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STUDY AND MATHEMATICAL MODELING OF THE PERFORMANCE INDICATORS OF SOLAR TOWER POWER PLANT

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Abstract: The solartower power plant as one of the major environment-friendly power source alternates of the classic fossil fuel based systems was studied in order to determine the best structural and physical design and operation values of its parameters via the build of a mathematical model plant. Ambient variables of about eight months in Baghdad city, Iraq was induced as an input for the operation of the mathematical model and resulted that the collector's diameter was the main factor for the goal of increasing the gained power. Also, both practical and mathematical results showed that the output power is highly dependent on the height of the tower, while the tower's diameter has the least influence on the output power of the solar tower system when compared with the studied parameters of the system.

Key words: Baghdad, Solar tower, Mathematical model, performance

1. INTRODUCTION

The huge expansion in energy demand for various aspects, the negative financial implications of this demand on other needs of human beings, and the recorded devastating adverse environmental impacts due to the use of traditional fossil fuel resources, were the ignition sparks for investigating naturally available clean power sources such as the solar power and keep researching the possible modifications for this kind of utilities. Many researchers were encouraged to tackle this topic in order to explore proper resources for sustainable energy that may fundamentally fulfill future energy needs. However, the yellow sun was always considered as an inspiring principle source of everlasting renewable energy [1]. Hence, the solar chimney is one of the important methods for implying the idea, which acts as a hydroelectric energy plant, but it uses hot air in place of water, and this makes it beneficial for the arid area [2]. The solar chimney idea as a clean production technology for renewable solar energy that may absorb the diffuse radiation during times of overcast weather was published in 1903, by IsidoroCabanyes, as a suggestion for the solar chimney.A 50 kW prototypes was built in Manzanares, 150 km south of Madrid, Spain. It was planned to be used for a period of three years. The prototype produced electricity for seven years, thus proving the efficiency and the reliability of this new kind of solar power generating system. Lofty solar updraft towers could produce 100 or 200MW each and power production cost may go down below 0.07 €/kWh. One of the main pros of this kind of renewable energy production system is the remarkable low maintenance cost which so crucial for sunny areas where water is scarce as they do not require cooling towers [3]. Less expensive and large scale solar power production systems have become an interesting target for recent studies, in order to enhance their performance and productivity, rather than only focusing on the fluid flow and heat conservation [4]. However, the temperature dissemination length ways the collector radius and the air mass deviation with temperature change and its impact on the power generation has rarely reported.

The main goal for the current study is to use the mathematical analysis in order to model the variations of the temperature inside the collector and describe the temperature change domination on the hot air mass flow rate for a solar tower`s basic design. A comparison shall be made for the tentative model with the prototype of the Spanish utility Union in Manzanares.

2. MATHEMATICAL ANALYSIS

The covering formula, equation (1), for the stream of air alongside the circularly shaped collector may better be explained upon the energy balance that is illustrated by Figures 1 and 2:

$$-h_{cf}\cdot T_f - h_{rcg}\cdot T_g + k_1\cdot T_c = S_1 + h_w T_a + h_{rs} T_s \quad (1)$$

Where: S_1represents the absorbed heat flux by the collector cap (W/m^2), T_a,T_c, T_s, T_g and T_f stand for the surrounding; collector cap; sky; ground soil and airflow temperatures(^{o}C), h_w,h_{cf} ,h_{rs},h_{rcg} stand for the coefficient of wind heat transfer; convection heat transfer coefficient (collector – Air flow side); coefficient of sky radiation heat transfer; and coefficient of radiation heat transfer between two parallel plates (W/m^2 ^{o}C). k is a constant and the collector`s airflow energy balance equation (2), is:

$$\left(\frac{d}{dr}+(2\pi r)(k_2+k_3)\right)T_f-(2\pi r)k_3T_g-(2\pi r)k_2T_c=0 \quad (2)$$

Where: $k_2=\frac{h_{cf}}{mC_p}$, $k_3=\frac{h_{gf}}{mC_p}$

In which, h_{gf} stands for the convection heat transfer coefficient (ground – Air flow side) in (W/m^2.^{o}C), m stands for the air flow rate (kg/s) and C_p stands for the air flowrate specific heat (W.s/kg.^{o}C).

