THE EFFECT OF TOWER GEOMETRY ON THE PERFORMANCE OF THERMOSYPHON SOLAR TURBINE

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ABSTRACT

The power of a 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. In this work, the effect of tower geometry on the performance of this thermosyphon solar turbine was studied theoretically. Three models with equal cross section area were studied in this work. The first one has a rectangular cross section with 150 m length and 10 m depth. The second model has a triangular cross section with equal triangle length of 58.9 m. The third model has a circular cross section having a diameter of 43.7 m. It was found for the three models that, there is an increase in temperature difference between inlet and outlet of the tower, heat losses from tower walls, friction losses through the tower, inlet air velocity to the tower and consequently specific power of wind turbine located at tower bottom with the enlargement in tower height. The values for the above parameters were found to be larger for rectangular cross section tower than their values in the other two cases. It is preferred to use rectangular cross section tower because of the gross values of inlet air velocity and specific power in this case. The values of inlet air velocity and specific power for rectangular cross section tower, for tower height 500 m, were found to be 108% and 126% respectively of their values for triangular cross section tower, and 111% and 137% respectively of their values for circular cross section tower.

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

INTRODUCTION

Energy is the main requirement for any development in each country. 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]. Special attention is given to the use of wind energy and solar energy. A major disadvantage of the most renewable energy sources is their low specific power. In the field of wind energy, the specific power of a wind turbine can be improved by the rise in the wind speed at the wind turbine location [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 [8].

There is a need to investigate the influence of tower shape on the performance of wind turbine located at tower bottom. The aim of this work is to study theoretically the effect of three favorable tower shapes on the performance of wind turbine located at tower bottom and to decide which one is suitable.

The mathematical models used in this study are explained in the next section, followed by the results and conclusions of this work.

MATHEMATICAL MODELS

Three tower forms with equal cross section area were studied in this work. The first one has a rectangular cross section with 150 m length and 10 m depth. The second model has a triangular cross section with equal triangle length of 58.9 m. The third model has a circular cross section having a diameter of 43.7 m, as shown on Figure 1. The models considered in this work take the following parameters into account: tower height, solar radiation intensity and inlet temperature to the tower. The heat losses from 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 during the calculations.

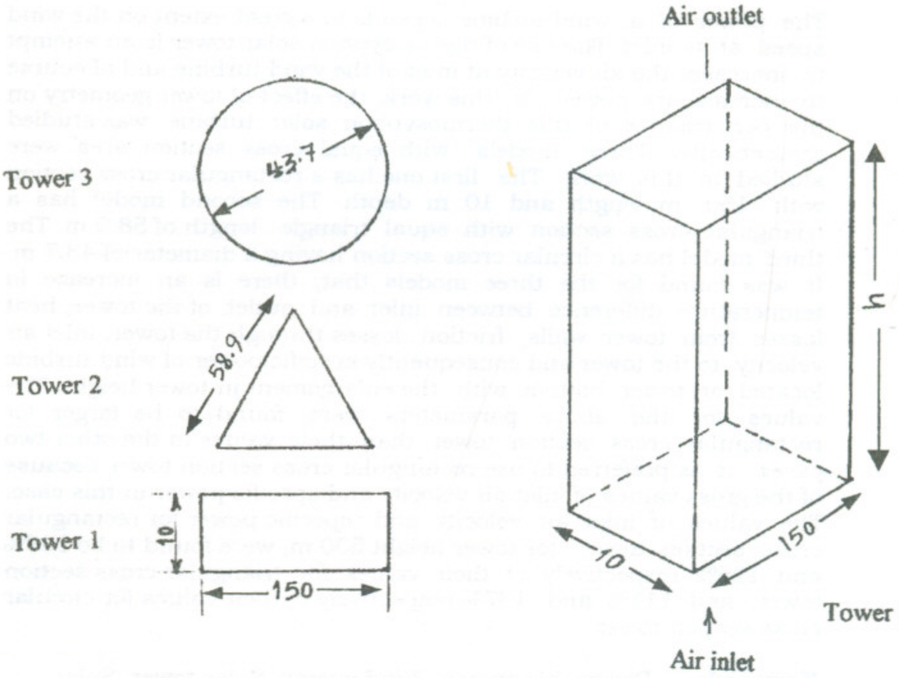

Figure 1 Dimensions of three towers used in this study

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

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

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 the inlet, v_2 is the 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 atmospheric density at any height h is calculated using the following relation [8,9]

