and outlet of the tower, inlet air velocity to the turbine and specific power. The yearly specific energy generated from the turbine, the yearly unworking time due to low and very high wind speed and the yearly working time were calculated for the solar turbine and for the free wind turbine and compared together. A computer program was written for this purpose.

RESULTS AND DISCUSSION

Effect of Wind Speed at the top of the tower

Figure 2 represents the relation between wind speed and the pressure drop at the top of the tower. The wind speed at the top of the tower v_{2h} results in a pressure drop, which increases with the rise in wind speed and will be zero when the wind speed reaches zero according to equation (8). Figure 3 shows the variation in inlet air velocity to the solar turbine and its specific power with the wind speed at the top of the tower. The increase in wind speed results in an enlargement in both inlet air velocity and specific power. Figure 4 clarifies the effect of wind speed on the friction losses through the tower. There is a rise in friction losses with the increase in wind speed. This is due to the rise in the air velocity inside the tower which has the main effect on the friction losses. Figures 5,6 represent the effect of wind speed on the temperature difference between inlet and outlet of the tower and the heat losses from tower wall Q_{loss}. It is seen that, there is a decrease in both temperature difference and heat losses by the increase in wind speed. The heat losses from the tower wall depend mainly on the temperature difference inside and outside the tower. This clarifies the decrease in heat losses with the increase in wind speed.

The Comparison between the Energy Generated from Solar Turbine and free Wind Turbine

Figure 7 shows, for the two turbines, the variation of inlet air velocity to solar and free turbines with 10 m level wind speed in location. There is a growth in inlet air velocity with the increase in wind speed. Although the value of inlet air velocity to the free wind turbine v_{2h} seems to be sometimes greater than that for the solar turbine, the yearly mean inlet air velocity to solar turbine is found to be grosser, about 117 % of the corresponding value for free wind turbine and 233 % of the mean wind speed in location at 10 m level. The yearly specific energy generated from solar turbine in Kharga is found to be 157 % of its value from the free wind turbine at tower height with the absence of thermosyphone solar tower.
The yearly mean inlet air velocity to the turbine (m/s), the yearly specific energy generated (kW hr/m^2), the yearly unworking time due to low wind speed (hr), the yearly unworking time due to very high wind speed (hr) and the yearly working time (hr) are represented on Table 2 for both solar turbine and free wind turbine in Kharga.

CONCLUSIONS

In the present work, the effect of wind speed at the top of the tower on the performance of thermosyphon solar turbine as well as on the energy generated was studied theoretically. One location in Egypt, where solar radiation intensity is expected to be high, was chosen for this study.

It was found that, the wind speed at the top of the tower results in a pressure drop which affects the performance of the thermosyphon solar turbine. This pressure drop increases with the rise in wind speed and will be zero only when the wind speed reaches zero. It was found also that, the increase in wind speed at the top of the tower results in an increase in friction losses through the tower, a decrease in temperature difference between inlet and outlet of the tower and a decrease in heat losses from tower walls. The inlet air velocity to the turbine and consequently specific power were found to be increased by the rise in wind speed. Therefore, the effect of wind speed at the top of the tower must be taken into account during thermosyphon solar tower calculations. By comparing the performance of the solar turbine and the free wind turbine which is located at tower height without the use of thermosyphon solar tower, it was found that the mean inlet air velocity to the solar turbine and the yearly specific energy generated are higher than the corresponding values for the free wind turbine. These values for the solar turbine were found to be 117 % and 157 % respectively of their values for the free wind turbine.

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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
a	height constant
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_o	tower bottom height
h_{turb}	head corresponding to turbine power
k_{air}	thermal conductivity of air
k_w	thermal conductivity of the wall
L_t	tower length
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
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_o	wind speed at 10 m level above ground

v_1	velocity of air at the inlet of the tower
v_2	vertical velocity of air at the exit
v_{2h}	horizontal wind speed at the top of the tower
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 the 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
τ_y	yearly time