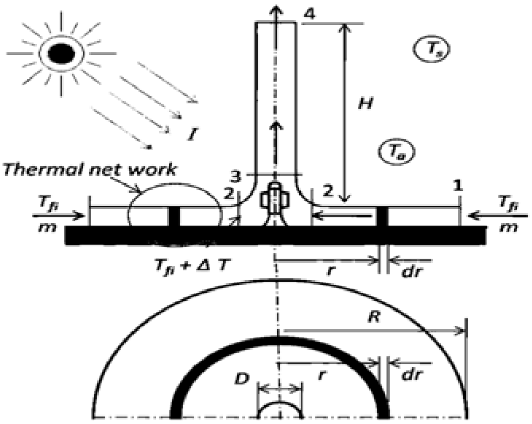


Fig. 1. Simplified schematic of the solar tower

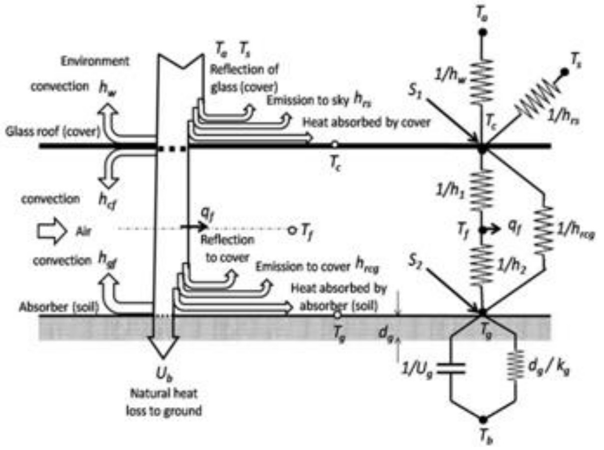


Fig. 2. Schematic of the solar tower collector`s thermal distribution

With the assumption that the convective heat exchange constant between the cap and the air flow, and between the air flow and the ground is the same, the following equation (3) may be used in order to calculate it [5]:

$$h_{cf}=h_{gf}=\frac{k_f}{d_h}Nu \quad (3)$$

Where k_f stands for the thermal conductivity (W/m.^{o}C), d_h represents the collector's hydraulic diameter (m) and Nu is Nusselt number.

Hence, the energys balance equation (4) of the collector`sground soil is:

$$-h_{gf}T_f+k_5T_g-h_{rcg}T_c=S_2+U_bT_a \quad (4)$$

$$k_5=h_{gf}+h_{rcg}+U_b \quad (5)$$

Where S_2 stands for the absorbed heat flux by the groundsoil (W/m^2).

The coefficient of total ground heat loss U_b is determined as follows [6], equation (6):

$$U_b=\frac{1}{\frac{d_g}{k_g}+\frac{1}{U_g}} \quad (6)$$

While the ground heat transfer coefficient U_g is calculated as follows, equation (7):

$$U_g=2\sqrt{\frac{k_g\rho_gC_{pg}}{\pi t}} \quad (7)$$

Where d_g stands for the depth of damp and k_g represents the ground bed thermal conductivity.

The solution of equations (1), (2) and (3) via the use of equations (4), (5), (6) and (7) for the air flow temperature T_f yields the following :

$$\frac{dT_f}{dr}=(2\pi r)k_6\left(k_{10}I-T_f+k_{11}T_a+k_{12}T_s\right) \quad (8)$$

Where:

$$k_6=\frac{k_1(k_4k_5-h_{gf}k_3)-h_{rcg}(h_{gf}k_2+h_{rcg}k_4+h_{cf}k_3)-h_{cf}k_2k_5}{k_1k_5+h_{rcg}^2} \quad (9)$$

$$k_7=\frac{(h_{rcg}k_2+k_2k_5)\alpha_1+(h_{rcg}k_2+k_1k_3)\tau_1\alpha_2}{k_1k_5+h_{rcg}^2} \quad (10)$$

$$k_8=\frac{k_2(h_{rcg}U_b+h_wk_5)+k_3(h_wh_{rcg}+U_bk_1)}{k_1k_5+h_{rcg}^2} \quad (11)$$