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

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 the inlet as atmospheric and the exiting pressure is the same as the atmospheric pressure at the exit altitude. The exit pressure can then determine as [8,9]

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

Where P is the pressure at height h, T_a and P_a are the ambient temperature and pressure.
The exit temperature T_2 can be estimated using the following relation

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

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

$$A_t=hU \qquad (5)$$

Where U is the circumference. The heat losses through the wall Q_{loss} is determined by the following relation [10]

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

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.

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

Where α_{out} is the heat transfer coefficient between the tower wall and outside air, assumed to be constant at 28.4w/m^2 K° [8,11], 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/mK° 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]

$$\alpha_{ins}=Nu\,k_{air}/D_H \qquad (8)$$

Where

$$Nu=0.023\,Re^{0.8}Pr^{0.3} \qquad (9)$$

and k_{air} is the thermal conductivity of air, assumed constant as 0.026 W/mK [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].

$$D_H=4\,A_c/U \qquad (10)$$

Where A_c is the cross sectional area of the tower.
The density of air at exit ρ_2 is determined from the ideal gas law as

$$\rho_2=P_2/R_a\,T_2 \qquad (11)$$

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

$$\dot{m}=\rho_1A_1v_1=\rho_2A_2v_2 \qquad (12)$$

Where A_1 and A_2 are the cross sectional area of the tower at inlet and outlet respectively, assuming to be equal, v_2 is the velocity of air at the top of the tower.
The frictional head losses through the tower $h_{l\ fric}$ are calculated from the following relation

$$h_{l\ fric}=f\,h\,v_t^2/2g\,D_H \qquad (13)$$

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]

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

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 relation

$$h_{turb} = v_1^2 \eta_{total}/2g\, c_q \tag{15}$$

Where c_q is the discharge coefficient through the turbine, assumed to be 0.6, and h_{total} is the total efficiency of converting kinetic energy of wind to electric energy, can be taken in practice as 0.405 [13,14].

The specific power of a wind turbine is estimated as

$$sp_1=0.5\, \rho_1\, v_1^3 \eta_{total} \tag{16}$$

The above equations (1-16) were solved for the three models 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 tower and specific power of wind turbine located at tower bottom. A computer program was written for this purpose. The calculations were achieved mainly at constant values of solar intensity 600 W/m² and inlet temperature 293 K° for tower height range 50-500 m.

RESULTS AND DISCUSSION

The Effect of Tower Geometry on the Temperature Difference between Inlet and Outlet of the Tower

Figure 2 shows the variation in temperature difference between inlet and outlet of the tower ΔT with tower height, for the three models considered in this work. There is an increase in ΔT with the increase in tower height. Also, the temperature difference for tower with rectangular cross section is grosser than the temperature difference for the towers with triangular and circular cross section. This is due to the gross surface area of the tower in this case.