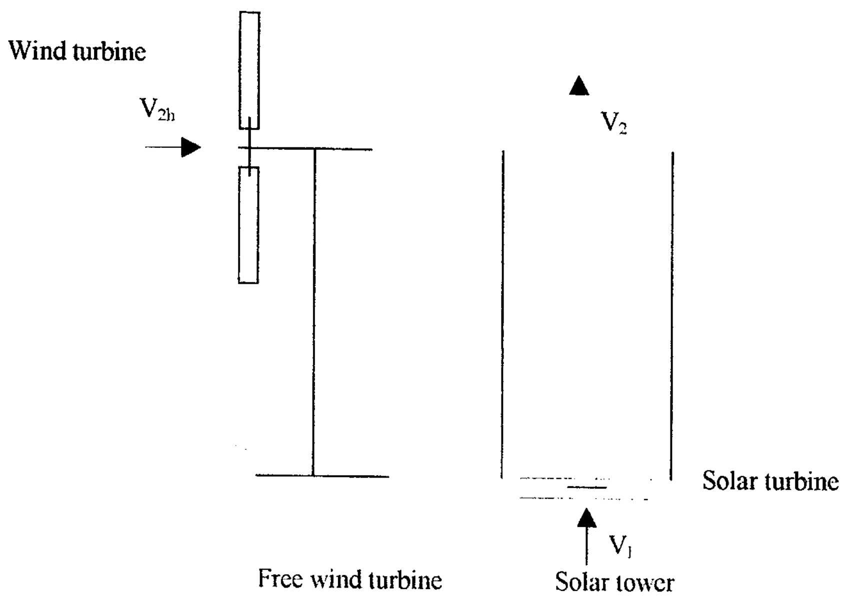

Fig. 1 The location of solar turbine and free wind turbine

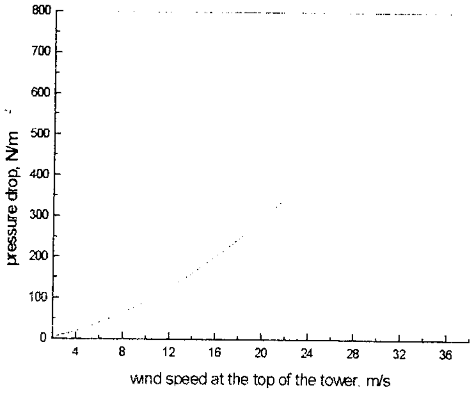

Fig. 2 Variation of pressure drop with wind speed at the top of the tower

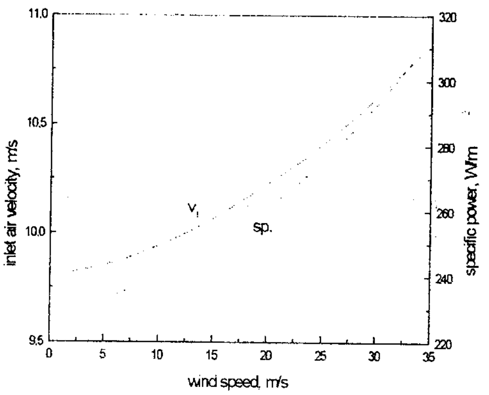

Fig. 3 Variation of inlet air velocity and specific power of solar turbine with wind speed at the top of the tower

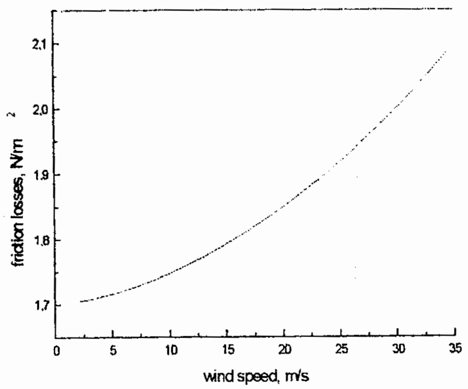

Fig. 4 Variation of friction losses through the tower with wind speed

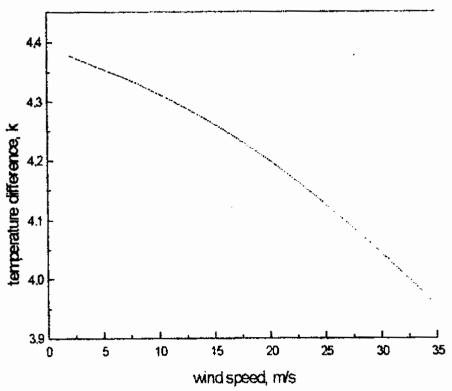

Fig. 5 Variation of temperature difference between inlet and outlet of the tower with wind speed