$$k_9=\frac{h_{rcg}(h_{rcg}k_3+k_2k_5)}{k_1k_5+h_{rcg}^2} \quad (12)$$

With the assumption that:

$$\theta=k_{10}I-T_f+k_{11}T_a+k_{12}T_s \quad (13)$$

Thus, equation (8), becomes:

$$\frac{d\theta}{dr}+(2\pi r)k_6\theta=0 \quad (14)$$

Hence, the final solution for that equation would yield:

$$T_f = T_{fi} e^{-k_6\pi\left(R^2-r^2\right)} + \left(1 - e^{-k_6\pi\left(R^2-r^2\right)}\right)\left(\left(k_7/k_6\right)I + \left(k_8/k_6\right)T_a + \left(k_9/k_6\right)T_S\right) \tag{15}$$

where r and R stand for the collector radius and the maximum collector radius (m).

The chimney is the next important part of the solar tower that needs to be analyzed, and according to Zhou, Yang, Xiaco and Shi [7], the chimney`s velocity and the air mass flowrate of the hot air can be determined as follows:

$$V_2 = \frac{1}{3}\sqrt{\frac{2\Delta P_{tot}}{\rho_2}} = \frac{1}{3}\sqrt{\frac{0.00353 gH\left(2\Delta T_{12} + H\left(\gamma_a - \gamma\right)\right)}{\rho_2}} \tag{16}$$

Where ΔP_{tot} represents the total difference in pressure between the base of chimney and the surrounding (Pa), H stands for the tower`s height (m) and γ, γ_a represent the temperature lapse of air flow in the adiabatic chimney and of ambient air respectively (^{o}C/m).

The power output $P$is determined as [3]:

$$P = \frac{1}{2}\rho_2 \cdot A_{chimney} V_2 V_{\max}^2 \tag{17}$$

Where $A_{chimney}$ stands for the chimney's cross-sectional area (m^2) and V_{max} represents the maximum air velocity inside the chimney (m/s).

3. DATA ACQUISITION

The output temperature from the chimney depends on various factors such as the ambient variables, in addition to the solar chimney`s configurations that are characterized by the solar chimney dimensions. The direct and indirect solar radiations are determined for Baghdad city according to the mathematical model that was suggested by Stine & Gayer for horizontal surfaces [8], for an eight months period that covers the major climatic changes during winter and summer seasons. The output of these calculations is tabulated in Table 1.

Table 1. The Total incident solar flux on horizontal surfaces and the ambient temperature for Baghdad city

Local Time (hour)															
	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19
Total incident solar flux on the horizontal south facing the wall (W/m^2)															
Jan.	0	0	0	113	272	410	502	534	504	415	277	118	0	0	0
Aug.	0	96	285	496	687	837	935	970	942	852	708	522	312	120	0
Ambient Temperature (°C)															
Jan.	6	6	5	6	9	10	14	16	17	20	20	19	17	16	14
Aug.	30	30	31	33	36	38	41	43	45	46	46	45	45	43	41

4. RESULTS AND DISCUSSION

Starting from equation (16), which obviously shows that the chimney`s velocity is highly related to the temperature difference between the inlet and outlet sides of its collector, henceforwardthe air mass flow ratemay well be calculated in accordance to equation (15). The change of the solar tower system`s air mass flow rate as a result of the temperature rise inside the tower`s chimney is illustrated in Figure 3. Furthermore, the system`s output power might be determined via the application of equation (17).