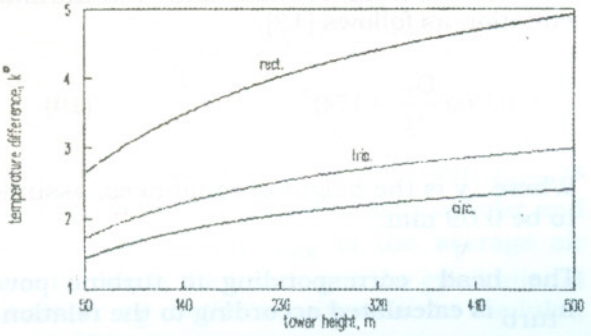

Figure 2 Effect of tower geometry on the temperature difference between inlet and outlet of the tower

The Effect of Tower Geometry on the Heat Losses from Tower Walls

Figure 3 clarifies the effect of tower height on the heat losses from tower wall Q_{loss}. There is an increase in the heat losses with the enlargement in tower height. Also the heat losses are grosser for rectangular cross section tower than the heat losses for triangular cross section tower and they are grosser for triangular cross section tower than that for circular cross section tower. The heat losses from the tower wall depend mainly on the temperature difference inside and outside the tower. This clarifies the increase in heat losses for rectangular cross section tower and with tower height increase.

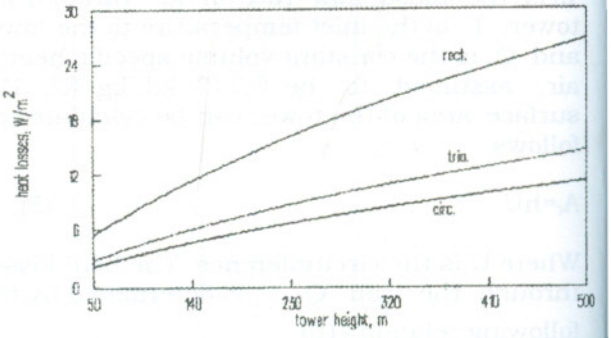

Figure 3 Effect of tower geometry on the heat losses from tower walls

The Effect of Tower Geometry on the Friction Losses through the Tower

Figure 4 represents for the three towers the effect of tower height on the pressure drop through tower due to friction ΔP_{fric}. There is a growth in friction losses with the increase in tower height. It is seen also that, the friction losses are grosser for rectangular cross section tower than the other two cases. The friction losses increase with the increase in the air velocity inside the tower and tower height, and decrease with the increase in the hydraulic diameter of the tower. In this work, the hydraulic diameters for the towers with rectangular, triangular and circular cross section were taken as 18.75 m, 33.98 m and 43.7 m respectively. This explains the increase in friction losses with tower height and why friction losses through rectangular cross section tower are gross.

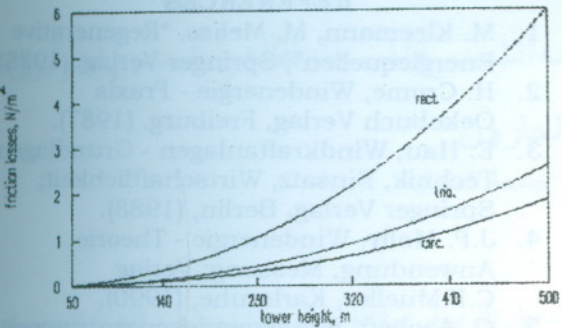

Figure 4 Effect of tower geometry on the friction losses through the tower

The Effect of Tower Geometry on the Air Velocity at the Inlet of the Tower

Figure 5 shows, for the three models, the variation of inlet air velocity to the tower with tower height. There is a growth in inlet air velocity with the increase in tower height. At the same value of tower height, the inlet air velocity for rectangular cross section tower is larger than the other two cases. For tower height 500 m, the inlet air velocity for rectangular cross section tower is 111% of its value for circular cross section tower.