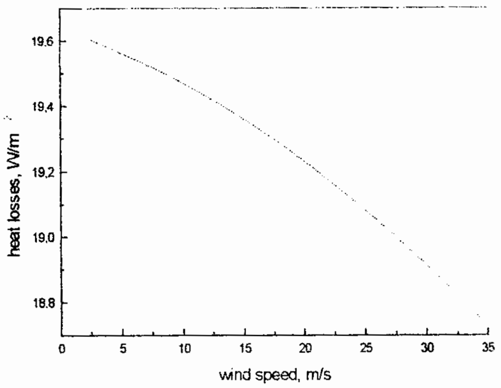

Fig. 6 Variation of heat losses from tower walls with wind speed

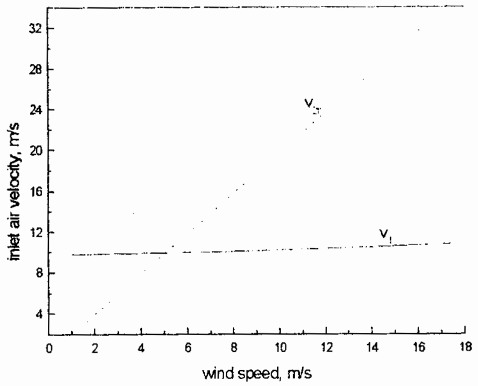

Fig. 7 Change of inlet air velocity to solar and free turbines with wind speed in location

Table 1 wind speed frequency distribution for Kharga

v_o, knot	1-3	4-6	7-10	11-16	17-21	22-27	28-33	>=34
m/s	0.51-1.54	2.1-3.1	3.6-5.1	5.7-8.2	8.7-10.8	11.3-13.9	14.4-17	>=17.5
τ_y, hr	1748.4	1841.1	2349.1	2246.9	414.6	64.2	0.73	0

Table 2 yearly mean inlet air velocity, sp. energy, unworking and working time for solar and free turbines

solar turbine					free wind turbine				
v_{1m}	energy	τ_{unl}	τ_{unh}	τ_w	v_{2hm}	energy	τ_{unl}	τ_{unh}	τ_w
9.9	1530	0	0	8322	8.5	972	1748	575	6115

تأثير سرعة الرياح عند قمة البرج على الآداء والطاقة المتولدة من التربينة التى تعمل تحت تأثير ظاهرة السيفون الحرارى

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ملخص البحث

تتأثر الطاقة المتولدة من التربينة الهوئية بدرجة كبيرة بسرعة الرياح عند مدخلها. إستخدام البرج الشمسي الذى يعمل تحت تاثير ظاهرة السيفون الحرارى هو محاولة لزيادة سرعة الرياح عند مدخل التربينة وبالتالى زيادة قدرتها. فى الأبحاث السابقة التى أجريت فى هذا المجال لم يتم دراسة تاثير سرعة الرياح والتى تتغير تغيرا كبيرا مع الزمن على آداء البرج الشمسى هذا. ولذلك فى هذا البحث تمت دراسة تأثير سرعة الرياح عند فوهة البرج العليا على آداء التربينة الشمسية الموضوعة باسقل البرج.

تم إختيار مكان فى جنوب مصر حيث شدة الإشعاع الشمسي هناك تكون مناسبة وهى منطقة الخارجة بالصحراء الغربية. وتم فى هذا العمل أيضا مقارنة الطاقة المتولدة من التربينة الشمسية الموضوعة بأسفل البرج بنظيرتها التربينة الهوائية الموضوعة على إرتفاع يساوى إرتفاع البرج الشمسى ولكنها تعمل حرة بدون إستخدام البرج الشمسى.

ومن أهم نتائج هذا البحث مايلى:

وجد أن سرعة الرياح عند قمة البرج تعمل على خفض الضغط عند القمة وتم إستنتاج معادلة لذلك توضح العلاقة بين سرعة الرياح عند القمة والنقص فى الضغط، ووجد أن النقص فى الضغط يزداد كلما زادت سرعة الرياح عند القمة ويقل كلما قلت ويساوى صفر إذا إنعدمت سرعة الرياح عند القمة. ولقد وجد أيضا أنه بزيادة سرعة الرياح فى المنطقة يزداد الفقد فى الإحتكاك خلال البرج ويقل الفقد الحرارى خلال جدرانه كما يقل الفرق بين درجتى الحرارة عند مخرج ومدخل البرج. وكذلك وجد أيضا ان زيادة سرعة الرياح تؤدى إلى زيادةسرعة الهواء عند مدخل التربينة وبالتالى زيادة قدزتها والطاقة المولدة منها.

بمقارنة الطاقة المولدة من التربينة الشمسية والتربينة الهوائية الحرة وجد أن سرعة الهواء المتوسطة خلال السنة عند مدخل التربينة الشمسية وبالتالي الطاقة المولدة منها تكون أكبر منها في حالة التربينة الهوائية الحرة بدون البرج الشمسى. فقد وجد ان السرعة المتوسطة عند مدخل التربينة الشمسية تساوى ١١٧% من قيمتها بالنسبة للتربينة الهوائية الحرة. اما الطاقة المولدة من التربينة الشمسية خلال السنة فمن المتوقع ان تساوى ١٥٧% من التربينة الهائية الحرة مما يعطى لإستخدام البرج الشمسى هذا أهمية كبيرة.