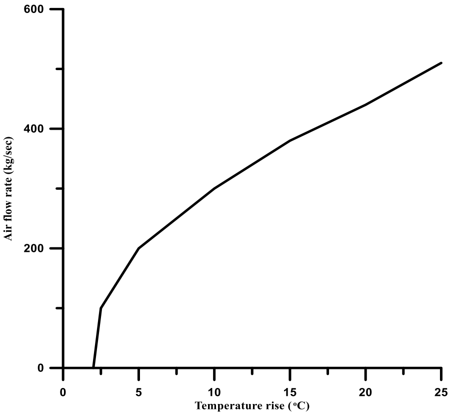
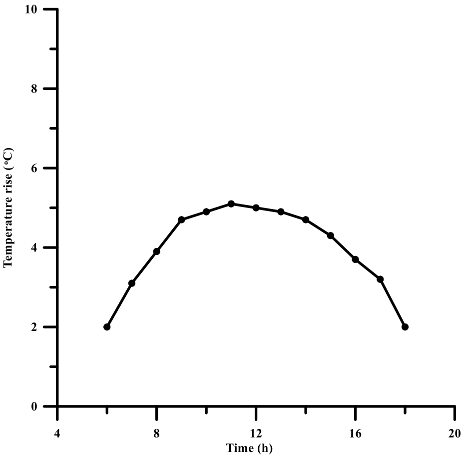


Fig. 3. The deviation of air mass flow rate vs. temperature rise inside the collector

The sunshine time temperature rise and the chimney`s velocity for Aug. and Jan. are presented in Figures 4 and 5 respectively, from which it appears that the temperature rise is proportionally related to the chimney`s configuration, ambient temperature and solar radiation intensity. Consequentially, these will affect the velocity inside the chimney, in accordance with equation (16). The velocity reaches higher values during Aug. tests when temperatures rise is higher as compared to that during Jan.



(a)

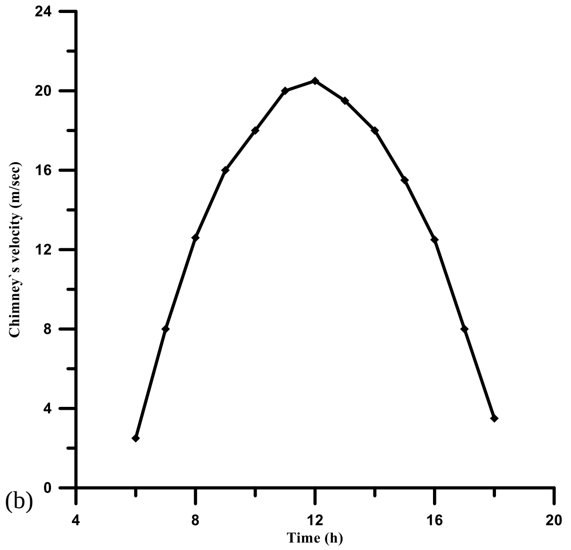


Fig. 4. The variation of the temperature rise in solar collector: (a) and the chimney`s velocity (b) with the time during Aug