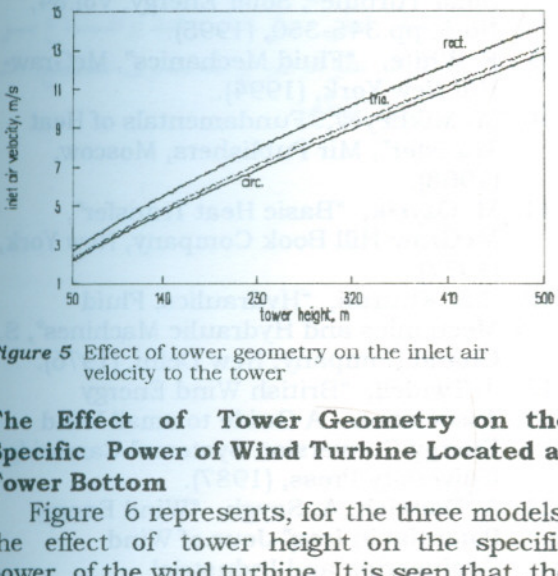

Figure 5 Effect of tower geometry on the inlet air velocity to the tower

The Effect of Tower Geometry on the Specific Power of Wind Turbine Located at Tower Bottom

Figure 6 represents, for the three models, the effect of tower height on the specific power of the wind turbine. It is seen that, the specific power increases with tower height in the three cases and the specific power for tower with rectangular cross section is greater than that in the other two cases. The enlargement in specific power with the increase in tower height is accompanied with the increase in inlet air velocity to the tower. For tower height 500 m, the specific power of the wind turbine for rectangular cross section tower is 137% of its value for circular cross section tower.

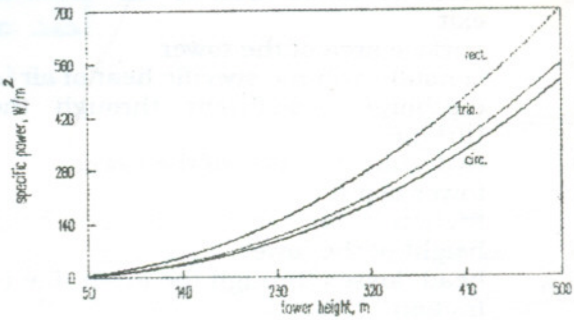

Figure 6 Effect of tower geometry on the specific power of wind turbine located at tower bottom

CONCLUSIONS

In the present work, the effect of tower geometry on the performance of thermosyphon solar tower, 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 three favorable tower shapes. The first one has a rectangular cross section with 150 m length and 10 m depth. The second model has a triangular cross section with equal triangle length of 58.9 m. The third model has a circular cross section having a diameter of 43.7 m.

It was found that, the increase in tower height results in an increase in temperature difference between inlet and outlet of the tower, heat losses from tower walls, friction losses through the tower, inlet air velocity to the tower and specific power of the wind turbine located at tower bottom. It was found also that, the above parameters having grosser values for rectangular cross section tower than their values in the other two cases. The use of rectangular cross section tower is found to be better than the triangular cross section tower and circular cross section tower because of the large values of inlet air velocity and specific power in this case. For tower height 500 m, the inlet air velocity for rectangular cross section tower is 111% of its value for circular cross section tower and the corresponding specific power of the wind turbine located at tower bottom is 137% of its value for circular cross section tower.

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
$h_{1\,fric}$	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_{sol}	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 the 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 the inlet
v_2	velocity of air athe 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 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