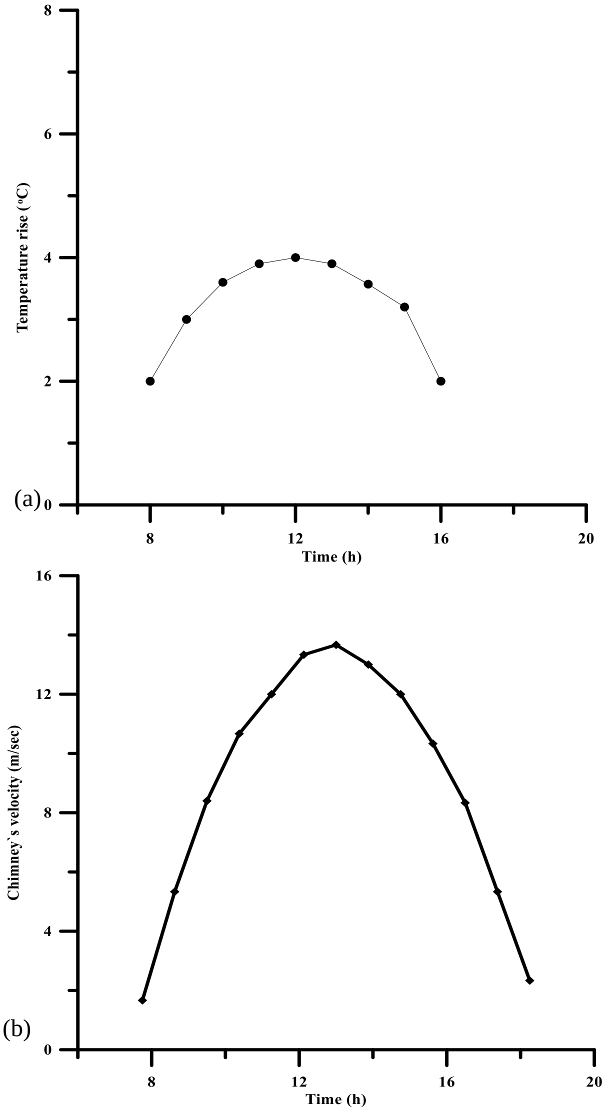


Fig. 5. The variation of the temperature rise in solar collector: (a) and the chimney`s velocity (b) with the time during Jan

Following the absorption of solar heat by the ground soil, its temperature will increase and hence initiates the re-emittance of that heat towards the air flow rate. This is illustrated by Figure 6 that demonstrates the temperature variation of the collector`s outlet and the surrounding during the sunshine time of Aug., as based on equation (15).

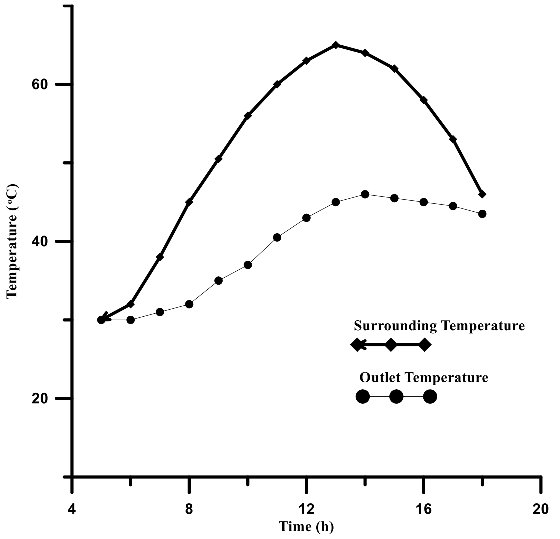
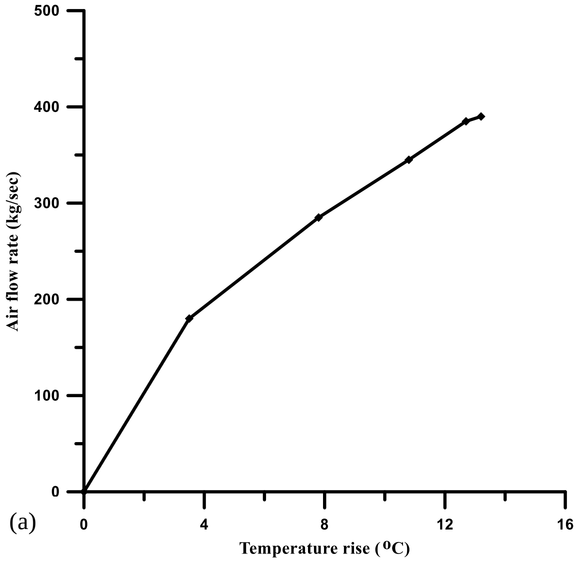


Fig. 6. The collector outlet and surrounding temperature variation during Aug

In order to have a good comparison base for the overall performance of the solar tower, the prototype Manzanares is examined for the air mass flowrate and power outlet variations versus similar temperature rise that are mentioned previously. The results of these comparisons are presented in Figure 7 during the clear sky sunshine circumferences on Jan. (summer time).The Manzanares system results show, mostly, similar results to the previous ones regarding the air mass flow rate and the output power, in a sound compatibility of the used mathematical model for such kind of systems, which quarantees their use for further studies.



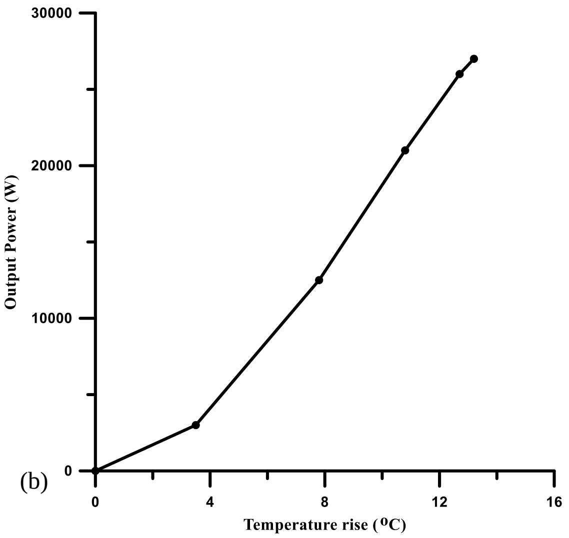
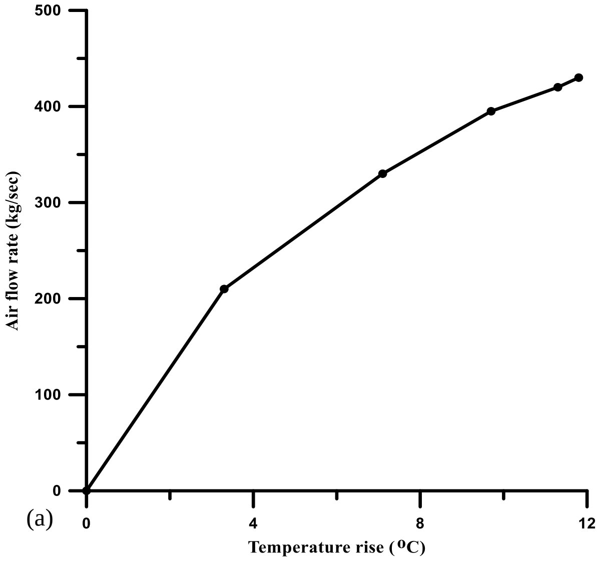


Fig. 7. The solar tower performance during Jan. for Manzanares prototype; (a) Air flow rate vs. Temperature rise. (b) Output power vs. Temperature rise

A better understanding for the possible impacts of the configuration of solar tower system on its performance, would be gained via the one by one change of the main dimensions while keeping other parameters, and test the output power in accordance. Figure 8 shows the performance indices of the solar tower system as a result of changing its chimney`s height to 300m instead of 195m. The air flow rate is clearly increased higher than 430kg/s while its power output exceeded the 42500W, while the temperature rise for these increasesis lowered to about 11.8°C, as compared to the values of Manzanares prototype of 390kg/s, 27000W and 13.2°C respectively. This would frame the conclusion that the dominant impact on chimney velocity is related to the chimney height in order to compensate forthe effectof the temperature rise. The output power gain with this change represents about 157% of the original power.



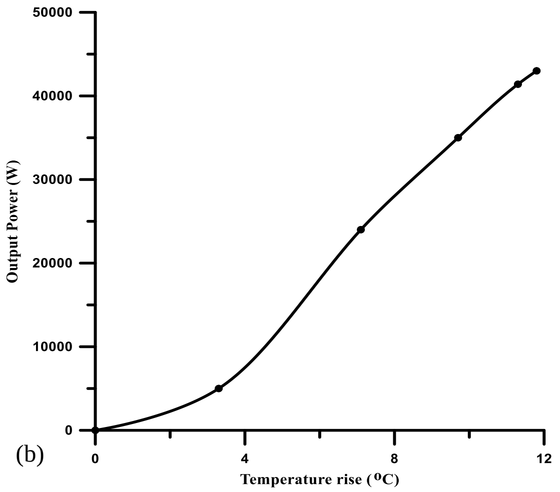
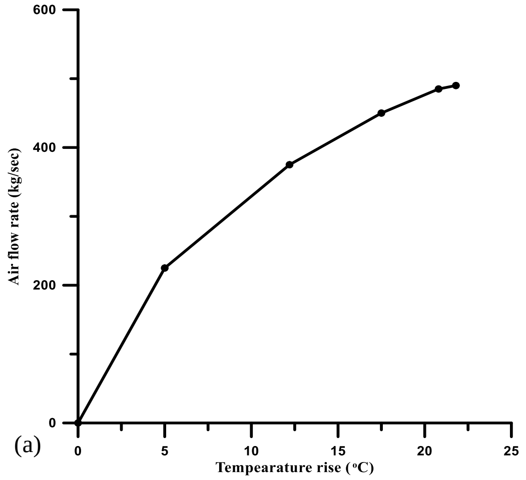