REFERENCES

1. M. Kleemann, M. Meliss, "Regenerative Energiequellen", Springer Verlag, (1988).
2. H. Crome, Windenergie - Praxis Oekobuch Verlag, Freiburg. (1987).
3. E. Hau, Windkraftanlagen - Grundlagen, Technik, Einsatz, Wirtschaftlichkeit; Springer Verlag, Berlin, (1988).
4. J.P. Molly, Windenergie - Theorie, Anwendung, Messung; Verlag C.F.Mueller, Karlsruhe, (1990).
5. G. Aachen, Windenergiekonzentratoren - Theoretische und experimentelle Studie zur Erhoehung der Leistungsdichte von Windturbinen in Wirbeln; BWK 35(1983)5.
6. W. Haaf, K. Friedrich, G. Mayr, J. Schlaich, "Solar Chimneys - Principle and Construction of the Pilot Plant in manzanares", Int.J.Solar Energy, pp. 3 20, Vol.2 (1983).
7. A.S. Sabry, "Modeling and Simulation of Solar Chimney", Proceeding of Fifth Int. Conference of Fluid Mechanics, Cairo, (1995).
8. S. Perez, B. Tooker, T.A. Bussi, "Theoretical Study of a Thermosyphon Solar Turbine", Solar Energy, Vol.54, No.5, pp.345-350, (1995).
9. F. White, "Fluid Mechanics", McGraw-Hill New York, (1994).
10. M. Mikheyev, "Fundamentals of Heat Transfer", Mir Publishers, Moscow, (1968).
11. M. Ozysik, "Basic Heat Transfer", McGraw-Hill Book Company, New York, (1977).
12. R.S. Khurmi, "Hydraulics, Fluid Mechanics and Hydraulic Machines", S. Chand Company, New Delhi, (1976).
13. J. Twidell, "British Wind Energy Association - A Guide to small Wind Energy Conversion Systems" Cambridge University Press, (1987).
14. A. Darwish, A. Saygh, "Wind Energy Potential in Iraq" Jour.of Wind Engineering and Industrial Aerodynamics, pp 179-189, 27(1988).

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تأثير الشكل الهندسى للبرج الشمسى على آداء التربينه الشمسية المستغله لظاهرة السيفون الحرارى

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ملخص البحث

تعتمد قدرة التربينة الهوائية بدرجة كبيرة على سرعة الرياح عند مدخل التربينة. إستخدام البرج الشمسى وظاهرة السيفون الحرارى هو محاولة لزيادة سرعة الرياح عند مدخل التربينة الهوائية وبالتالى زيادة قدراها. فى هذا البحث يتم دراسة تأثير الشكل الهندسى لهذا البرج الشمسى على آداء التربينه أسفله لمعرفة أى الأشكال أفضل . تم إختيار ثلاث أشكال هندسيه للبرج من أكثر الأشكال شيوعا للدراسه فى هذا البحث. وقد روعى فى إختبار أبعادها أن تكون مساحة مقطعها متساوية. البرج الأول من هذه الأبراج هو البرج ذو مساحة المقطع المستطيلة، وطول قاعدته ١٥٠مترا وعرضها ١٠ متر. أما البرج الثانى فقاعدته على شكل مثلث متساوى الأضلاع، وطول صلع قاعدته٥٨,٩ مترا. والبرج الثالث ذو مساحة مقطع دائريه وقطر القاعده ٤٣,٧ مترا.

ومن أهم نتائج هذا البحث ما يلى:

وجد أن الزيادة فى إرتفاع البرج للأشكال الثلاثة المختارة تتسبب فى إرتفاع فرق درجات الحرارة بين مخرج ومدخل البرج، إرتفاع كمية الحرارة المفقودة بالحمل والتوصيل عن طريق جدران البرج، إرتفاع الفقد نتيجة لإحتكاك الهواء مع جدران البرج، زيادة سرعة الهواء عند مدخل البرج وكذلك زيادة القدرة النوعية للتربية الهوائية الموضوعة أسفل البرج. كما وجد أن الزيادة فى هذه البارامترات تكون كبيرة فى حالة البرج ذو مساحة المقطع المستطيلة عنها فى حالة البرج ذو مساحة المقطع المثلث وفى حالة المقطع المثلث عنها فى حالة المقطع الدائرى. ولذلك فإنه يفضل إستخدام الأبراج مستطيلة المقطع عن المثلثة والدائرية المقطع نظرا لزيادة سرعة الهواء عند مدخل البرج وبالتالى زيادة القدرة النوعية للتربية فى هذه الحالة . فعلى سبيل المثال وعند إرتفاع برج يساوى ٥٠٠متر وجد أن سرعة الرياح عند مدخل البرج المستطيل تساوى ١١١% من نظيرها للبرج الدائرى المقطع. أما القدرة النوعية للتربينة فى حالة البرج المستطيل فهى ١٣٧ % من قيمتها للبرج الدائرى المقطع.