Fig. 8. The performance of solar tower during Jan., H= 300m; (a) Air flow rate vs. Temperature rise. (b) Output power vs. Temperature rise

The second parameter to be considred for a better understanding of the solar tower system is the radius of the system`s collector in order to determine the possible effects on the system`s performance. The increase of that radius from its initial value of 122m to the new 150m has yielded a considerable outcome on the performance indices as shown in Figure 9. An increase in the collector outlet temperature is noticeable in accordance with equation (15), which indicates that the temperature of the collector outlet is directly related to the solar intensity and to the collector's radius as well, hence temperature rise would increase as a result of any increase in the collector outlet temperature, and consequently, then the chimney velocity would increase according to equation (16), which results, in turn, a rise in the rate of air mass flow rate. A Comparison between the results in Figures 7 and 8, demonstrates the increase of maximum air mass flowrate, temperature rise and power output to the values of 490kg/s, 21.8°C and 60000W respectively, instead of the previous values of 390kg/s, 13.2°C and 27000W respectively. That remarkable increase represents the gain of more than the double of the initial output power; about 222%.



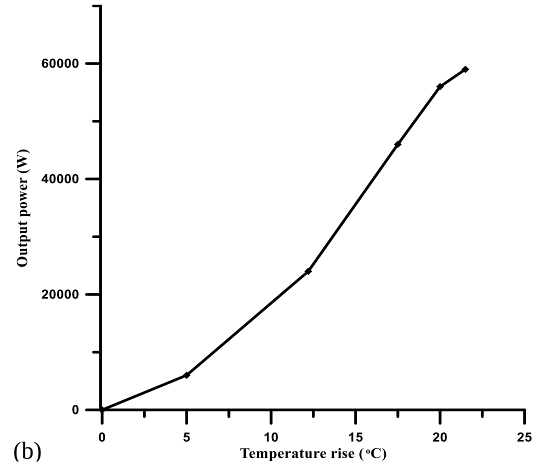
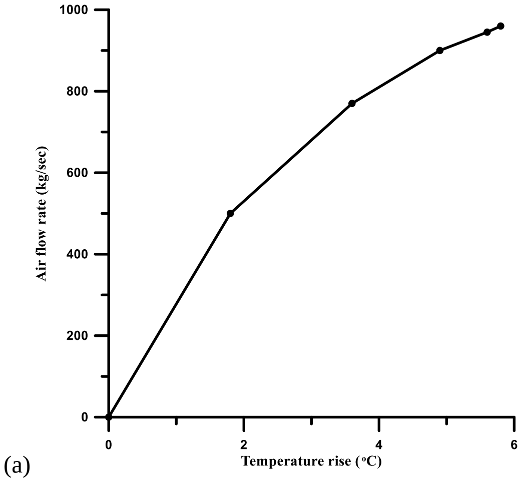


Fig. 9. The performance of solar tower during Jan., r=150m. (a)Air flow rate vs. Temperature rise. (b) Output power vs. Temperature rise

The third solar tower system configuration parameter that needs to be studied, for the possible influences on the performance indices, is the diameter of its chimney. Figure 10 shows that the increase of chimney's diameter from its initial value of 10m to 20m, produces a substantial increase in the air mass flowrate inside the chimney due tothe resulted expansion of the chimney's cross-sectional area, and as this would cause some what decrease in the temperature rise.

As a result of the preceeding consequences, a decrease in chimney's velocity would take place, hence the output power would not consequently increase in a significant manner as it was the case with the air mass flowrate. A comparison between the results of Figures 7 and 10, would demonstrate the increase of maximum air mass flowrate and power output to reach the values of 960kg/s and 31500W, respectively, instead of the previous values of 390kg/s and 27000W, respectively, while it shows a decrease in temperature rise to be 5.8°C instead of the past 13.2°C. The output power is increased here in by only 16% of its original value, which is too low when compared to the gain as a result of the previous increase of the collector`s radius case, although it is not that far from the case of increasing the chimney`s height.



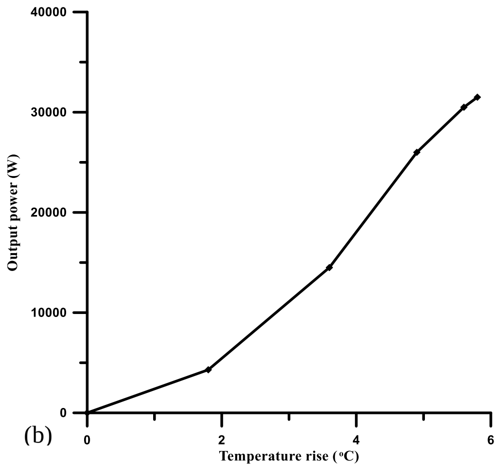


Fig. 10. The performance of solar tower during Jan., r=20m. (a) Air flow rate vs. Temperature rise. (b) Output power vs. Temperature rise.

5. CONCLUSIONS

The solar tower system is studied and mathematically analyzed in order to determine a functional formula for its performance indices and test the possible modification for its performance and the major effective parameters for the sake of achieving noticeable modification on that performance. The design paprameter are to be applied for the surrounding circumferences of Baghdad city for two different seasons; winter and summer in ordert to study the possible impact of that significant variation. The mathematical model results were first compared with the performance indicies of the Manzanares prototype for the design variable in order to quarantee the precission of the model. The comparioson results have shown excellent compatibility. The mathematical model`s test results showed that the outlet temperature of the collector is proportionally related to the collector's surface area and the solar radiation and conservable gain in solar tower power output is achievedviathe increase of the diameter of its collector, due to the rise in collector's outlet temperature thatrepresents the driving force to the rise of the air flowrate velocity inside the system`s chimney. A noticeablepower gain, although lower as compared with the increase of the collector`s diameter case, is proved to be achieved by the increase of the height of the system`s chimney thatboosts an increase in the air flow rate inside it but also decreases the difference in temperature. The least effective parameter on the performance indices is found to be the chimney`s diameter or it'scross-sectional area that leads to the relevant decrease in the air velocity inside it which in turns lowers the total power gain. Hence, any power enhancement efforts should focus primerly, on the the diamenter of the collector and moreover, the hight of the solar tower`s chimney.

6. REFERENCES

1. Chaichan, M. T., Kazem, H. A., (2011). *Thermal storage comparison for variable basement kinds of a solar chimney prototype in Baghdad – Iraq Weathers*, Int. J. of App. Sci. IJAS, **2**, pp. 2.
2. Neeraj, M., Rahul, M., Thakur, N. S., (2011). *Experimental analysis of a velocity field using variable chimney diameter for solar updraft tower*, Int. J. of Eng. Sci. and Technology IJEST, **3**, pp.4.
3. Schlaich, J., Bdrgermann, R., Schiel, W., Weinrebe, G., (2005). *Design of commercial solar updraft tower systems–Utilization of solar induced convective flows for power generation*, J. of Solar En. Eng. – trans. of ASME, **127**, pp.1.
4. Zhou, X., Yang, J., Xiao, Bo, Shi, X., (2008). *Special climate around a commercial solar chimney power plant*, J.of Eng. Energy ASCE, **134**, pp.1.
5. Hong, J. G., Jian, L. L., Shu, H. H., (2014). *Heat Storage Performance Analysis of Solar Chimney Power Plant System*, App.Mech. and Materials, **472**, 276-285.
6. Zhou, X., Xiao, Bo, Liu, W., Guo, X., Yang, J., Fan, J., (2010). *Comparison of classical solar chimney power system and combined solar chimney system for power generation and seawater desalination*, Sci. Direct pub., **250**(1), 1249-1256.
7. Zhou, X., Yang, J., Xiao, Bo, Guoxiang, H., Fang, X., (2009). *Analysis of chimney height for solar chimney power plant*, App. Therm. Eng., **29**, 178–185
8. Jeffrey, R. S., Brownson, (2013). Solar En. Conversion Systems, Ed(1), Academic Press, Cambridge, Massachusetts, pp. 403-427.

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